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ORIGINAL ARTICLE

Survey on *Aculops lycopersici* and operational factors potentially affecting successful pest management among 50 tomato producers in Germany

Alexander Pfaff[1] · **Elias Böckmann**[1]

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Abstract
Aculops lycopersici (Acari: Eriophyoidea) is a pest in tomato cultivation worldwide. In recent years, the number of reports of *A. lycopersici* infestations in tomato have increased in Germany. In the first half of 2019, a survey of 50 tomato producing farms was conducted to assess the occurrence of *A. lycopersici* and the impact this pest has on tomato cultivation in Germany. The participating farms represented ~ 3.5% of the 1448 farms in Germany with protected tomato production in 2019. Total tomato production area considered in the survey was 131.8 ha which corresponds to ~ 34% of the 385.63 ha of protected tomato production area in Germany in this year. *A. lycopersici* presence was reported by 33 of the 50 surveyed farms, within the last 5 years. Amongst these 50 participants it was the pest with the highest relative importance in terms of plant protection effort exerted. *A. lycopersici* occurrence was reported more frequently from production systems with a higher intensification. For instance, heating in cold months and a larger production area were considered intensification factors in this study. However, due to autocorrelation between intensification factors it was not possible to link increased occurrence to specific factors. As the intensification factors favouring *A. lycopersici* occurrence are more prevalent in integrated production, those farms faced *A. lycopersici* occurrence more often than the organic growers in this study. Plant protection strategies often combine broad treatments of sulphur with local abamectin treatments, removal of infested plant material and the introduction of natural enemies.

Keywords *Aculops lycopersici* · Distribution · Germany · Plant protection · Farmers perception · Survey

Introduction

Pest regimes in modern agriculture and horticulture are in a process of constant change (Kolar and Lodge 2001). The occurrence of new pests is facilitated by changes in climate (Hellmann et al. 2008), or by changes in production and cultivation methods, which especially allow airborne pests to spread swiftly and establish in new regions when favourable conditions are met. Another driver in this process is local and international trade and travel, which spreads less mobile and non-airborne pests into new regions (Kolar and Lodge 2001). Greenhouse production of tomato in Germany and its pest regime is not exempt from this. Currently the greenhouse cultivation area of tomato in Germany measures 385 ha (Destatis 2020). Among the pests that occur in tomato production in Germany, the tomato russet mite *Aculops lycopersici* (Tryon) is currently spreading and establishing on tomato production sites across the country.

The tomato russet mite *Aculops lycopersici* (Acari: Eriophyoidea), an eriophyoid mite, is considered a pest of several Solanaceae crops (Perring and Farrar 1986). *A. lycopersici* is currently found throughout the world in both tropical and temperate regions. Before 1999 *A. lycopersici* was rarely reported as a pest on tomato in Germany (Merz 2020). In recent years the economic impact of eriophyoid mites such as *Aculus scchlechtendali*, *Calepitrimerus vitis* and *A. lycopersici* has increased worldwide (Duso et al. 2010), as well as in Germany in the case of *A. lycopersici* (Merz 2020). *A. lycopersici* causes bronzing and a russeted appearance of leaves and stem as it feeds on surface cells, leading to the death of leaves and even complete plants since they no longer are able to photosynthesise (Royalty and

✉ Alexander Pfaff

1 Julius Kühn Institute, Institute for Plant Protection in Horticulture, Messeweg 11-12, 38104 Brunswick, Germany

Perring 1988). In contrast to several other eriophyoid mites, *A. lycopersici* has a superficial lifestyle and does not induce or inhabit galls on plant tissue (Van Leeuwen et al. 2010).

Several factors make *A. lycopersici* a problematic pest. It has a high reproduction rate, and at less than 0.2 mm in length, is very small in size (Haque and Kawai 2003). There are no plant protection products authorised for use specifically against *A. lycopersici* in tomato cultivation in Germany (BVL 2023). Authorised products against mites in general have been shown to be limited in efficacy, or are expected to be limited in efficacy due to them being contact acaricides (Vervaet et al. 2021). Although a number of studies have shown that certain predatory mites, for example *Amblyoseius fallacis* and *A. swirskii* (Brodeur et al. 1997; Park et al. 2010, 2011) feed on *A. lycopersici*, the practical implementation of biological control is limited (van Houten et al. 2013). More recent studies show very promising results for different predatory mites under semi-practical conditions but have yet to be confirmed with trials in practical cultivation (Pijnakker et al. 2022a, b; Vervaet et al. 2022; Castañé et al. 2022). In practice, recognition of *A. lycopersici* infestation coincides with symptom recognition on plants. Early symptoms such as light chlorosis on leaves, or light grey and brown shades on the stem are easily overlooked. Later, more obvious symptoms may be misdiagnosed. For instance stem and leaf browning might be mistakenly attributed to the fungus *Phytophthora infestans* (Crüger et al. 2002) in practice and by people unexperienced with the pest *A. lycopersici*. As yet there are no efficient *A. lycopersici* monitoring methods available for practical tomato cultivation (Pfaff et al. 2020).

Whenever new or invasive pests occur and negatively impact the production of food, in this case tomato production in greenhouses, information on the frequency of occurrence and case specific data from farms are essential for estimating economic damage potential. When farms with *A. lycopersici* presence are identified, a closer look at cultivation techniques and factors such as substrate, crop rotation, climatic conditions, applied pesticides or introduced beneficial arthropods might reveal intervention strategies that can be exploited to reduce the impact of *A. lycopersici*. The experience of farmers may help to better understand the pest dynamic of *A. lycopersici*, and could aid in the development of efficient countermeasures. To obtain this information, the presented survey of farms with tomato production was carried out.

Materials and methods

Survey details

A survey was developed and integrated into the professional survey platform https://umfrageonline.com and the domain "tomatenschaedlinge.org" was created to redirect participants to the survey on *umfrageonline*. In December 2018, a link to the survey was forwarded to the official plant-protection consultation services of the federal states, to private plant protection consultants and to grower organisations, with the request to disseminate the survey to tomato growers. In this way, an undocumented number of tomato-producing farms were contacted via E-Mail and invited to fill out the questionnaire. Aside from being offered the possibility to receive information on the results of the survey, no form of payment was offered to growers for participating in the survey. Due to a rather small number of participants by the end of February 2019, the decision was made to switch to phone interviews. The contact addresses of growers were obtained using google search engine. The following search terms were used: "Tomatenproduktion in [federal state]" or "Tomatenanbau in [federal state]" for each of the 16 federal states of Germany to achieve a spatial distribution of participants across Germany.

Criteria for integrating farms in the analysis:

- Production of tomato located in Germany
- At least 50 m^2 tomato cultivation area
- Production for commercial purposes
- The questionnaire was completed (all mandatory questions answered)

The questionnaire consisted of five parts:

- General information on participant and farm
- Crops, cultivars, cultivation methods
- Confirmed pests and diseases of tomato on the surveyed farm
- Impact of and measures against *A. lycopersici*
- Agreement on use of data for scientific purposes only

Determination of the sample size

Prior to the study, it was considered that with the workforce conducting the study, it would be realistic to reach up to 100 valid participants. This number also took into account the fact that many factors could potentially limit the number of growers who might take part, for instance the fact that it may be difficult or time-consuming to identify and locate potential farms that could participate, that without monetary incentives there may be a limited motivation for the invited growers to participate, and finally it was recognised that it may be difficult to determine the representativeness of the recruited participants beyond a rough estimation. In the light of this, additional questions were included in the questionnaire with the ability produce insight into farmers perception and strategies for the pest of interest that go beyond a quantitative analysis approach.

Statistical analysis

Statistical analysis was conducted where feasible; Fisher exact tests were used for categorical data, a nonparametric Wilcoxon rank sum test to test for dependence between tomato production area and *A. lycopersici* presence, and a linear model was used to check whether there was a correlation between production area and length of break between tomato seasons. An exact binomial test was used to test whether an initial infestation increased the likelihood that there would be continuous *A. lycopersici* presence in subsequent consecutive years (Clopper and Pearson 1934). All functions used in these analyses are part of the statistical software R (R Core Team 2021; version 4.1.0). For correction of multiple testing in the Fisher exact tests the "fdr"-method (Benjamini and Hochberg 1995) was applied.

Results

Acquisition of participants and metadata on participating farms

A total of 83 tomato producing farms had responded to the invitation to participate by the 5th of August 2019. Of the 29 online respondents, 17 were excluded for not having completed the survey. Of the 54 farms contacted via phone, 38 farms agreed to participate and all of them completed the survey. 12 valid online respondents plus 38 valid phone respondents resulted in a total of 50 valid participants becoming subject to the following analyses, half of what initially was aimed for. For the growers contacted via E-Mail, the calculation of a response rate is not possible as the total number of recipients contacted is not known. For the growers contacted via phone the response rate was 70.4%. Germany is divided into 10 regions by the first digit of the postal code and into 99 regions by the first two digits of the postal code. The distribution of participating farms separated by first digit is shown in Table 1. In Fig. 1, separation is based on the combination of first and second digit of the postal code. On the first digit-level it was possible to cover all 10 areas with participants.

The 50 farms that participated in the survey represent 3.5% of the total number of 1448 farms with tomato production in Germany in 2019 (Destatis 2020). Together the participating farms account for 131.8 ha tomato production area. The total area used for tomato production in Germany in 2019 was 385.63 ha, thus the surveyed farms account for 34.2% of this total area (Destatis 2020). The mean tomato production area of the 50 participating farms was 2.64 ha. The median production area was 0.2250 ha.

Of the 50 participating farms, 27 (54%) were producing integrated (i.e. committed to the guidelines of integrated pest management) with an average cultivation area of 47.457 m^2 and 23 farms (46%) were producing organic (at least following Regulation (EU) 848/2018), with an average cultivation area of 1593 m^2. The sizes of the participating farms is visualised in Fig. 2.

Of the 50 participants, 29 participants (58%) stated that they had attended an apprenticeship in horticulture or agriculture. Twenty participants (40%) stated that they had completed a university degree in horticulture or agriculture. Four participants (8%) stated that they had both an apprenticeship and a university degree and five participants (10%) stated that they had not finished a degree in horticulture or agriculture.

Of the 50 participants 48 (96%), stated the sources that they use to obtain information about plant protection. Experience exchange with other growers, and specialist literature were each stated 43 times (89.6%), followed by websites on plant protection with 41 mentions (85.4%), and plant protection courses which received 35 mentions (72.9%). Eight participants (16.7%) stated that they rely on decision-support-systems (DSS) for plant protection. Thirty-one participants (64.6%) indicated that they were interested in the utilisation of DSS, and 17 (35.4%) stated that they were not interested in using DSS.

Employees on participating farms

It was assumed, that the employee background, familiarity and experience with and in tomato farming might have an influence on detection and / or treatment success against *A. lycopersici*. 28 participants (46%) stated that the majority of employees doing cultivation work are permanently employed. Of these 28 participants, 21 participants (75% of 28) stated that the employees are regularly offered training sessions on the topic of plant protection. 21 participants (42%) stated that the majority of employees doing cultivation work are seasonal employees that had already worked on the farm previously. Of these 21 participants, 14 participants (66.7% of 21) indicated that regular training sessions on the topic of plant protection are offered to the employees. Only one participant (2%) stated that most of the employees doing cultivation work were seasonal employees that had not worked on the farm previously, and that no training sessions on the topic of plant protection were offered to employees. Fisher exact tests were used to test whether there was a correlation between *A. lycopersici*

Table 1 Postal code areas with quantity of participants

Postal code (first digit)	1	2	3	4	5	6	7	8	9	0	Σ
participants	2	4	8	7	5	4	4	7	5	4	50

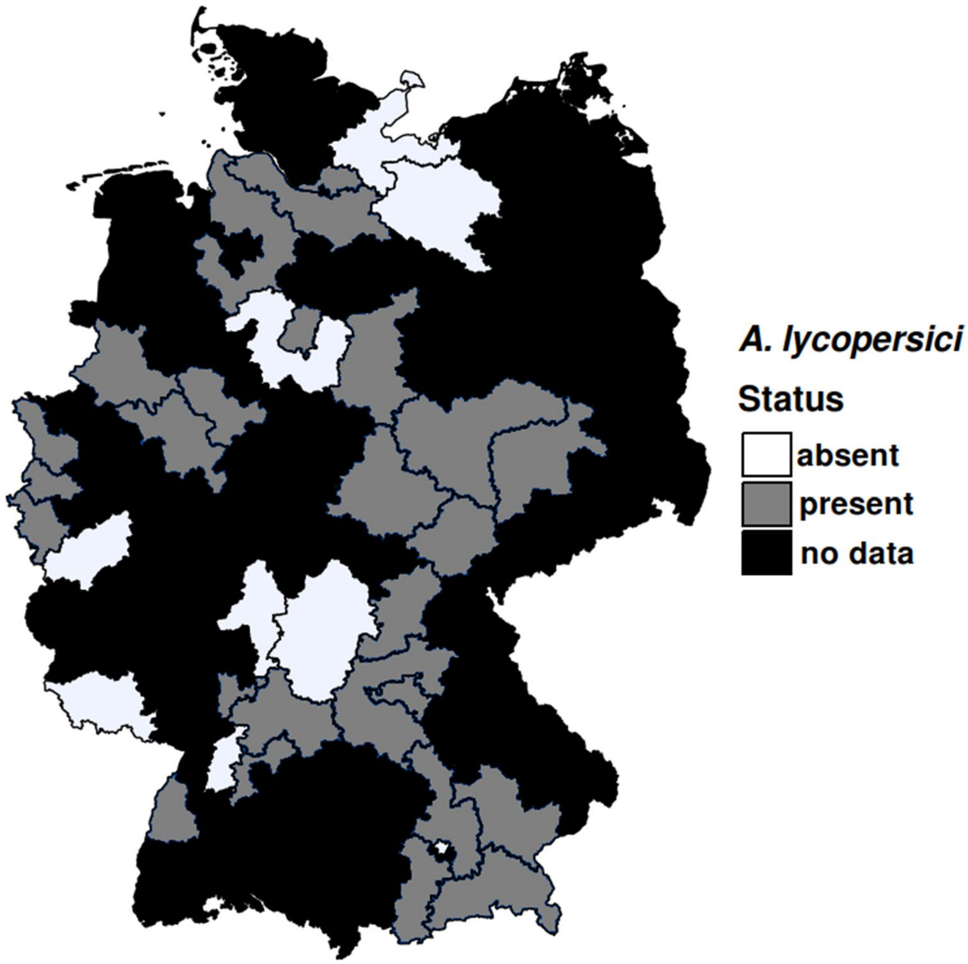

Fig. 1 Map of Germany, divided into 99 regions by the first two digits of the postal code. If *A. lycopersici* was found at least in one of the participating farms in a region, the region is marked grey. If it was found in none of the participating farms in one region, it is marked white. Black regions indicate that there were no participants from this region (note this does not mean, that there are no tomato-producing farms in this particular region). White only means, that the respective pest was not found in the participating farms in the particular region, not that it does not occur in any of this region's farms

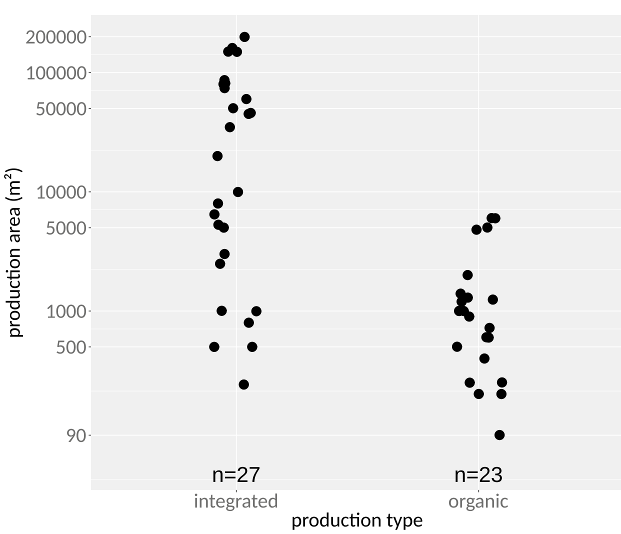

Fig. 2 Sizes of the participating farms displayed in m^2 on the y-axis divided by production type displayed on the x-axis. To improve visualisation, the y-axis has been log-transformed

incidence and employee demographics. No significant correlation was found between the two.

Relative importance of pests and diseases on participating farms

Participants were asked to name the most important pests (Table 2) and diseases (Table 3), in both cases results are displayed separately for farms with *A. lycopersici* presence and farms without *A. lycopersici* presence. Looking at most important pests *A. lycopersici* reached the highest relative importance in farms with *A. lycopersici* presence as well as in the overall ranking (farms with and without *A. lycopersici* presence combined). *Tuta absoluta* was considered important on 11 of 32 farms (34.4%) with *A. lycopersici* presence, making *T. absoluta* the third most important pest in this particular group of farms. On the contrary, none of the nine farms without *A. lycopersici* considered *T. absoluta* important. For the group of farms without *A. lycopersici* presence, seven from nine farms (77.8%) consider whiteflies important, making it the most important pest for this group of farms with a relative importance of 50%.

Table 2 Farmers were asked to name the three most important pests in their tomato cultivation and rank them in decreasing order

Pest	*A. lycopersici* present, relative importance, $n=32$	*A. lycopersici* absent, relative importance, $n=9$	Adjusted *p*	Total %, $n=41$
Aculops lycopersici	40.5 (27)	0.0 (0)	–	32.8 (27)
Whiteflies	24.8 (17)	50.0 (7)	1 (0.2623)	29.6 (24)
Tuta absoluta	17.0 (11)	0,0 (0)	0.8275 (0.08275)	13.8 (11)
Aphids	6.5 (6)	25.0 (3)	1 (0.3436)	10.0 (9)
Spider mites	6.5 (5)	16.7 (3)	1 (0.6625)	8.5 (8)
Golden twin-spot moth	1.3 (2)	0.0 (0)	1 (1)	1.1 (2)
Leaf miner fly	1.3 (1)	5.6 (1)	1 (0.3951)	2.1 (2)
Fruit fly	0.0 (0)	2.8 (1)	1 (0.2195)	0.5 (1)
Nematodes	0.6 (1)	0.0 (0)	1 (1)	0.5 (1)
Thrips	0.6 (1)	0.0 (0)	1 (1)	0.5 (1)
Caterpillar	0.6 (1)	0.0 (0)	1 (1)	0.5 (1)

This table shows the relative importance of the different pests. Calculation of the relative importance was as follows: naming a pest first resulted in three points for the respective pest, second in two and third in one. The sum of points for each pest was divided by the total sum of points within the respective group of farms (1: *A. lycopersici* present, 2: *A. lycopersici* absent, 3: total) and multiplied by 100 (results shown are rounded). The number of times the different pests were named appears in brackets next to the relative importance value

Table 3 Farms were asked to name the three most important diseases in their tomato cultivation and rank them in decreasing order

Disease	*A. lycopersici* present relative importance $n=24$	*A. lycopersici* absent relative importance $n=16$	Adjusted *p*	Total % $n=40$
Grey mould (*Botrytis cinerea*)	30.6 (13)	15.8 (8)	1(1)	24.5 (21)
Late blight (*Phytophthora infestans*)	8.3 (5)	43.4 (13)	0.0030(0.0003)	22.8 (18)
Tomato leaf mould (*Cladosporium fulvum*)	18.5 (10)	27.6 (7)	1(1)	22.3 (17)
Powdery mildew	27.8 (12)	9.2 (3)	0.6118(0.0556)	20.1 (15)
Fusarium wilt (*Fusarium oxysporum*)	2.8 (2)	0.0 (0)	1(0.5077)	1.6 (2)
Pepino mosaic virus	5.6 (2)	0.0 (0)	1(0.5077)	3.3 (2)
Early blight (*Alternaria solani*)	0.0 (0)	2.6 (1)	1(0.4)	1.1 (1)
Tomato mosaic virus	0.0 (0)	1.3 (1)	1(0.4)	0.5 (1)
Bacterial canker (*Clavibacter michiganensis*)	2.8 (1)	0.0 (0)	1(1)	1.6 (1)
Crazy roots (*Agrobacterium rhizogenes*)	1.9 (1)	0.0 (0)	1(1)	1.1 (1)
Verticillium wilt (*Verticillium sp.*)	1.9 (1)	0.0 (0)	1(1)	1.1 (1)

This table shows the relative importance of the different diseases. For calculation of the relative importance values refer to the caption of Table 2. The number of times the different diseases were named appears in brackets next to the relative importance value

With regard to diseases, *Botrytis cinerea* was the most important disease among farms with *A. lycopersici* presence mentioned by 13 of these farms (40.6%), whereas for farms without *A. lycopersici* presence *Phytophthora infestans* was the most important disease (Table 3). *P. infestans* was the only disease according to a Fisher exact test (followed by a correction for multiple testing) that showed a significant difference in importance between the two groups of farms, farms with, and farms without *A. lycopersici* presence.

Initial occurrence and persistence of *A. lycopersici* on participating farms

Thirty-three farms reported that *A. lycopersici* was present at some time on their farm in the five years preceeding 2019. 32 of those farms were able to report the year that *A. lycopersici* was first noted. Of those 32 farms, 26 farms reported that the first occurrence was between 2014 and

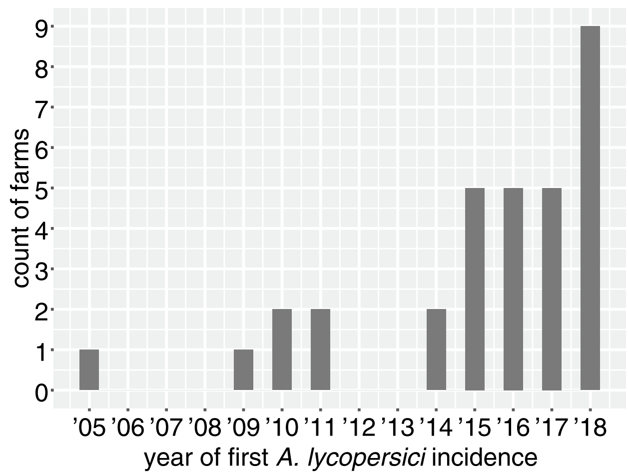

Fig. 3 First year of *A. lycopersici* occurrence on the farms that reported *A. lycopersici* presence. The y-axis shows the count of the farms and the x-axis shows the year

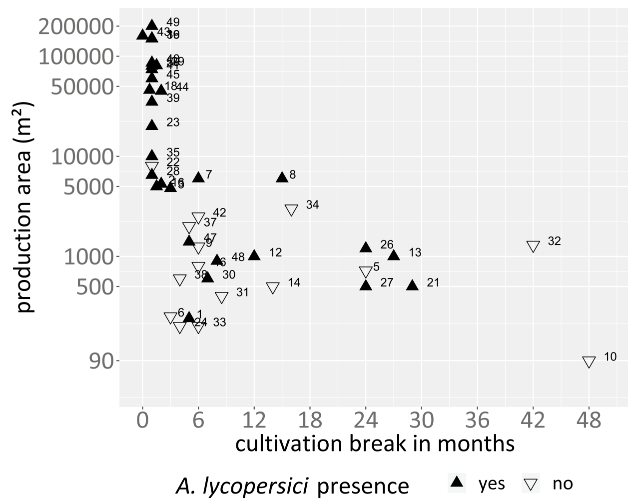

Fig. 4 *A. lycopersici* presence on the different farms. Each symbol represents one farm. The tomato production area is displayed on the y-axis and the cultivation break between tomato sets on the x-axis. To aid visualisation of small values, the y-axis has been log-transformed. The numbers next to the symbols indicate the IDs of the specific farms. 45 of 50 farms are displayed; five farms with production areas between 250 and 5000 m^2 did not state the length of their cultivation break

2018, with a peak of nine reports of first occurrences in the year 2018 (Fig. 3).

On 24 of the 33 farms (72.7%) *A. lycopersici* was present in every year following the year of the first occurrence i.e. only nine farms (27.3%) reported *A. lycopersici*-free seasons after the year of first occurrence. An exact binomial test revealed that an initial infestation increased the chance for continuous *A. lycopersici* presence in all consecutive years ($p = 0.01$). The production area of these nine farms ranged from 500 to 81,000 m^2. The mean production area was 16,855 $m^{2,}$ and the median production area was 1200 m^2. Seven of these nine farms (77.8%) were heated during the colder months, and the cultivation break between tomato sets on these farms ranged between one and 29 months.

Yield impact of *A. lycopersici*

Of the 33 farms affected by *A. lycopersici*, 12 farms (36.4%) reported a negative impact on yield despite plant protection measures. Nine of those farms (75%) reported a specific yield loss. The yield loss reported by these farms ranged between 0.5 and 15%, and on average amounted to 5.89%. 21 farms (63.6%) reported no negative impact on yield considering plant protection measures taken.

Farm and cultivation parameters and possible links to *A. lycopersici* presence

In Fig. 4, a large tomato cultivation area and a short cultivation break seem to co-occur. A nonparametric Wilcoxon rank sum test revealed that there was a dependency between *A. lycopersici* presence and cultivation area ($p < 0.00$). A linear model showed that cultivation break was a significant predictor for cultivation area ($p < 0.00$) with a coefficient of −0.1068 at an adjusted R^2 of 0.2799. *A. lycopersici* did not exclusively occur on farms with short cultivation breaks, but all 20 of the farms (40%), with a cultivation break between tomato sets of less than 3 months, with one exception, reported *A. lycopersici* presence. Similarly, all 23 farms (46%) with a cultivation area of 4800 m^2 or larger, with one exception, reported *A. lycopersici* presence. The latter is also reflected by the total combined cultivation area of the 33 farms with *A. lycopersici* presence of 129.09 ha which account for 33.3% of the German tomato production area. The combined cultivation area of the 17 participating farms without *A. lycopersici* presence sums up to 2.71 ha, representing approximately 0.7% of the German tomato cultivation area. The mean cultivation area of the participating farms with *A. lycopersici* presence was 3.911 ha and of those without was 0.159 ha.

Table 4 shows that the farm production type–whether the farm was integrated or organic—was a statistically significant predictor for *A. lycopersici* presence according to a Fisher exact test for independence ($p < 0.00$).

Fifteen of the 29 farms (51.7%) growing tomato in natural soils, and 19 of the 21 farms (90.5%) not growing in natural soils reported presence of *A. lycopersici* in their production systems (Table 5). The mixture of natural soil, compost and coir substrate was considered a natural soil in this analysis. According to a Fisher exact test, *A. lycopersici* presence

Table 4 *A. lycopersici* presence/absence on integrated and organic farms

		Integrated	Organic	Total count of farms
A. lycopersici presence	yes	23	10	33
	no	4	13	17
Total count of farms		27	23	50

A Fisher exact test for independence of *A. lycopersici* presence and production type revealed production type was a significant predictor of *A. lycopersici* presence ($p < 0.00$)

Table 5 Percentage of substrate types shown separately for farms with ($n = 33$) and farms without ($n = 17$) *A. lycopersici* presence in addition to the total frequency of *A. lycopersici* presence ($n = 50$)

Substrate	*A. lycopersici* present ($n = 33$)	*A. lycopersici* absent ($n = 17$)	Total frequency
Natural soil	42.4% (14)	82.4% (14)	56% (28)
Rock wool	27.2% (9)	0.00 (0)	18% (9)
Coir substrate	15.1% (5)	5.9% (1)	12% (6)
Perlite	12.1% (4)	0.00 (0)	8% (4)
Turf mixture	0.00 (0)	5.9% (1)	2% (1)
Turf + woodfibre	3.0% (1)	0.00 (0)	2% (1)
Natural soil + compost + coir substrate	0.00 (0)	5.9% (1)	2% (1)

Table 6 Frequency of removal of plant residues for farms with ($n = 32$) and without ($n = 17$) *A. lycopersici* presence and the combined total ($n = 49$)

Removal	*A. lycopersici* present ($n = 32$)	*A. lycopersici* absent ($n = 17$)	Total proportion ($n = 49$)
Immediately	46.9% (15)	47.1% (8)	46.9% (23)
WEEKLY	18.8% (6)	23.5% (4)	20.4% (10)
End of season	25.0% (8)	11.8% (2)	20.4% (10)
Remain	3.1% (1)	5.9% (1)	4.1% (2)
Two times per season	6.3% (2)	0.0% (0)	4.1% (2)
Monthly	0.0% (0)	5.9% (1)	2.0% (1)
Varying	0.0% (0)	5.9% (1)	2.0% (1)

depended on whether or not the tomatoes were grown in natural soil ($p < 0.00$).

Plant residues are removed at different time points and intervals in the participating farms (Table 6). A Fisher exact test did not reveal any significant difference regarding *A. lycopersici* occurrence both before and after correction for multiple testing.

Table 7 Presence and absence of *A. lycopersici* on farms that cultivate tomato in a crop rotation and farms that do not cultivate in a crop rotation

		Crop rotation		
		Yes	No	Total count of farms
A. lycopersici presence	present	13	20	33
	absent	11	6	17
Total count of farms		24	26	50

Fisher exact test for independence of *A. lycopersici* presence and crop rotation: $p = 0.13$

There was no significant effect on the presence of *A. lycopersici* depending on whether farms cultivate in a crop rotation or not (Table 7).

Of the 24 farms that grow tomato in a crop rotation with other crops, 21 farms provided information on the rotation crops (Table 8). None of the mentioned rotation crops acted as significant predictors for the presence of *A. lycopersici.*

Participants were asked whether they had reared fresh plants in the last 5 years on the farm, or whether they purchased them externally. Of the 33 farms with *A. lycopersici* presence, 23 farms (69.7%) received plants from external nurseries, six (18.2%) had reared fresh plants on the farm, and four farms (12.1%) had both on-farm reared and purchased plants in the last five years. Of the 17 farms without *A. lycopersici* presence seven farms (41.2%) had received plants from external nurseries, 6 (35.3%) had reared fresh plants on-farm, and 4 farms (23.5%) had both on-farm reared and purchased plants in the last five years. A Fisher exact test revealed that there was no difference between farms in terms of the presence/absence of *A. lycopersici*, depending on whether the farm had received plants from a nursery or had reared fresh plants on-farm in the last five years ($p = 0.14$).

Heating during the colder months was a statistically significant predictor of *A. lycopersici* presence according to a Fisher exact test for independence ($p < 0.00$; Table 9).

Most of the farms that did not heat during the colder months reported first symptoms in August and September, around one month later compared to the farms that heat. Farms that heat reported the first symptoms of the season in July and August (Fig. 5).

Utilised countermeasures against *A. lycopersici* infestation

Farms with *A. lycopersici* presence were asked to select known countermeasures against *A. lycopersici* from a list, indicating those they implement in their own control strategy against the pest. Each countermeasure was used at 14 (42.4%) to 18 (54.5%) of the 33 farms (Table 10).

Table 8 Frequency of crops grown in a rotation with tomato, shown separately farms where *A. lycopersici* was present (12 of 13 farms reported their rotation crops) and farms where *A. lycopersici* was not present (9 of 11 farms reported their rotation crops)

Rotation crops	Frequency of crops, *A. lycopersici* present (12 farms)	Frequency of crops *A. lycopersici* absent (9 farms)	Total frequency
Lettuce	6 (3)	5 (0)	14
Cucumber	6 (2)	5 (0)	13
Lamb's lettuce	4 (2)	3 (0)	9
Sweet pepper	3 (1)		4
Runner beans	2 (0)	2 (0)	4
Red radish		3 (0)	3
Kohlrabi	0 (1)	2 (0)	3
Spinach	1 (1)	1 (0)	3
Eggplant	2 (0)		2
Celery		1 (0)	1
Potted herbs	0 (1)		1
Radish	0 (1)		1
Winter greening	1 (0)		1
Courgette		1 (0)	1

Shown is the frequency of the mentioned rotation crops for 17 of 19 organic farms with crop rotation, and four of the five integrated farms with crop rotation (second number in brackets)

Table 9 *A. lycopersici* presence/absence on farms that do and farms that do not heat during the colder months

		Heating		Total count of farms
		Yes	No	
A. lycopersici presence	Yes	27	5	32
	No	8	9	17
Total count of farms		35	14	49

Fisher exact test for independence of *A. lycopersici* presence and heating: $p < 0.00$

No significant differences were found between farms that reported that *A. lycopersici* caused significant yield loss, and those that did not report yield loss.

Participants had the opportunity to describe specific countermeasures or strategies they have used against *A. lycopersici* in more detail. Ten participating farms (20%) supplied a free-text answer. Answers usually consisted of specific combinations of countermeasures that had been explicitly asked about. One participant mentioned an additional (not previously asked about) measure—"herbal mixtures". Another farm mentioned, that the first and strongest

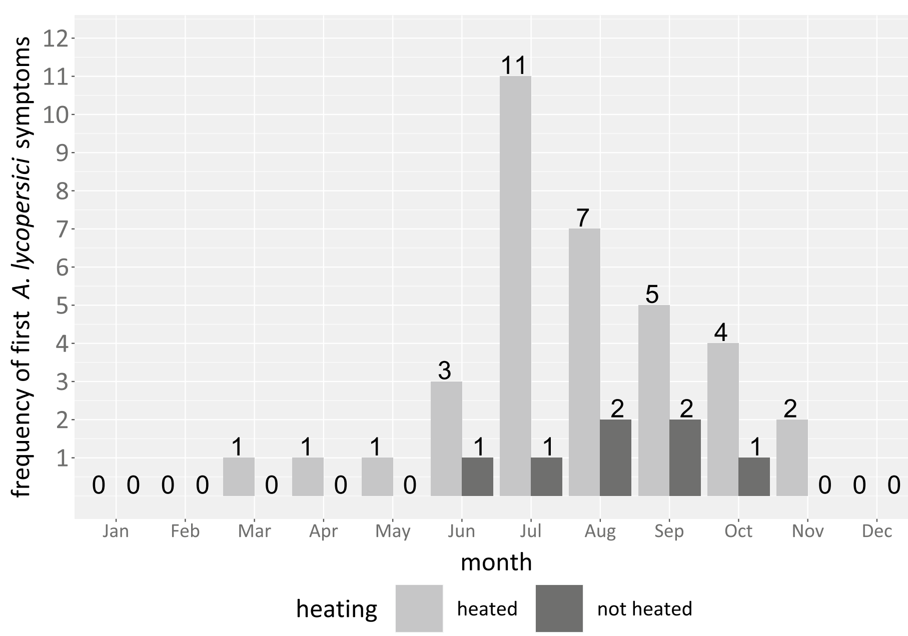

Fig. 5 Month when first *A. lycopersici* symptoms of the year were usually observed on farms with *A. lycopersici* presence (participants were able to name multiple months). The information is provided for both farms where the greenhouse was heated during the colder months and farms where the greenhouse was not heated

Table 10 The countermeasures that farms with *A. lycopersici* presence have taken to combat the pest

Farm ID	Acaricides	Sulphur spray	Sulphur vapourizer	Removal of symptomatic leaves	Removal of whole plants	Predatory mites	No. measures
1		x				x	
2			x				
4		x		x	x	x	
15	x						
21	x			x	x		
26		x		x	x		
27					x	x	
35	x		x	x			
40	x	x	x	x	x	x	
41	x	x	x	x	x	x	
45	x	x	x	x	x	x	
48	x			x	x	x	
3						x	
7						x	
8		x	x	x			
12						x	
13							x
16	x		x	x	x	x	
17		x	x			x	
18	x	x	x				
19	x	x	x	x	x		
20	x						
23	x		x		x	x	
28							x
29		x	x		x		
30				x			
36	x			x	x	x	
39	x	x	x	x	x		
43	x	x	x	x	x		
44		x	x				
47				x	x		
49		x	x	x	x		
50		x	x		x		
SUM	15	16	17	17	18	14	2
Adjusted *p*	1 (0.3005)	1 (1)	1 (0.4813)	1 (0.2818)	1 (0.4688)	1 (0.2728)	-

Farm IDs that are in bold show that the farm reported a negative impact on yield caused by *A. lycopersici*. Fisher exact test with 'false discovery rate' (fdr) (Benjamini and Hochberg 1995) correction for repeated sampling found no significant difference in the frequency of the different countermeasures used between farms that reported a negative impact on yield and those that did not. *P* values not enclosed in brackets are 'fdr' corrected; *p* values in brackets are the values prior to correction

symptoms usually occur in areas that are most exposed to sunlight. Detailed answers can be viewed in Table S2 in the supplementary information.

Of the 15 farms that have applied acaricides, nine farms supplied specific detail about which acaricides they applied. Abamectin-based products were used by all nine farms that provided this detailed information. Spirodiclofen, potash soap and Azadirachtin were each applied on one farm.

Of the nine farms that applied predatory mites specifically against *A. lycopersici, A. swirskii* was chosen most often; five farms applied this mite. *Phytoseilulus persimilis*, *Amblyoseius cucumeris*, *Amblyoseius barkeri* and *Amblyoseius californicus* were each chosen by one farm.

Besides predatory mites specifically introduced against *A. lycopersici*, a total of 14 different Arthropods, and one nematode species were introduced on participating farms. Data on this are provided in Table S1 in the supplementary information for farms with and without *A. lycopersici* presence.

The intensification factors that *A. lycopersici* presence is shown to be dependent on are all more prevalent in integrated rather than organic farms (Table 11).

Discussion

Survey metadata

The survey that was carried out focussed on pests and diseases in tomato production. At a later stage during questioning the questionnaire revealed that the main focus of the survey was the pests *A. lycopersici* and *Tuta absoluta*. In this study, pest-specific data were only presented for *A. lycopersici*.

Fifty participants took part in the survey between January and August 2019. With this limited sample size and due to a low response rate for some of the non-mandatory survey questions there was insufficient statistical power to run quantitative analyses—to model dependencies and derive reliable conclusions about several of the potential explanatory factors for *A. lycopersici* incidence and damage levels. This study does, however, provide several interesting findings from a qualitative angle.

The fact that only 3.5% of the 1448 tomato producers in Germany participated and at the same time 34.2% of the 385.63 ha German tomato production area is covered by those 3.5% reveals, that mainly farms with considerably larger tomato production area than the average farm participated in the survey. This imbalance needs to be taken into account when interpreting the results. 38 of the 50 participants (76%) included in the analysis were contacted via phone. The phone numbers of these tomato producing farms were obtained via google search engine. This means there is a selection bias for farms that maintain a web page with unknown effect on the results. Those factors in consequence limit the representativeness of the results. Having acknowledged this limitation, the displayed data is useful giving as it does, a unique insight into German commercial tomato production facing *A. lycopersici* infestation which, to date, is not available in a structured and published format.

Table 11 Factors that *A. lycopersici* occurrence was statistically dependent on, shown separately for integrated and organic farms

	Integrated	Organic
Production area ≥ 6000 m^2	17 of 27	0 of 23
Heating in cold months	23 of 26	12 of 23
Cultivation in artificial substrate	21 of 27	0 of 23
Cultivation break between tomato seasons ≤ 3 months	18 of 24	0 of 20
A. lycopersici present	23 of 27	10 of 23

In total there were 27 integrated farms (54%) and 23 organic farms (46%). Note that if the total for one of the factors is not 27 or 23, respectively, this means that not all participants answered this question

It was possible to avoid regional clusters of participants in this survey. The 50 participants were spread over all ten postal code areas (first digit of the German postal code), although, display of participants by the two-digit postal code reveals several areas where there were no participating farms. These areas might not have any professional protected tomato cultivation, or it may simply be that no farms in this area were contacted. Despite the fact that there are some areas where no farms participated, the map visualises that *A. lycopersici* occurs throughout Germany from south to north and west to east–its presence is not restricted to one specific region (Fig. 1).

Relevance of *A. lycopersici* as a pest in German tomato cultivation

This study focusses on the farmers perception. For all results displayed it must be considered, that they are based on the assumption that the participants answers are valid. The number of participants that experienced first *A. lycopersici* occurrence on their farms culminates towards the end of the surveyed window from the year 2004 to 2018 (Fig. 3). It is possible that *A. lycopersici* may have gone unnoticed for some time due to there being less experience with this pest in practical cultivation in the past when symptoms appeared late and were of minor nature. However, in the more devastating *A. lycopersici* incidences in which sometimes whole crops have been lost, it is unlikely that farmers would not have identified that *A. lycopersici* was the cause. Twenty-four of the 33 farms (72.7%) that experienced an *A. lycopersici* occurrence, experienced *A. lycopersici* presence and damage in every year following the year of first occurrence; initial infestation significantly increased the likelihood that *A. lycopersici* would continuously present in consecutive years. This shows, that within-farm eradication attempts are either not conducted at all, are conducted in an inefficient way, or they are simply not possible with the given circumstances in the farms that face continuous *A. lycopersici* presence. These results indicate that outbreaks in subsequent years could be a consequence of an initial infestation rather than a result of new independent migration events. However, a continued infestation through the use of fresh plants from external nurseries or other entrances with plant material or tools and packaging cannot be excluded as a potential yearly infestation source.

A. lycopersici reached the highest relative importance in the group of farms with *A. lycopersici* presence and also in the overall ranking of relative pest importance amongst all participating farms (Table 2). *A. lycopersici* was closely followed by whiteflies and by *Tuta absoluta*. "Importance" here refers to the plant protection effort exerted on the specific farm against the specifically named pest. The high plant protection effort demanded by *A. lycopersici* indicates a significant economic relevance for tomato producers and at the same time that there likely is room for improvement of *A. lycopersici* management in practice. In most cases the high plant protection effort seems to have prevented the farms from experiencing significant yield losses caused by *A. lycopersici*. Only 12 of 33 farms (36.4%) reported that yields were negatively affected by *A. lycopersici*. Unfortunately give that only nine participants reported a specific yield loss it is not possible to reliably quantify yield loss.

Due to the limited number of participants and/or answers, it was not possible to identify significant differences in the importance of specific pests (Table 2) or diseases (Table 3) with the exception of *P. infestans,* when the two groups of farms—with and without *A. lycopersici* presence—were compared. There were no mentions of *T. absoluta* as being important on farms without *A. lycopersici* presence in contrast to reported high relative importance on farms with *A. lycopersici* presence. Additionally, *P. infestans* was significantly more important on farms without *A. lycopersici,* compared to farms with *A. lycopersici*. This could mean that *A. lycopersici* favours some conditions similar to those favourable for *T. absoluta* and opposed to those favourable for *P. infestans*.

Intensification factors

Farms with large production areas and short cultivation breaks between tomato sets more often reported *A. lycopersici* presence (Fig. 4). Production area and cultivation break, among other factors included in this survey, can be categorised as intensification factors. As shown for production area and cultivation break, intensification factors tend to correlate or are mutually dependent upon one another. Mutual dependence for instance is the case for heating in cold months and short cultivation breaks as heating is usually only required when cultivation takes place in colder months, and cultivation in colder months usually only takes place when the cultivation break between tomato sets is short. Solely looking at large production area, it is questionable whether a large production area itself has an influence on *A. lycopersici* incidence. The described correlation likely is a result of the correlation between some of the intensification factors. *A. lycopersici* incidence was significantly higher in farms that heated during the colder months (Table 9). *A. lycopersici* requires temperatures of around 25 °C to reach its highest reproduction rate (Haque and Kawai 2003). This likely explains why first *A. lycopersici* symptoms are noticed earlier in the season on farms that heat in the cooler months (Table 9). Since only seven farms in the group without heating reported the months in which first symptoms were noticed, the conclusiveness of the presented data on heating in relation to *A. lycopersici* incidence is limited.

Growing in artificial substrate in special bags allows for precise water and fertiliser dosage to achieve optimal plant growth and high yields (IVA 2017). Since substrate bags, as opposed to natural soil, can easily be changed and renewed, problems with soilborne diseases are minimised. This allows farmers to disregard crop rotations and grow crops such as tomato over multiple seasons in a row in specialised greenhouses (IVA 2017). However, cultivation without crop rotation and with minimal breaks between tomato sets, as cultivation in substrates such as rock wool allows, comes at a cost. It might favour *A. lycopersici* survival by providing almost a year-round presence of the host crop. Organic growing associations usually only permit cultivation in natural soil (Bioland e.V. 2020). At the same time, due to soilborne diseases wider crop rotations are realised in farms that cultivate in natural soil that naturally result in a larger cultivation break / more time without a suitable host plant present. As mentioned, some of the factors overlap, and it is not possible to derive if and how severely the growing medium (Table 5) or substrate affect *A. lycopersici* incidence and persistence. To answer this question detailed studies on *A. lycopersici* survivability in soil, on plant residues, on greenhouse structures at varying temperature and humidity or on the effect of rotations with specific crops are needed. In summary, the data accumulated with this survey support the assumption that *A. lycopersici* favours one or more of the often-correlating intensification factors investigated in this survey: (i) short breaks between tomato seasons, (ii) heating in cold months, (iii) cultivation in non-natural soil, and (iiii) large cultivation area. Since these factors were more prevalent in integrated farms that participated as compared to the organic farms (Table 11), an explanation is provided as to why *A. lycopersici* incidence is significantly higher in the participating integrated farms (Table 4).

Plant protection measures against *A. lycopersici*

The nine farms that reportedly achieved *A. lycopersici*-free seasons after previous seasons with *A. lycopersici* presence (Fig. 3) were thoroughly checked for similarities in production factors and plant protection measures but no factors could be identified. The absence of a key countermeasure on those farms could mean that successful on-farm eradication relies on the creation of unfavourable conditions for *A. lycopersici*, both during and between the growing seasons.

There were no significant differences in specific countermeasures taken against *A. lycopersici* between farms on which *A. lycopersici* negatively affected yields, compared to those on which it did not (Table 10). This means that a standard effective countermeasure could not be identified amongst the participating farms. It is possible that not only the type of measure, but also the early detection and fast reaction on the initial outbreak is of importance. This could be traced back to the lack of reliable early detection methods for this pest (Pfaff et al. 2020).

The chance for participants to describe custom strategies and countermeasures against *A. lycopersici* did not reveal any novel methods not already reported or published in the literature. Strategies mostly consisted of repeated treatment with acaricidal substances, use of predatory mites, the removal of infested plant material or a combination of all three approaches. One participant responded to this question by stating that the first and strongest symptoms occur in the areas that are most exposed to sunlight. Assuming that those are the tomato plants most likely experiencing drought stress, this confirms previous findings that there is stronger population growth on plants that are in a state of drought stress (Pfaff et al. 2020). Naturally, the greenhouse areas most exposed to sunlight are the warmest and this favours *A. lycopersici* which has shown to have its peak population growth at around 25 °C (Haque and Kawai 2003).

During the survey window, the products Vertimec Pro and Agrimec Pro—both containing Abamectin were the only products specifically authorised for use against *A. lycopersici* in Germany. This explains why they were chosen by nine of the 15 farms that applied acaricides. Efficacy of Abamectin against *A. lycopersici* has been shown in the past (Royalty and Perring 1987; Kashyap et al. 2015). The other three compounds applied against *A. lycopersici*, Spirodiclofen, potash salt and Azadirachtin each mentioned by a different single farm were authorised in tomato, but not specifically against *A. lycopersici*, although a side effect on *A. lycopersici* is possible and likely the reason why they were mentioned. Abamectin is harmful to several predatory mites (Alhewairini and Al-Azzazy 2021). The negative effects on beneficial arthropods likely explain why Abamectin treatments often are restricted by farmers to *A. lycopersici* infection nests, or why local Abamectin treatments are combined with broader Sulphur treatments e.g. described by three farms. A broad variety of beneficial arthropods were introduced on the participating farms. Even if there were further acaricidal compounds available against *A. lycopersici* they would need to be highly specific in targeting *A. lycopersici* to not interfere with the established regime of beneficial arthropods in commercial tomato cultivation.

Among the participating farms, *A. swirskii* was the beneficial arthropod most often introduced specifically against *A. lycopersici*. *A. swirskii* was introduced on five of the participating farms. *A. swirskii* predates all life stages of *A. lycopersici* (Park et al. 2010). However, *A. lycopersici* has the ability to seek refuge from predators between trichomes on tomato plants (van Houten et al. 2013) and in doing so is likely able to limit the effectiveness of introduced predators to an uncertain extent.

Conclusion

This study provides a detailed picture of 50 tomato producing farms and how they are affected by *A. lycopersici*. Yearly, the number of farms where a first *A. lycopersici* occurrence is reported, has increased between 2005 and 2018 amongst participating farms and *A. lycopersici* incidence is not concentrated to certain regions in Germany. *A. lycopersici* was the pest with highest relative importance on the participating farms and 22 of 23 farms with a cultivation area of 4800 m^2 or more report the presence of *A. lycopersici*. Repetition of the survey to detect possible changes in relative importance and on the farms affected, would clarify whether these findings are consistent over time, or if the status of *A. lycopersici* in Germany is still subject to change. Several intensification factors (1. Heating in cold months, 2. Large cultivation area, 3. Short break between tomato seasons, and 4. Not cultivating in natural soil) statistically favoured *A. lycopersici* occurrence, but autocorrelation prohibited the identification of a causal link to specific factors. Initial infestation of *A. lycopersici* significantly increased the chance for continuous presence in consecutive years. Detailed trials on *A. lycopersici* survivability and population dynamics under varying environmental conditions could help provide causal links to some of the aforementioned factors. Plant protection strategies in different combinations often consisted of broad treatments of sulphur, local abamectin treatments, removal of infested plant material or introduction of a wide variety of beneficial arthropods. None of the countermeasures could be identified as providing better or lasting control of *A. lycopersici* with the data gathered in this survey. Therefore, efficacy trials under practical conditions are advisable.

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Declarations

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

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