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Botanical extracts for insect management: lessons from participatory research in peri-urban horticultural systems of central Argentina

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Abstract

We evaluate botanical insecticides as a technological device for synthetic input substitution in peri-urban horticultural system transitions. For that purpose, a Participatory Action Research (PAR) framework was proposed, and garlic extracts (GE) performance was evaluated for pest and natural enemy regulation in lettuce crops in conventional and agroecological contexts. Through three PAR cycles under real production conditions, we observed GE effectiveness on aphids, thrips and natural enemies. Additionally, context-specific adaptations were noticed: for conventional systems, it is useful near harvest and serves as a trust-building tool while reducing synthetic insecticide dependence. Instead, for agroecological systems, it highlighted biodiversity's relevance for system redesign.

Keywords: Agroecological transitions - Agroecological Crop Protection (ACP)- Participatory Action Research (PAR) - Input substitution - Garlic extract - Lettuce crops - Aphid and thrips management.

Sustainable Development Goals: SDG 2: Zero hunger, SDG 15: Life on land and SDG 17: Partnerships for the goals

1. Introduction:

The overuse of synthetic insecticides has negative effects on the environment (Pavela 2016; Potts et al. 2016; Deguine et al. 2023) threatens farmer and consumer health (Pavela 2016), promotes insecticide resistance by major pests (Jensen 2000; Gao et al. 2012; Bass et al. 2015) and decreases natural enemy populations, reducing natural pest control (Nahar et al. 2020). The increasing evidence of these synthetic pesticides' detrimental effects has led to a global movement towards their substitution for more environmentally friendly practices (Tittonell 2014; DeLonge et al. 2016). Botanical insecticides have been widely recommended as alternatives to synthetic insecticides for crop protection (Dougoud et al. 2019; Isman 2020; Ngegba et al. 2022). They can significantly reduce the use of synthetic insecticides (Hikal et al. 2017) by replacing them, taking part in pesticide rotations, or synergizing with the toxicity of certain conventional insecticides (Isman 2020). In agroecological systems, they are also an alternative to the use of synthetic inputs (Gliessman 2017; Altieri et al. 2017). Despite significant growth in botanical insecticide literature and scientific research over the last decades, their commercialization, market expansion, and adoption have been slower than expected (Isman 2020, Pavela 2016). The lack of studies on botanical insecticides effectiveness in field trials, is one of the main reasons why their use is still restricted (Isman 2017).

Botanical insecticides play an important role as a technological device during the "substitution stage", which is a bottle-neck period that takes place in transition processes from conventional to more sustainable systems (Tittonell 2014). This phase is crucial since many farmers abandon the transition process at this point due to productive and economic high vulnerability (Tittonell 2019). According to Isman and Grieneisen (2014), the greatest effects on the implementation of botanical insecticides would result from emphasizing research on the utility of the extracts in field trials conducted in collaboration

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with local farmers. In this regard, open innovation approaches such as participative and active research enable collective knowledge generation (Fernandes de Oliveira et al. 2022; Mauser et al. 2013; Catullo et al. 2020; Lacoste et al. 2021). Taking all this into consideration, a participatory research methodology where professionals and farmers integrate their capacities and knowledge to contribute to "botanical insecticides—know-how" is imperative.

A myriad of plant essential oils and extracts have shown bioactivity on insects in screening studies and observations under laboratory conditions (Isman and Grieneisen 2014; Haddi et al. 2020). National extension services in 20 countries use garlic (*Allium sativum* L.) as one of the most widely used homemade botanical extracts for insect pest management in low-income countries (Dougoud et al. 2019). While there are many studies on the use of garlic for pest management (Isman and Grieneisen 2014; Anwar et al. 2016), little is known about its use under real productive conditions. The application of aqueous garlic extract (GE) in field trials has led to heterogeneous levels of control of hemipteran and lepidopteran pests (Fening et al. 2013; Baidoo and Mochiah 2016) while the effects on pests' natural enemies are largely unknown.

Lettuce (*Lactuca sativa* L.) is one of the most important leafy vegetable crops worldwide (FAO 2021) and globally, synthetic insecticides are commonly used for insect pests control (Barrière et al. 2014). It hosts several pests that compromise its production (Barrière et al. 2014); aphids (Hemiptera: Aphididae) and thrips (Thysanoptera: Thripidae) constraints it by direct damage (feeding) or indirectly as several virus vectors (Nebreda et al. 2004). In Argentina, it is one of the most widely grown vegetable crops (Marinelli et al. 2023) due to its short production cycle and quick payback period. In this sense, GE may constitute an alternative as an input substitution (Catullo et al. 2020) as well as a way to diversify productive strategies, and encouraging transition to agroecological systems (Ferrer et al. 2022).

According to Isman (2020) availability and registration are two of the principal barriers to using this kind of input in crop protection. In Argentina, there is a garlic extract registered in the official entity (National Agrifood Health and Quality Service - SENASA) and homemade garlic extracts are among the most used between agroecological farmers. Yet, at present, there is little information about using GE for primary insect pests in leafy vegetable crops. Experiments conducted under real farmers' productive conditions in a participatory research framework may contribute to a better understanding of GE use for primary insect management as well as the required adaptations to be considered for different productive management systems.

In an effort to bridge the gap between knowledge development and application, in the present work we introduce findings from field trials exploring timing and application strategies to enhance the effectiveness of botanical extracts in managing insects in horticultural productive systems. In this sense, our study contributes novel scientific and empirical insights, particularly focusing on input substitution

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stages farmers employing both conventional (synthetic insecticides) and agroecological (bioinputs and redesign) insect management practices.

The objective of this study was to evaluate the effects of GE for insect pests and natural enemies management in lettuce crops. A Participatory Action Research framework is proposed in order to test this technological device suitability as an input substitute in transitions for conventional and agroecological peri-urban contexts.

2. Materials and Methods

2.1 Study area and vegetable production systems

Field experiments were carried out during the spring-summer season from 2017 to 2020 in the eastern zone of the Agrifood Region of Central Córdoba (ARCC), a vegetable crop production area proximal to the metropolitan city of Córdoba, in Córdoba Province, Argentina (Marinelli et al. 2021, 2023; Giobellina et al. 2022). Nearly 72,880 tons per year of vegetables and fruits are produced annually in the ARCC, mostly by family farms not exceeding 10 ha (Marinelli et al. 2021). Approximately 70% of these farms are based on a vast diversity of vegetable crops, such as leafy vegetables (with a high frequency of lettuce), roots, tubers, bulbs, brassicas, and fruit vegetables (Marinelli et al. 2023). The management of these systems is predominantly "conventional", based on the use of synthetic inputs, while production is commercialized exclusively in the central market of the city (Giobellina et al. 2022). Production systems based on agroecological principles (FAO 2019; Wezel et al. 2020) are also present in the ARCC, but in a smaller portion of cultivated land. These farmers sell their products directly to consumers in the local agroecological market (Giobellina et al. 2022).

2.2 Participatory research

To study the efficacy of GE in controlling pests through field experiments with farmers, a participatory research was proposed through an adaptation of the Participatory Action Research (PAR) annual cycles (Fig. 1) according to the five stages described by Catullo et al. (2020). To study the efficacy of GE in pest control through field experiments in collaboration with farmers, we proposed a participatory research framework adapted from the annual cycles of Participatory Action Research (PAR) as described by Catullo et al. (2020), comprising five stages.

Stage 1. Diagnosis and planning (Fig. 1.1). An open workshop took place with local farmers, researchers, extensionists, technicians, and members of social organizations on August 14th 2017, at the Malvinas Argentinas Community Integrator Center (CIC). This workshop objective was to allow farmers to share their main production problems (diagnose) but also to define strategies and alternatives to evaluate (planning). Once the main problems were defined, professionals offered information about potential and available technologies such as botanical insecticides, along with an explanation of their origin, purpose, and usage. By doing so, it placed the farmers in a position where they could express their opinion and decide what to test in their productive systems. Farmers who manifested interest to be part of the experience were included as co-researchers (Cornish et al. 2023), and personal data was collected (contact information and productive system location) in order to move to the next PAR stage.

Figure 1. Participatory Action Research (PAR) iterative cycle stages: 1) diagnosis and planning stage; 2) protocol and experiment co-design at the co-researcher productive system; 3) on-farm experimentation stage under real productive conditions; 4) joint analysis and discussion during the feedback stage; and 5) socialization stage with PAR stakeholders and other professionals. This stage also represents the beginning (stage 1) of a new PAR cycle, except for year 3 (conclude PAR cycles because of SARS-COV19 pandemic).

Stage 2. Protocol and experiment co-design (Fig. 1.2). After open workshops, co-researchers' farms were visited by a professional team (composed of at least one researcher and one extensionist). During this visit, research questions were negotiated and narrowly formulated between professionals and co-researchers. In order to address these questions, professionals and co-researchers drafted a protocol outlining all the agreements, activities, and responsibilities for all parties carried out on the on-farm experimentation.

Stage 3. On-farm experimentation (Fig. 1.3). While co-researchers continued with their everyday activities, professionals performed the sampling and data collection. Although special emphasis was given to minimizing interference with the daily farm practices, the active participation of co-researchers was a priority, promoting knowledge exchange between the actors during this stage.

Stage. 4. Feedback (Fig. 1.4). Once field trials were completed, all the data were analyzed first by professionals and then shared with co-researchers, enabling joint analysis and discussion. Data analysis took place according to the statistical approach but also through integration of co-researcher observations and empirical knowledge during the experimentation process. In order to communicate all final results, technical reports were produced and made available as public material to consult.

Stage 5. Socialization (Fig. 1.5). At the end of each cycle, during the last stage, all results and learnings from the different on-farm trials that took place during the year were shared, and new queries and self-proposed co-researchers arose, facing the next PAR cycle. There were technicians, civil society organizations, decision-makers, and other farmers present at each workshop. The purposes of this stage were: i) to share results and present the knowledge that emerged from the synthesis of both co-researchers and professionals; ii) to engage in discussions among all present stakeholders and define new questions (what's next?); and iii) to register new self-proposed farmers for the next PAR cycle.

Three PAR cycles were carried out (from 2017 to 2020 field campaigns) following the same process described above. All relevant information provided by stakeholders during the PAR process was registered in notebooks and pictures (in order to record actions and moments that would help graphical description of each stage). Overall participatory research framework was analyzed according to two main purposes: a) knowledge generation and b) real-world action, conducted in a democratic and collaborative manner (Vaughn and Jacques 2020). To this end, three dimensions were considered for each stage analysis: participation level (of involved stakeholders), action (involvement and enacting change) and knowledge co-creation (different products).

2.3 Evaluation of GE effects on insects

The evaluation of the effects of GE on insects was carried out between 2017 and 2020. Experiments took place during the spring-summer seasons (August to January) in 2017–2018: “year 1”, 2018–2019: “year 2” and 2019–2020: “year 3”. Years 1 and 2 experiments were carried out together with co-researcher called “A”, who belonged to the “Asociación de Productores de Córdoba" –APRODUCO and follow a conventional management in his farm (31°21’39,4”S, 64°07’54,5”O). During 2019-2020, experiments were carried out with co-researchers “B” – “C”, who practice agroecological managements in their farms (31°32'01.3"S 64°09'40.5"W and 31°19'47.7"S 64°09'10.9"W, respectively) and are members of the Local Agroecological Market. These two prevalent management approaches are frequently observed in peri-urban productive systems, providing an ideal contrast for examining transition scenarios towards more sustainable food systems (Dumont and Baret, 2017; Altieri et al. 2017).

In all cases, evaluations of GE effects on pest and natural enemy abundance were carried out on lettuce *(Lactuca sativa*, var. Kikel). GE was sprayed using a 20-liter backpack sprayer, right after sampling, during morning hours when environmental conditions were favorable (T< 25 ºC; wind speed< 7-8 km/h) (Franke et al. 2010).

2.3.1 Year 1 (2017-2018 campaign)

The first year of on-farm trials took place at the co-researcher’s 60-year conventional management system (A). To evaluate GE in real production context of co-researcher A three treatments were evaluated: 1) spraying with GE through a weekly application of ‘RENAP 100’, a commercial garlic extract in a solution of 150 mL/10 L water; 2) spraying with insecticide by weekly application of the usual synthetic chemicals lambda-cyhalothrin and imidacloprid, according to co-researcher A frequent management (imidacloprid + lambdacialothrin: 17.5 a.i.g./100 L + 6.25 a.i.g./100 L); and 3) spraying with water by weekly application as a control treatment. The experiment was performed in a 130 m × 30 m productive plot, where three subplots (15 × 30 m each) were treated with GE and the other three were treated as controls. These two subplots were located on the southern end of the plot to avoid interference with the farmers’ usual practices. The remaining area received the usual insecticide treatment, and two subplots were delimited for sampling. In the center of each subplot, a similar 3 × 5 m area was delimited, and weekly visual counting sampling (see details below in the sampling procedure) was performed during the entire crop cycle (41 days), from transplanting (November 4th, 2017) to harvesting (December 14th, 2017), to evaluate insect abundance for each treatment.

2.3.2 Year 2 (campaign 2018-2019)

Co-researcher A farm was again the scenario for the second on-farm trial, but some modifications were incorporated according to observations and lessons from year 1. On the one hand, three subplots (10 × 30 m) corresponding to each treatment (GE, insecticide and control) were separated by 20 m to reduce possible overlapping of treatments, as GE-active compounds are highly volatile. On the other hand, samples were taken from spring (September 18th, 2018) until summer (January 11th, 2019), considering that aphid and thrips activity seasonally varies (aphid activity starts between August and September, the last days of winter, while thrips activity starts between November and December, the last days of spring).

2.3.3 Year 3 (campaign 2019-2020)

During the third year, on-farm trials took place at two agroecological farms with co-researchers B and C in productive systems where agroecological management has been established for more than 10 years. On each farm, the experiments were carried out in plots of 50 × 3 m divided into two equal-sized parcels of 25 × 3 m, where GE and control treatments were applied. Insecticide use was not considered because co-researchers B and C do not use any synthetic chemicals for insect management. To avoid overlapping treatments, sampling was performed at the center of each parcel, leaving 20 m between treatments.

2.3.4 Sampling procedure

The following variables were quantified: 1. Visual direct counting by *in situ* sampling; and 2. counts of aphids and thrips using sticky traps. A nondestructive sampling method was defined for co-researchers so that they could sell all lettuce produced. On each *in situ* sampling date, 20 plants per treatment were selected for sampling. Specifically, five randomly chosen plants from four consecutive rows within the central area of each treatment subplot were inspected. Each plant underwent a detailed examination (lasting 3-5 minutes), and all the observed insects were counted and recorded.

During the second- and third-year trials, one yellow (for winged aphids) and one blue (for thrips) 12 cm × 12 cm sticky trap were placed in the center of each treatment plot to detect the arrival or activity of winged individuals of both aphids and thrips (Bravo-Portocarrero et al. 2020; Serra et al. 2023). The traps were replaced weekly before treatment and taken to the Laboratory of Agronomic Zoology at the Faculty of Agricultural Sciences of the Córdoba National University for insect taxonomic identification at the genus or species level (Delfino 1983; De Borbón 2005; Hoddle et al. 2019).

2.4 Statistical analyses

The data were analyzed through generalized linear mixed models using Poisson or negative-binomial distributions, which are suitable for counting data. The abundances of aphids, thrips, total herbivores and natural enemies were considered the response variables; treatment (GE, control and insecticide) was the fixed effect, and the sampling date was included as a random factor. All the analyses were performed using the “glmmTMB” package (Brooks et al. 2017) in R (R Core Team 2023), which allows us to run zero-inflated models, as some of our variables contain too many zero counts. Assumptions were checked

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using the performance package (Lüdecke et al. 2021), while differences between treatments were evaluated by means of the "emmeans" package (Lenth 2018).

3. Results

The participation of stakeholders, the actions undertaken, and the co-constructed knowledge differed across the five cycles of Participatory Action Research (PAR) (Table 1). Each cycle involved varying levels of engagement, specific actions tailored to the needs and context of that stage, and the development of unique insights through collaborative processes.

3.1 Diagnosis and planning stage

During stage 1 of year 1, three general productive problems were identified by farmers: soil fertility, soil-borne diseases, and insect pest management. In relation to the last concern, farmers specifically demanded alternatives to synthetic insecticides for aphid (Aphididae) and thrips (Thysanoptera) control in lettuce, and GE was selected as the alternative to be tested. Regarding stakeholders participation during this stage (Table 1), professionals' level of participation was slightly higher as they organized the workshop and ignited their participation through the proposed strategy. Decision-making was a result of the expressed farmers' concerns about production and insect pest management (Table 2, year 1).

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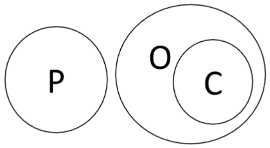
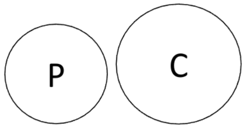
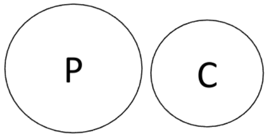
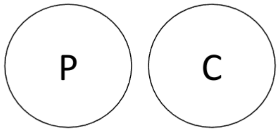
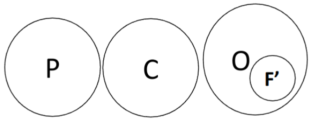
Table 1. Participation degree, identified action and Knowledge co-construction through all five PAR cycle stages during the three year campaigns, based on the methodology proposed by (Catullo et al. 2020).

Stage \ Dimension	1) Diagnosis and planning	2) Protocol and experiment co-design	3) On farm experimentation	4) Feedback	5) Socialization
Stakeholders participation level					
Action	Problem identification and definition of an alternative to be tested with farmers in their fields Self proposed farmers co-researchers to develop the following PAR stages	Research questions definition Experimental design considering co-researchers’ real productive context	Strong P intervention during sampling and surveys C contributed with everything necessary to ensure the continuity of the trial Bonds of trust developed New topics* were addressed between C and P	Data statistical analysis Empirical knowledge Scientific-technical knowledge Shared lessons, design and protocol adjustments to be considered for next PAR cycle	P and C present results and relevant learnings Interaction with community members present during the workshop New problems delimitation and possible solution to be defined with the community
Knowledge Co-construction	Stakeholders actively involved after collective discussion (legitimacy of their active participation)	Research Protocol agreed between P and C	Analyzed data Emergent information and not expected results	Technical report synthesizing both scientific and empirical knowledge	New Farmer co-researchers volunteered. Next PAR cycle (until 2020 - SARS COVID-19)

P: Professionals; C: farmer co-researchers; O: other community stakeholders (other farmers and farmer´s associations, professionals from different institutions, decision makers); F’: new Farmer co-researcher/s for next PAR cycle. Circle size represents each actor's participation degree during each stage.

*Id and diagnose of problems in other crops, biodiversity and natural enemies identification and importance, severe pests and curative alternative tools.

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3.2 Protocol and experiment co-design stage

As GE was the technology selected to be tested, for years 1 and 2, research questions were defined as follows: a) is GE more effective than synthetic insecticides in controlling aphid and thrip populations in lettuce? and b) are natural enemies affected by GE and synthetic pesticides in a similar way? Year 3 inquiries were the same, but in an agroecological productive context. A protocol was developed according to each co-researcher productive context (Table 1).

3.3 On-Farm experimentation stage

Each field trial was the space for sampling according to the experimental design, but it was also the arena for emergent and unexpected information while time-sharing with farmers (Table 2). By spending time on the field, relaxed moments where possible and discussions on different subjects took place, allowing another kind of interaction and not expected information emerged (Table 2). During the second year of field trials, it was possible to discuss ecological interactions and their promotion with the co-researcher A. The professional team's recommendation to include a question about natural enemies, allowed this ecological service to become visible to co-researcher. Then professionals provided information about how it is possible to promote natural enemy action if implementing biodiversity management, such as diversified plant strips. For co-researchers B and C, attention was given to alternatives for severe pest control (aphids or caterpillars in coles) (Table 2).

Table 2. Summary of selected statements made by co-researchers during the PAR cycle and the context in which these statements were made.

Year	Statements	Context
Year 1	"Insects have become resistant to the products we usually use for pest control. I have been using the same products for at least 10 years, increasing the dose and frequency of products."	Farmers made it clear during stage 1. They wanted to explore alternatives for pest control, as they noticed that insects, particularly aphids and thrips, become resistant to the products they usually use (neonicotinoids and pyrethroids).
	"If overlapping is possible when using GE, then I can apply it in strips, reducing the amount of product to be used."	During stage 4, Co-researcher A saw a chance to use GE in strips, lowering the quantity of product to apply because of its volatility.
	"My wife ate the lettuce that we harvested from this experience, normally she never did it before."	This was brought up in stage 4, since family members did not consume products harvested from synthetic insecticides treated plots.
Year 2	"I realize that we can use botanical extracts even when harvest time is near." "I used GE when I noticed an infestation of aphids a few days before harvest. I did not miss the possibility of harvesting and selling the product."	Mentioned at stage 2 as during stage 4, co-researcher A expressed concern about the time between product application and harvest time, as aphids spoil the aesthetic appearance of the product and often define its entrance to the city central market. Registered GE has no pre-harvest interval.
	"It is relevant to consider the time of year when insects are more active."	During stage 4 of year 1, co-researcher A noticed the relevance of considering both (aphids and thrips) insects population dynamics. Therefore, in the second year's on-field trial the effect of GE was tested on three different moments: early spring, spring, and early summer.
Year 3	"To control aphids we need ladybugs, but to have ladybugs, we also need some aphids to be present."	When co-researchers B and C agreed to participate in stage 1, they expressed precise ideas regarding the ecological interactions taking place in their systems.
	"We may sell our products at the Local Agroecological Market, as people do not complain about the presence of some insects on our products."	Co-researchers B and C shared (stage 1) that they could sell their products on alternative markets where consumers may have a clearer position about consuming fresh products without synthetic insecticide application.
	"Having flowers is relevant for natural enemies as they inhabit there."	At stage 3, co-researchers B and C showed interest not only on plagues but also on natural enemies and the importance of flowers on the field borders or limits.
	"We need tools for severe pests management, such as caterpillars on cabbage and cucurbits"	During the feedback stage, co-researcher B was concerned about severe pests that they were unable to regulate.

3.3.2 GE effect on insect regulation

During on-field trials in lettuce crops, several insect orders were sampled: Hemiptera, Thysanoptera, Lepidoptera, Coleoptera, and Diptera, among others. Aphids (Hemiptera, Aphididae) and thrips (Thysanoptera) were the most abundant herbivorous insects. More than 90% of the captured aphids were identified as *Nasonovia ribisnigri* (Mosley), which was also the only species that developed colonies on lettuce crops. Two genera of thrips were observed: *Frankliniella* sp. and *Caliothrips* sp., which were the most abundant. The natural enemies most frequently observed were ladybugs (Coleoptera, Coccinellidae), predatory bugs (Hemiptera, Geocoridae, and Anthocoridae), predatory flies (Diptera, Syrphidae), and parasitoids (Hymenoptera), quantified as the number of mummy aphids. Only thrips, aphids, and total natural enemies were analyzed, as the count of the other insects was low and did not allow statistical analysis.

Table 3. Insect visual counting on lettuce plants in control, garlic extracts (GE) and insecticide treatments during on-farm research experimentation for insect management in conventional and agroecological farms. Values represent the average number of insects per plant across the sampling season.

Farm management	On-farm campaign*	Treatment	Thrips	Aphids	Natural enemies
Conventional	Year 1 (A)	Insecticides	1.19 (± 1.24) a	1.18 (± 0.90) a	0.02 (± 0.02) a
		GE	1.06 (± 1.10) b	0.84 (± 0.64) b	0.04 (± 0.05) b
		Control	0.98 (± 1.02) b	0.99 (±0.76) ab	0.07 (± 0.08) c
	Year 2 (A)	Insecticides	2.38 (± 1.07) ab	1.71 (± 1.43) a	0.10 (± 0.05) a
		GE	2.13 (± 0.97) a	1.83 (± 1.53) a	0.22 (± 0.11) b
		Control	2.47 (± 1.11) b	2.19 (± 1.84) b	0.35 (± 0.17) c
Agroecological	Year 3 (B)	GE	3.49 (± 0.93) a	7.96 (± 3.02)	0.25 (± 0.07)
		Control	4.29 (± 1.14) b	7.79 (± 2.96)	0.32 (± 0.08)
	Year 3 (C)	GE	3.43 (± 1.10) a	3.86 (± 1.48)	1.99 (± 0.73)
		Control	6.62 (± 2.12) b	4.67 (± 1.76)	2.42 (± 0.85)

Same letter indicates that there was no significant difference (Tukey HSD, $p < 0.05$). GE: garlic extract. * (A), (B), (C): Co-researcher ID.

Regarding pests regulation effects, a decrease in thrips abundance was observed in almost all field trials as an effect of the GE treatment for both visual counting (Table 3) and sticky color trap sampling (Table 4). During the first year under conventional management, thrips were more abundant in the insecticide treatment group than in the GE and control groups (x^2 = 14.35, DF = 2, $p<0.001$). No significant differences were observed between GE and control. In the second year, the lowest thrips abundance was observed in the GE and insecticide treatment groups compared to that in the control group (x^2 = 8.77, DF = 2, $p=0.012$). Using sticky color traps (Table 4) during year 2, plots treated with GE and the control showed lower thrips abundance than those treated with insecticide (x^2 = 12.13, DF = 2, $p=0.002$). At both agroecological management sites (third year), GE had fewer thrips than did the control plots (x^2 = 12.06, DF = 1, $p<0.001$ for co-researcher B; x^2= 30.14, DF = 1, $p<0.001$ for co-researcher C). During the third year, a lower abundance of thrips was again observed, during third year, in the GE treatment than in the control at both agroecological management sites (for co-researcher B: x^2 = 7.60, DF = 1, $p=0.006$; co-researcher C: x^2 = 111.32, DF = 1, $p<0.001$). The values of x^2 and p showed that, as a result of sampling occurring after weeding, co-researcher C showed the largest difference.

Concerning aphids, the observed GE effect was similar to that on thrips (Table 3). Compared with the insecticide treatment, GE showed lower aphids abundance during year 1 (x^2= 15.15, DF = 2, $p<0.001$) and for color sticky traps during year 2 GE treatment had fewer winged aphids than the insecticide and control treatments (x^2= 22.63, DF = 2, $p<0.001$) (Table 4). However, during year 3, there were no significant differences between the GE and control groups, neither in terms of the visual counting sampling method nor in terms of the color of the sticky traps.

Table 4. Abundance of winged aphids and thrips in lettuce crops captured in yellow and blue sticky traps, respectively, during two years of on-farm experimentation under insecticides and garlic extract (GE) treatments, with water used as the control. Values represent the average number of insects per trap across the cropping season.

On-farm campaign	Farm management	Co-researcher*	Treatment	Thrips	Winged aphids
Year 2	Conventional	A	Insecticides	65.1 (± 13.9) a	8.80 (± 2.34) a
			GE	56.5 (± 12.1) b	4.84 (± 1.33) b
			Control	58.6 (± 12.5) b	7.97 (± 2.12) a
Year 3	Agroecological	B	GE	70.9 (± 20.7) a	4.03 (± 0.91)
			Control	82.3 (± 24.0) b	2.87 (± 0.70)
		C	GE	145 (± 24.8) a	12.6 (± 2.96)
			Control	175 (± 29.7) b	15.0 (± 3.48)

The same letter indicates that there was no significant difference (Tukey HSD, $p < 0.05$). * (A), (B), (C): Co-researcher ID.

In relation to natural enemies, a clear negative effect was observed in both Insecticides and GE treatments during field trials in years 1 and 2 in conventional management. The greatest abundance was detected in the control plots (Table 3), followed by the GE and insecticide plots (x^2= 24.98, DF= 2, $p<0.0001$). Field trials with agroecological co-researchers B and C showed lower abundance of natural enemies in GE, but only as a trend.

3.4 Feedback stage

During this stage, unexpected information arose as results were revised also by co-researchers (Table 2). For instance, the relevance of application time and harvest, as co-researcher A noticed that GE may be used even closer to harvest time as it does not have any pre-harvest interval (Table 2, year 2; Table 5). The same co-researcher also suggested that if overlapping occurs when using GE, then strip application may be possible (Table 2, year 1; Table 5), and shared with professionals that he felt confident to explore the effectiveness of GE in other crops (e.g. he observed that if GE was used during blossoms in eggplant, the fruit would not be damaged by thrips) (Table 5). On the other hand, with agroecological co-researchers B and C, the role of GE had a better performance as a preventive tool, but it was not enough for severe pests such as aphids and caterpillars in cabbages (Table 2, year 3; Table 5). Protocol adjustments were also considered thanks to discussion during this stage. The Year 1 experimental design was modified for the second year of the on-field campaign in three aspects. The first adjustment was to introduce time replicates to address aphid and thrips population dynamics (for details, see the year 2 campaign experimental design in the Materials and Methods section), as co-researcher A suggested (Table 2). Second, the distance between treatments should be increased considering GE volatility to avoid possible treatment overlap (at least 20 m). This event was reinterpreted by co-researcher A, who considered that because of GE volatility it could be applied on stripes, reducing the amount of product and cost of application (Table 2; Table 5). Further studies should be carried out to confirm this proposal. Finally, the third modification was the use of sticky color traps to detect winged insect activity between weekly visual counting and registration.

3.5 Socialization stage and a new PAR cycle

Over the course of the three years, this stage was organized by professionals but results were presented by either them and/or co-researchers when they felt like doing so, empowering them as stakeholders and strengthening an incipient ‘campesino a campesino’ dialogue and practice (Holt Giménez 2008). Strategically, the first-year socialization stage took place on the premises of one of the research institutions in order to bring farmers to an academic space. In the second year, it took place in reverse, inviting academic actors and decision-makers to a farmers' organization facility in the ARCC. Finally, at year 3 stage 5 was adapted to the SARS-COV19 pandemic, so a webinar was proposed (Table 5).

4. Discussion

4.1 PAR outcomes

At the stage 1 workshop, insect pest control and insect resistance to frequent synthetic insecticides emerged as some of the main issues, and GE was the potential alternative to test. Participation was translated to action, through active farmers involvement, definition of the main problems and the alternative to be tested, as well as their self-convening to continue in further PAR stages. Field trials were research arenas to apply, learn about it, improve and validate GE. Outcomes evaluation, modifications to protocols, trial designs, and guidelines for new trials were always agreed upon by co-researchers and professionals during on-field activities or as the products of collaborative workshops. This environment promoted learning through action, where the generation of new knowledge from collective experience became relevant in addition to what the scientific approach might say about a phenomenon (Catullo et al. 2020; Sachet et al. 2021; Cornish et al. 2023).

Table 5. Significant lessons from the three year Participatory Action Research (PAR) cycles evaluating GE device with ARCC horticultural farmers.

Year	PAR Year 1	PAR Year 2	PAR Year 3
For Professionals	Better GE performance than synthetic insecticides for thrips and aphids management GE had a lower effect on natural enemies than synthetic insecticides	Better GE performance for thrips management than insecticide and control treatments. Good GE performance for aphids management but lower than insecticides. GE had a lower effect on natural enemies than synthetic insecticides Treatment distance to prevent overlapping in experimental design	Better GE performance for thrips management than control treatment. GE may had effect on natural enemies When using repellents should be accompanied by other management practices that redirect its location in the system
For farmer co-researchers	Can GE be applied in strips lowering product quantity and costs for application?	No pre-harvest interval GE for thrips management in other crops (e.g. eggplant blossom)	Good as preventive but not efficient for severe insect pests

Emergent information and not expected results	Treatment overlapping	Farmer felt confident to use GE on other crops and start wondering about natural enemies and biodiversity management	Should GE be used with other biodiversity strategies to improve its efficacy?
Considerations for timing and application strategies	Preventive, weekly application needed		
	Possible strip applications	Optimal for application close to harvest	GE needs integration with other biodiversity management strategies to move towards systems redesign
Socialization strategy	Co-researchers and professionals present results in a research academic institution (CIAP-INTA)	Co-researchers and professionals present results at a community hall belonging to a farmers' organization	Socialization stage through a webinar (SARS-COV): https://www.youtube.com/live/Che9zQkl2Xs?si=-UhMOQBJU-dyxLrx
Future perspectives	Strip application and economic impact research	Conventional versus agroecological productive contexts	Push- pull strategy

As mentioned by Cornish et al. (2023), knowledge co-creation arises due to interactions between different stakeholders with different cognitive backgrounds that are put at stake in action through a concrete experience and enabled the beginning of a more democratic and horizontal bond between stakeholders for the remaining research PAR process (Cargo and Mercer 2008; Vaugh and Jacques 2020).

Action in contextualized research (Fernandes de Oliveira et al. 2022; Ohly et al. 2023) additionally offered useful information about the co-researchers' validation process, which differed between management systems. For conventional co-researcher, GE is a tool that may be used close to harvest. This is a crucial factor because the city food market has rigorous regulations on pesticide residues, and GE has no pre-harvest interval (Table 2), while most used synthetic insecticides do have a 10 to 15 days interval. Paradoxically, if a product is infested with insects or has visible damage, it is penalized for price or rejected for sale.

In contrast, for agroecological co-researchers, although GE is already an appropriate tool for them, participatory trials have served to understand two important aspects of its use (Table 5): a) for the curative management of severe pests, other control tools may be necessary (e.g. bioinsecticides such as entomopathogens); and b) insects will stay in the system after being repelled by GE, so its use should be combined with biodiversity-based strategies such as push-pull paradigm (Cook et al. 2007; D'Annolfo et al. 2021), moving the system towards redesign in transition processes (Altieri et al. 2017). In addition, they did not feel the same pressure as conventional co-researcher when selling lettuce with visible insects

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or damage, as consumers from the local agroecological market are tolerant in this regard. Therefore, damage thresholds differ depending on where they sell their products: city concentrator market or differential markets such as agroecological market.

By carrying out field trials with farmers, knowledge about the best timing and application strategies contributed with information about how to optimize the efficacy of botanical extracts for pest insect management, as Isman (2017) postulated. Both conventional and agroecological perspectives allowed us to identify positive (less risk for health and environment, less effect on natural enemies than synthetic insecticides) and negative aspects (requiring frequent applications, not effective for severe pests) regarding GE as a feasible technological device for synthetic insecticide substitution (Isman 2020; Fening et al. 2013; Baidoo and Mochiah 2016). In this sense, it can be useful in first stages of transition processes, as an alternative tool to the usual synthetic insect management but also to promote more complex regulation mechanisms through biodiversity management.

4.2 GE effect on insect regulation

The lower presence of thrips in the GE treated plots compared to the insecticide and control plots demonstrates its regulatory effect on their populations in lettuce. The low insecticide treatment effect on thrips abundance during year 1 could be related to the presence of resistant individuals in that thrips population. It is important to note that co-researcher A had already observed the low efficiency of applying synthetic insecticides to control thrips, which was one of the main motivations for joining the trials (Table 2, year 1). When the frequency of insecticide-resistant individuals in a population is high, the expected level of control is not achieved (Gao et al. 2012). It has been globally reported that thrips are resistant to neonicotinoids (Bass et al. 2015) and pyrethroids (Jensen 2000), which are the most frequently used synthetic insecticides in the study area. This aligns with previous studies on Brassicaceae crops (Fening et al. 2013; Baidoo and Mochiah 2016). On the other hand, similarities between the GE treatment and the control may be due to the proximity between the two experimental plots causing overlapping of treatments (the experimental design considered minimal interference with the daily practices of farmers co-researchers). As part of the co-design building with co-researcher A both treatments were placed on the same side of the experimental plot design (see experimental design for years 1, 2 and 3 in the Materials and Methods section). The GE effect on insects is strongly related to the presence of sulfur (Zhao et al. 2013; Martins et al. 2016; Shang et al. 2019; Dougoud et al. 2019) and volatile substances (Baidoo and Mochiah 2016), such as diallyl sulfide (Anwar et al. 2016), so the treatments may have overlapped given the volatility of some of the bioactive compounds. To reduce possible treatment overlap, the year 2 experimental design was modified, and a 20 m distance between treatments was established

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(longer distance possible between treatments, considering the typical productive plot to minimize interference among treated plots).

In year 3 trials, GE was particularly effective in the agroecological co-researcher C system (Table 1), especially after a weeding event in the experimental plot. One hypothesis for why GE was particularly effective after weeding was that thrips displaced from weeds preferentially moved to the control plot. Although further studies are needed, this event highlights, on the one hand, the repellent effect of GE on thrips and, on the other hand, the importance of combining the use of repelling botanical extracts (such as GE) and plant traps within the "push-pull" framework (Cook et al. 2007; D'Annolfo et al. 2021). It also emphasizes, as Altieri (2017) has mentioned, that GE as an input substitute must give way to system redesign, through other biodiversity management strategies based on new ecological interactions.

In relation to aphids, during years 1 and 2, the observed GE effect on aphids was similar to that on thrips (Table 3). However, during year 3, there were no significant differences between the GE and control groups, neither in terms of the visual counting sampling method nor in terms of the color of the sticky traps. According to these observations, GE may regulate aphid populations, although it seems to be less consistent than on thrips.

In terms of the treatment's effects on natural enemies, both GE and synthetic insecticides had a negative effect in contrast to the control in conventional context. Yet, it was less pronounced in GE than in synthetic insecticides treatment. In agroecological systems, the impact of GE was noticeable only as a trend. Any potential effect of GE on the abundance or activity of natural enemies appears to be significantly lower than that of synthetic insecticides. Analogous outcomes were documented for cabbage crops, for which natural enemies were significantly less prevalent in insecticide-sprayed plots than in garlic- and pepper-sprayed plots (Fening et al. 2013; Baidoo and Mochiah 2016). The lower natural enemy abundance in the GE plots might be explained by the density-dependent response of some natural enemies to the lower abundance of herbivorous prey/hosts (Gould et al. 1990; Ruberson et al. 1998; Baidoo and Mochiah 2016), by possible GE repellency or side effects on natural enemies (Fening et al. 2013; Ndakidemi et al. 2016). GE can also interfere with the olfactory stimuli of natural enemies when searching for prey or hosts (Hikal et al. 2017). In any case, GE can be considered as an important tool for chemical insecticide substitution, regulating herbivores (Nahar et al. 2020) while biological control (regulation ecosystem service) evolves and the system moves towards redesign transition stage (Altieri 2017; Duru et al 2015).

Conclusions

Different potential applications of GE as an insect management tool were identified through a participatory research framework: as a chemical input substitute in conventional systems and as a tool for

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insect regulation in agroecological systems. Through contextualized and concrete actions, the iterative PAR cycle encouraged actor participation, protocol and experimental design improvements, and knowledge co-creation. Studying this technological device in real production conditions through participatory research methodologies allowed, not only to understand GE effect on target insect populations, but also the particular adaptations for its use in different production contexts.

In general, GE regulates main pests. In conventional contexts, it is useful especially close to harvest, and has significantly lower effect than synthetic insecticides on natural enemies. Using GE also allowed discussion of other insect management practices and made visible biological control for the conventional co-researcher. Botanicals such as GE may be either used alone or in mixture with conventional insecticides, while other strategies may be incorporated by conventional farmers. Additionally, as substitution input transition is a critical stage, it could also be useful to build trust while reducing reliance on synthetic insecticides.

In agroecological systems, GE showed great performance in regulating thrips populations and had no significant effect on aphids or natural enemies. Through participatory research two important aspects emerged for future research: i) GE may be combined with other practices of biodiversity management, both to improve its efficacy (e.g. combined in a “push-pull” strategy) and to move towards systems redesign stage; ii) an alternative tool for severe pests should be considered, as repellents may not be sufficient to regulate that kind of event.

It is crucial to stress that while weekly use of GE is beneficial as a preventive measure, its primary purpose is not lethal action; therefore, it may not be successful for curative measures. When presenting GE as an insect management tool, this information needs to be explicit, so farmers may adjust expectations about its effect and its incorporation for insect management in their systems. Technicians who recommend GE also need to be aware of how it works when assisting farmers. This is why the PAR’s socialization stage becomes so relevant, as all results and main lessons are shared with other community members, highlighting meaningful lessons for all different stakeholders (other farmers, extension agents, institutions, decision makers, etc).

Botanical insecticides, such as garlic extract, are only one of many other technological devices to move insect management strategies into more sustainable practices. In this sense, botanicals serve as an alternative to synthetic insecticides in conventional management and for insect regulation in agroecological peri-urban horticultural systems. Field trials performed in collaboration with grower communities provided valuable insights into appropriate research designs. Finally, GE allowed a higher pest control with less natural enemies collateral damage compared to synthetic insecticides, especially in conventional systems.

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Disclosure statement

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval

The authors approve.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The authors consent to publication.

Availability of data and material

The datasets generated and analyzed during the current study are available in the INTA repository at http://hdl.handle.net/20.500.12123/16782

Authors' contributions

All the authors contributed to the investigation of this study. Conceptualization, A.C.E. and G.M.A.; Methodology, A.C.E., V.M., N.L.R. and S.G.V.; Writing – Original Draft, G.M.A. and A.C.E.; Writing–Review & Editing, G.M.A., A.C.E., V.M., S.G.V., N.L.R., B.J.G., and B.M.; Formal analysis, V.M., G.M.A. and A.C.E.; Project administration, A.C.E.; Funding Acquisition, A.C.E. and S.G.V.; Supervision, A.C.E. and N.L.R.

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