Research Article

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Enhanced and sustainable control of *Myzus persicae* by repellent plants in organic pepper and eggplant greenhouses

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Abstract

BACKGROUND: Repellent plants (RPs), generally used to keep pests away from crops in integrated pest management, have been shown to reduce the need for synthetic insecticide sprays in various agroecosystems. However, few studies have evaluated the pest control efficiency of RPs over the entire growth period of crops. To evaluate the effect of RPs against *Myzus persicae* and explore the application and management modes of RPs in the field, we planted mint (*Mentha haplocalyx*), mung bean (*Vigna radiata*), celery (*Apium graveolens*) and coriander (*Coriandrum sativum*) near the ventilation openings of commercial greenhouses.

RESULTS: Five-month sampling results showed that mung bean and mint treatments significantly reduced *M. persicae* population levels over the entire growth period, whereas celery and coriander reduced aphid infestations during the main harvest period of eggplant. The four RP species showed the strongest repellence during their fast-growth periods. Mung bean and mint shortened the activity period of *M. persicae* in pepper by delaying the pest in reaching its peak activity. Celery and coriander reduced aphid density on eggplant during their main activity period. Mint, celery and coriander inhibited population growth in *M. persicae* in the laboratory, revealing the potential value of RPs in reducing *M. persicae* population levels in the field.

CONCLUSION: Mint, mung bean, celery and coriander planted near ventilation openings could be used to control *M. persicae* infestations in commercial greenhouses. Early planting and timely replanting of RPs is a more effective, environmentally friendly and suitable method for organic pest control compared with chemical pesticides.

Keywords: agroecosystem; integrated pest management; repellent plants; entire growth periods; activity period

1 INTRODUCTION

There is growing evidence that sustainable intensification of agricultural systems offers synergistic opportunities to produce agricultural and natural capital outcomes.[1] As an example of the redesign of intensive agricultural systems, integrated pest management (IPM) uses non-chemical or botanical insecticide measures to suppress pest populations and a range of curative management tactics with synthetic insecticide use as the last resort.[2] As part of IPM, conservation biological control has been shown to reduce the use of synthetic insecticides in a variety of cropping systems while maintaining or increasing crop yields.[3,4]

It is common practice to add specific plants to a cropping system to increase the efficiency of biological control systems.[5–7] Among these, repellent plants (RPs), intercropped with cultivated crops, can disrupt pest colonization and reduce pest performance, thus protecting crops.[8] Field and laboratory studies have shown that extracts, essential oils and volatile organic compounds (VOCs) of RPs have important effects on pest behaviour (e.g. colonization).[9,10] Consequently, there is increasing interest in the use of essential oils as alternatives to chemical pesticides.[11,12] However, information on the application of living RPs, particularly how they function in different crops and under different application conditions, is scarce.[13,14] Nevertheless, evaluating the impact of RPs on pests of different crops is necessary to enhance their application in IPM.

The green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), widely distributed in temperate regions, is a polyphagous insect pest of protected vegetables. Infesting more than

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40 families of host plant species worldwide,[15] it causes considerable damage to crops and transmits various plant viruses, resulting in significant economic losses.[16] At present, the green peach aphid is combated almost exclusively using synthetic insecticides.[17] However, the declining availability of many insecticides due to resistance and deregistration, reflecting increasing awareness of their environmental and human health effects, has driven the adoption of ecologically friendly practices.[18,19] Field and laboratory studies have shown that the essential oils and/or VOCs of RPs negatively affect aphids.[20–23]

This study aimed to evaluate the effect of RPs against *M. persicae* and explore the application and management of RPs in the field. Candidate RP species were selected based on recommendations in previous studies of plants that may have repellent effects on aphids.[24,25] The repellent effects of four RP species, mint (*Mentha haplocalyx*), mung bean (*Vigna radiata*), celery (*Apium graveolens*) and coriander (*Coriandrum sativum*) were tested on *M. persicae*, which usually infests pepper and eggplant plantations during their growth period in organic greenhouses. Furthermore, to identify the repellent mechanisms of the RPs used, we examined their effect on the orientation and population dynamics of *M. persicae* in laboratory assays.

2 MATERIALS AND METHODS

2.1 Field assays

Field experiments were conducted at Noah Organic Farm (40° 09N, 116°99N), Pinggu County, Beijing (China) in 2019. Pepper (*Capsicum annuum* var. Zhongjiao 105, from the Institute of Vegetable and Flowers, CAAS) and eggplant (*Solanum melongena* var. Jingqieheilongwang F1, from the National Engineering Research Center for Vegetables) seeds were sown in plastic trays in nursery greenhouses. When the fourth true leaf appeared, and pepper and eggplant saplings were approximately 25 cm tall, they were transplanted in two plastic greenhouses on 21 and 25 March 2019, respectively. Each greenhouse was divided equally into nine blocks (8 × 12 m, with five rows of beds, each of 80 plants). Two RP treatment and control plants were replicated three times in individual blocks following a randomized block design (n = 3) (Figure 1). Plots within the same greenhouse were separated using a polyethylene screen. Mint, celery, mung bean and coriander seeds were obtained from the National Engineering Research Center for Vegetables (Beijing, China). Mint and celery plants with four to five true leaves, and mung bean and coriander seeds were planted in two rows (0.6 m apart in each column and 0.3 m apart in each in row; 34 plants per plot) at ventilation openings at the front of the greenhouse; control plants were left bare, as shown in Figure 1. Organic vegetable management standards (e.g. soil management, fertilization, pests, diseases and weed management) followed the Ecocert Organic Standard V05.2. Equal volumes of insecticides and fungicides were sprayed on the treatment plants according to the need for control, as described by Li *et al.*[26]

Natural populations of *M. persicae* were sampled starting on day 17 after planting and this continued weekly until the end of the pepper and eggplant harvest on 2 and 13 September, respectively. Five crop plants were chosen randomly from each plot. On each crop plant, the numbers of *M. persicae* (including all instars) on two leaves of similar age on the upper, middle and lower parts of the plant were counted.

2.2 Laboratory assays

Pepper (var. Zhongjiao 105), eggplant (var. Jingqieheilongwang F1), mint, celery, mung bean and coriander were cultivated in pots in separate greenhouses at 25 ± 2°C. All plants were cultivated without the use of pesticides or fertilizers and were watered to avoid physiological stress. Six-week-old plants were used in the laboratory assays. Apterous green peach aphids collected from pepper were reared on radish sprouts (*Raphanus sativus*) under controlled conditions [25 ± 1°C, 60 ± 5% relative humidity (RH) and a 16:8 h light/dark photoperiod]. Viviparous wingless aphids (8 days old) were used in the laboratory assays.

The first laboratory assay on the repellent effect of RPs on *M. persicae* was conducted under controlled conditions (25 ± 1° C, 60 ± 5% RH and a 16:8 h light/dark photoperiod). One pepper/eggplant leaf (abaxial side upwards) and 3 g of RP leaves were placed in opposite halves at the bottom of a Petri dish (diameter = 150 mm, height = 20 mm). As a control, a single pepper/eggplant leaf was placed in a Petri dish. Leaf petioles were wrapped with wet absorbent cotton to maintain leaf turgidity. Twenty viviparous wingless aphids (8 days old) were placed in the centre of the Petri dish using a fine paintbrush. Assays were repeated for each RP species as a separate treatment, with

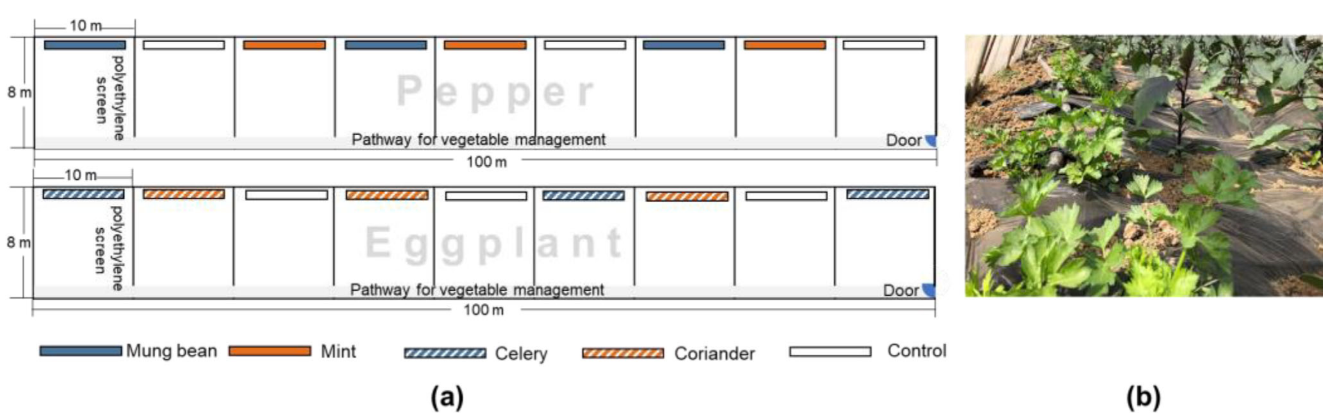

Figure 1. (a) Experimental design of different repellent plants in the commercial greenhouse. (b) Repellent plant (celery) strips were planted in two rows at ventilation openings at the front foot of the greenhouse. Each greenhouse was divided into nine plots (8 × 12 m with five rows of beds of 80 crop plants) using polyethylene screens. Mung bean and mint were planted in the pepper greenhouse. Celery and coriander were planted in the eggplant greenhouse.

30 replicates for each treatment ($n = 30$). The numbers of aphids on the crop leaves were recorded after 1 and 2 h.

The effect of RPs on the population dynamics of *M. persicae* was determined in the same way, except that 20 viviparous wingless aphids (8 days old) were placed onto the pepper/eggplant leaf. There were 30 replicates for each treatment ($n = 30$). The numbers of aphids on the crop leaves were recorded after 24 and 48 h.

2.3 Statistical analysis

To evaluate the impact of RPs on the population dynamics of *M. persicae*, we divided the crops into three growth periods: pre-harvest (seedling to fruiting period), main harvest (beginning of the harvest until the daily output is less than one-fifth of the peak harvest period) and late harvest (period from a daily output of less than one-fifth of the peak harvest to the end of the harvest). We also divided the RP growth periods into seedling, fast growth (rapid growth or flowering to fruiting) and late growth, as shown in Table 1.

According to Fazekas,[27] aphid activity can be divided into three periods based on the total number of individuals sampled. Peak activity was defined as the time when 50% of the total number of individuals for the season was reached, and this was established graphically from the cumulative abundance curve. Individuals in the early, main and late activity periods accounted for 0–25%, 25–75% and 75–100% of the total number of individuals sampled, respectively. Within each period, the average density of *M. persicae* was calculated.

Because the majority of *M. persicae* density data in the field did not follow a normal distribution (Shapiro–Wilk test, $p < 0.05$) and/or homoscedasticity (Bartlett's test, $p < 0.05$), the data sets for the number of samples with 50% or more of the peak density of *M. persicae*, mean populations of *M. persicae* during the crop harvest periods, and mean populations of *M. persicae* in RP development periods were compared among treatments using non-parametric Kruskal–Wallis tests followed by a multiple comparison with the least significant difference (LSD) test ($p < 0.05$).

In the greenhouse experiment, the population decline rate (PDR) was calculated as follows:

$$\mathrm{PDR} = (C - T)/T \times 100\% \tag{1}$$

where C and T are the number of aphids in the control and treatment groups, respectively.

In laboratory assays, the repellent index (RI) and population deterrence index (PDI) were used.

$$\mathrm{RI} = (C - P)/P \times 100\% \tag{2}$$

$$\mathrm{PDI} = (P/C - C/O)/(C/O) \times 100\% \tag{3}$$

where C and P are the mean numbers of aphids in the control and treatment groups, respectively. O is the initial mean number of aphids. Differences in the RI and PDI between the two RPs in the same crops were analysed using the Mann–Whitney U-test ($p < 0.05$).

We also tested for a difference in aphid abundance over time using generalized additive mixed models (GAMMs) with a Poisson error distribution in the *mgcv* package.[28] The GAMM function allows models to incorporate non-linearity over time. The block was added as a random intercept on the model to avoid any bias in model predictions that could occur if one or a few individual sites had a high sampling effort (using the smoothing basis for block as random effects, bs = re).[28] The *lme* subcomponent allows comparison of the fixed and random factors that minimize residual deviance in the mixed model, using glmmPQL (MASS package).[29] The smoothing *gam* subcomponent can be compared using the coefficient of determination (and the two comparisons tend to be in broad agreement), with *gam* in *mgcv*. All data analyses were performed using R v. 4.2.0.[30]

3 RESULTS

3.1 Repellent effect of different RPs on *M. persicae*

The model-predicted estimates for different RPs showed that temporal trends in abundance were strikingly out of phase with different RPs in pepper [GAM: (date, 20.91) $F = 491.6$, $p < 0.001$] and eggplant [GAM: (date, 15.88) $F = 250.2$, $p < 0.001$] (Figure 2a,c; Table 2). In the pepper greenhouse, *M. persicae* infestations were more frequent on controls than plants treated with mung bean or mint (Figure 2a), resulting in a significantly low number of samples with an aphid density above 50% of the investigation peak in RP-treated plants ($X^2 = 6.72$, df = 2, $p = 0.035$; Figure 2b). Although the *M. persicae* population on eggplants treated with celery or coriander fluctuated greatly, the number of control samples with an aphid density above 50% of the investigation peak was significantly greater than for RP-treated plants ($X^2 = 7.20$, df = 2, $p = 0.027$; Figure 2d).

During the pre-harvest period for pepper plants, the number of *M. persicae* individuals on RP-treated pepper plants was significantly lower than on control plants ($X^2 = 5.60$, df = 2, $p = 0.061$; Figure 3a). During the main-harvest period for pepper, the number of aphids on RP-treated plants remained significantly lower than on the control ($X^2 = 6.72$, df = 2, $p = 0.035$; Figure 3a). Similarly, the number of *M. persicae* on RP-treated plants was significantly lower than on the control in the late harvest period of pepper ($X^2 = 6.88$, df = 2, $p = 0.032$; Figure 3a). In the pre- and

Table 1. Growth periods of repellent plants or harvest time of crops in the study

Period	Seedling	Fast growth	Late growth
Mung bean	21 March to 19 May	20 May to 14 July	15 July to 2 September
Mint	21 March to 12 May	13 May to 4 August	5 August to 2 September
Celery	25 March to 30 May	31 May to 8 August	9 August to 13 September
Coriander	21 March to 23 May	24 May to 18 July	19 July to 9 September
	Pre-harvest	Main harvest	Late harvest
Pepper	21 March to 21 April	21 April to 18 August	18 August 2 September
Eggplant	21 March to 25 April	25 April to 15 August	15 August to 13 September

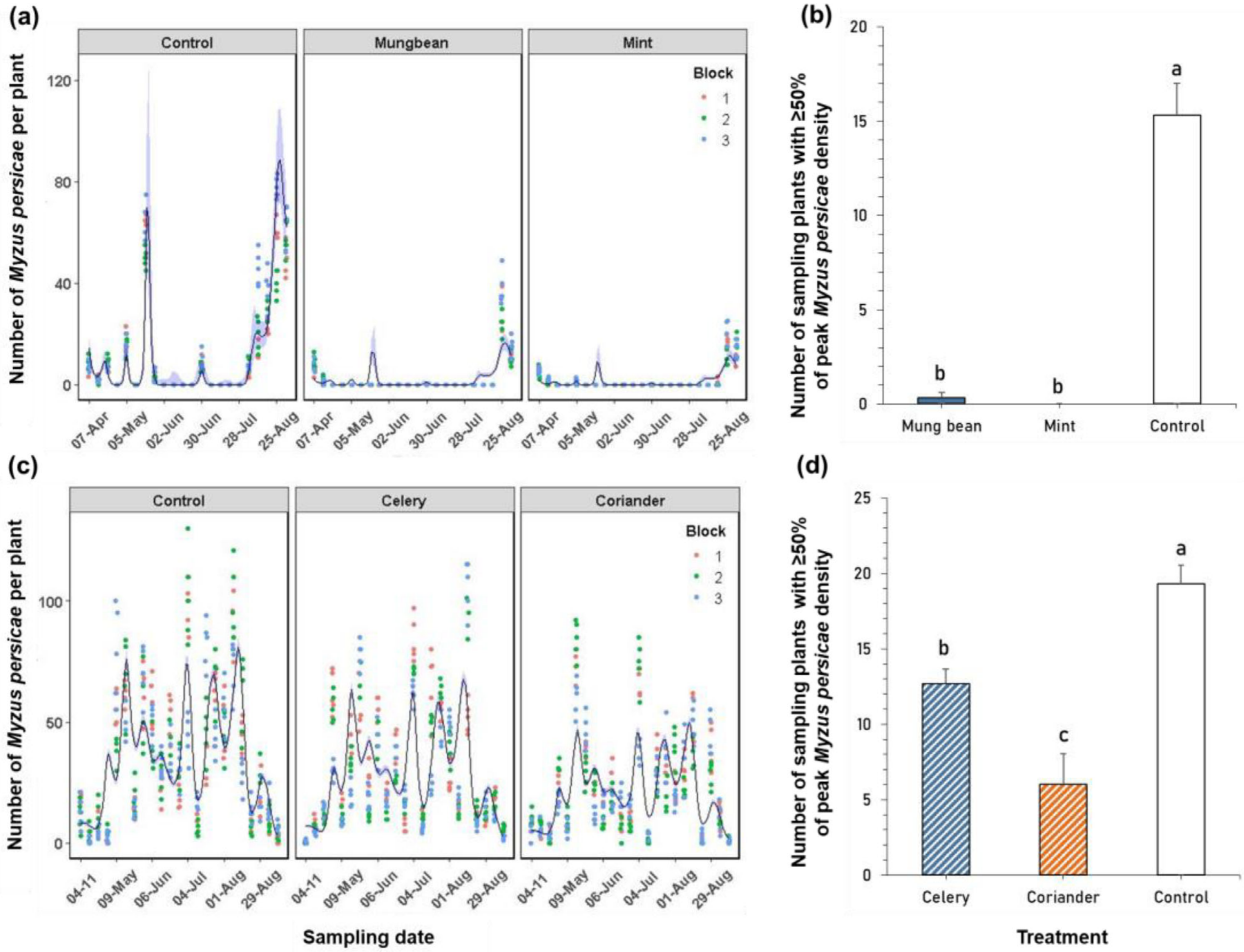

Figure 2. Model estimates for random intercepts and random smoothing coefficients for year in each of the repellent plants (a, c), derived from the generalized additive mixed model (GAMM). Data points (filled circles) show raw data for surveys 1–3 in the block. Note the varying *y*-axis scales across sites. (b) Number of samples with 50% or more peak *Myzus persicae* density on pepper. (d) Number of samples with 50% or more peak *M. persicae* density on eggplant. Different lowercase letters in (b) and (d) indicate significant differences with LSD test at $p < 0.05$.

Table 2. Generalized additive mixed model (GAMM) results for the best model explaining temporal variation in aphid abundance over time. Note that the summary results are for the GAM component of the GAMM in mgcv

Crops		Est. (±SE)	*t*-value	*p*-value	edf	Ref. df	*F*-value	*p*-value	R^2 adj
Pepper	Intercept	−1.59 (0.84)	−1.89	0.059					0.824
	Mung bean	−1.68 (0.05)	−35.38	< 0.001					
	Mint	−2.05 (0.06)	−35.19	< 0.001					
	date.cs				20.91	20.91	491.6	< 0.001	
Eggplant	Intercept	3.29 (0.02)	195.59	< 0.001					0.513
	Celery	−0.18 (0.01)	−14.53	< 0.001					
	Coriander	−0.48 (0.01)	−38.30	< 0.001					
	date.cs				15.88	15.88	250.2	< 0.001	

edf, estimated degrees of freedom for smoothing splines; Est., estimate for parametric coefficients in the model; Ref. df, reference degrees of freedom used in computing the statistic test; SE, standard error of the estimate.

late-harvest periods of eggplant, there was no significant difference between the number of *M. persicae* on RP-treated and control plants (pre-harvest: $X^2 = 2.78$, df = 2, $p = 0.249$; late-harvest: $X^2 = 1.16$, df = 2, $p = 0.561$; Figure 3b). In the main harvest period of eggplants, during which we observed a small outbreak of aphids in all crops, the number of *M. persicae* on plants treated with celery and coriander was significantly lower than on control plants, with the lowest numbers of *M. persicae* observed in coriander-treated plants (main harvest: $X^2 = 7.20$, df = 2, $p = 0.027$; Figure 3b).

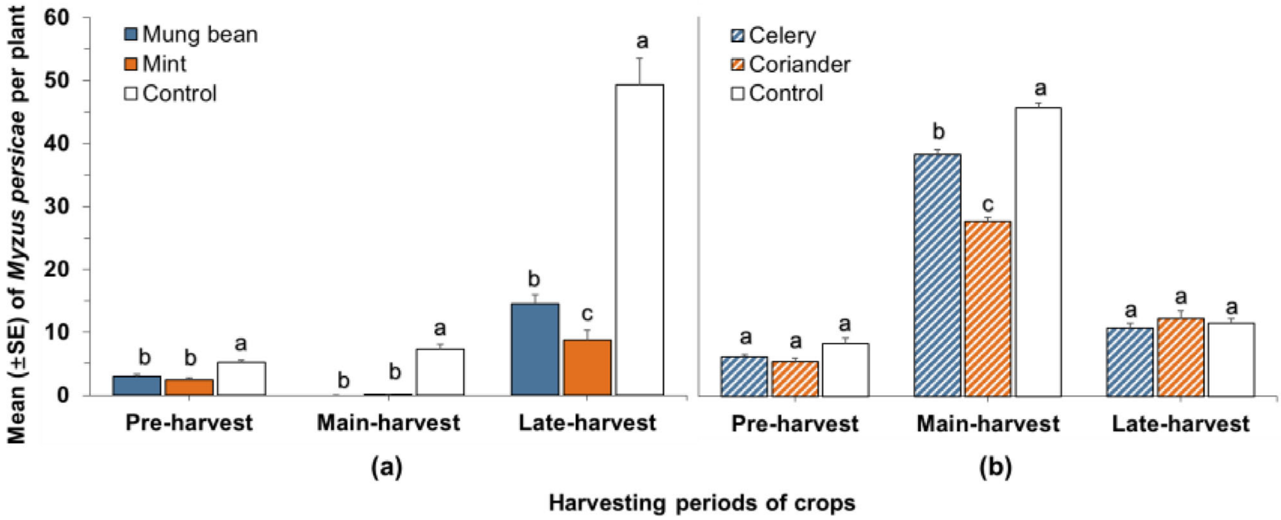

Figure 3. Mean (± SE) *Myzus persicae* per plant during different harvest periods of pepper (a) and eggplant (b) with different repellent plants in field assays. Lowercase letters indicate significant differences among treatments by the Kruskal–Wallis test followed by LSD multiple comparison test at $p < 0.05$.

On excluding the seedling and late-growth periods of celery and coriander, the number of *M. persicae* on RP-treated plants was significantly lower than on control plants (Table 3). The density of *M. persicae* on pepper treated with mung bean and mint during their late growth period was significantly higher than in other periods (mung bean: $X^2 = 7.45$, df = 2, $p = 0.024$; mint: $X^2 = 7.45$, df = 2, $p = 0.024$; Table 3). The repellence rate during the fast-growth period was greater than during the other periods (Table 3). Mung bean and mint showed strong repellent effects on pepper in the field during their fast-growth periods.

Although the *M. persicae* density during the fast-growth period of celery was significantly higher than in other periods ($X^2 = 5.60$, df = 2, $p = 0.061$; Table 3), it was significantly lower than on the control plants ($U = 0$, $p < 0.05$), suggesting that celery had repellent effects on *M. persicae* on eggplant under certain conditions. No significant differences were found among the three growth periods for coriander ($X^2 = 3.47$, df = 2, $p = 0.177$; Table 3). Celery showed repellence during the seeding and fast-growth periods, and coriander in the fast-growth and late-growth periods (Table 3).

3.2 Seasonal activity and population dynamics of *M. persicae*

The seasonal activity of *M. persicae* varied with the RP (Figure 4). The main activity period for *M. persicae* on control pepper plants started on 16 May, whereas it started on 19 August on pepper treated with mung bean and mint. The length of the main activity period for plants treated with mung bean (7 days) and mint (10 days) was shorter than for control plants (100 days). Activity peaks for all treatments occurred in mid-to-late August (Figure 4a). The number of aphids on pepper treated with mung bean and mint in the early and late activity periods was significantly lower than that in control plants (early: $X^2 = 5.51$, df = 2, $p = 0.063$; late: $X^2 = 6.54$, df = 2, $p = 0.038$; Table 4). Mung bean and mint shortened the main activity period for aphids on pepper and delayed the time to reach peak activity by 10 days, which would reduce damage during the main harvest period of pepper.

The main activity period of eggplant occurred between June and July. The onset of the main activity period with coriander occurred on 17 May. The length of the main activity period was 62 days on the control plants, which was slightly shorter than on plants treated with celery (76 days) and coriander (77 days). The activity peaks in different treatments generally occurred on 30 July (Figure 4b). No significant effect on *M. persicae* density was observed during the early activity period ($X^2 = 0.80$, df = 2, $p = 0.670$). During the main activity period, the *M. persicae* density on eggplant treated with celery and coriander was significantly lower than on the control ($X^2 = 7.20$, df = 2, $p = 0.027$). The *M. persicae* population on eggplant treated with coriander was

Table 3. Density of *Myzus persicae* and population decline rate on pepper during different repellent plant growth periods

Growing period of repellent plant		Seeding	Fast growth	Late growth
Mung been	No. of *M. persicae*	1.28 ± 0.13 b*	0.00 ± 0.00 c*	6.24 ± 0.58 a*
	PDI	90.00 ± 1.01	100.00 ± 0.00	75.87 ± 2.25
Mint	No. of *M. persicae*	1.49 ± 0.15 b*	0.00 ± 0.00 c*	10.92 ± 1.02 a*
	PDI	71.49 ± 2.89	100.00 ± 0.00	75.00 ± 2.33
Celery	No. of *M. persicae*	24.77 ± 1.38 b	34.81 ± 1.28 a*	25.59 ± 2.53 b
	PDI	10.88 ± 4.98	28.81 ± 2.61	—
Coriander	No. of *M. persicae*	25.54 ± 1.34 a	32.29 ± 2.64 a*	29.63 ± 2.36 a
	PDI	—	27.81 ± 5.88	16.55 ± 6.65

Data are mean ± SE. PDI, population deterrence index. *Significant difference compared with control by Mann–Whitney *U*-tests at $P < 0.05$. Lowercase letters indicate significant differences among treatments by the Kruskal–Wallis test followed by LSD multiple comparison test at $P < 0.05$.

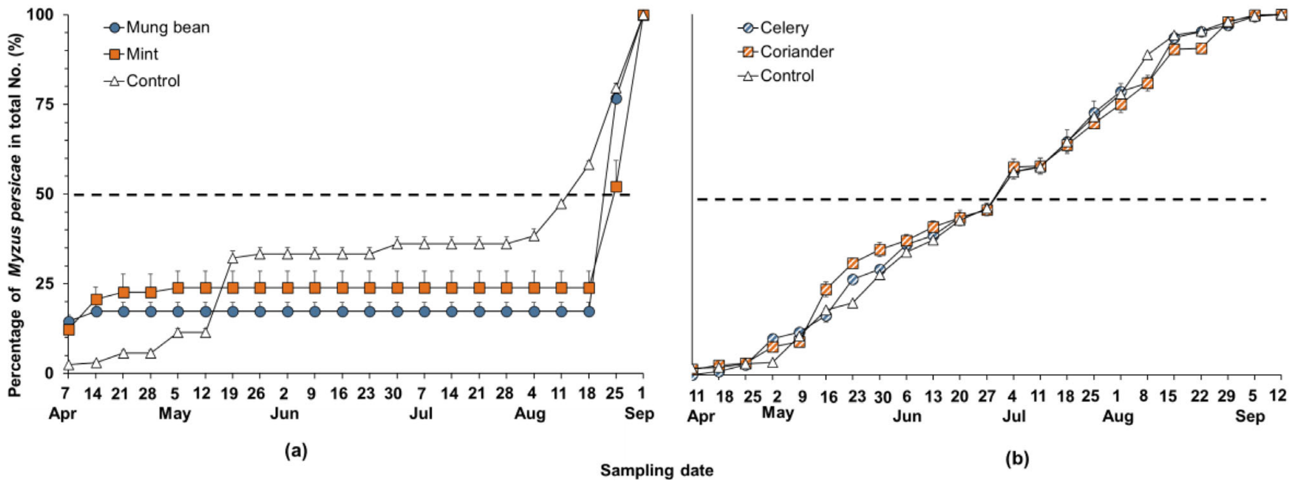

Figure 4. Cumulative seasonal activity curves for *Myzus persicae* in pepper (a) and eggplant (b) with different repellent plants in field assays. Black lines indicate 50% *M. persicae*.

significantly lower than on the control during the late activity period (Table 4). Although celery and coriander failed to delay the peak activity of *M. persicae* on eggplant, aphid density during the main activity period was significantly lower than on the control, indicating that celery and coriander could effectively control the density of *M. persicae* during the pest's main activity period.

3.3 Laboratory assays

The average percentage repellence data indicated that the four selected RPs repelled or prevented green peach aphids from landing and feeding on the host crop (Figure 5). The repellent activity of the RPs varied with species and sampling time. Mint was more repellent to green peach aphids than mung beans, regardless of time (1 h: $U = 0.0$, $p< 0.001$; 2 h: $U = 4.0$, $p < 0.001$; Figure 5a). The repellent index of coriander was significantly higher than that of celery at 1 and 2 h (1 h: $U = 28.0$, $p < 0.001$; 2 h: $U = 32.0$, $p < 0.001$; Figure 5b). The repellent activities of the RPs all weakened slightly with increased sampling time (Figure 5).

The four selected RPs showed a negative effect on *M. persicae* population growth on pepper leaflets. The PDI of *M. persicae* treated with mint was significantly higher than that of *M. persicae* treated with mung bean at 24 h ($U = 129.0$, $p< 0.001$; Figure 6a) and 48 h ($U = 76.0$, $p < 0.001$; Figure 6a). No significant effects were found between celery and coriander treatments, even over time (1 h: $U = 367.0$, $p = 0.219$; 2 h: $U = 446.0$, $p = 0.953$; Figure 6b).

4 DISCUSSION

Intercropping with functional plants is a promising eco-friendly approach to reducing pest infestations (i.e. *Bemisia tabaci*).[31–35] However, many studies have only evaluated the effect of RPs over a short period. Consequently, information on the repellent effect of RPs during different growth periods of crops in the field is scarce. Previous studies have reported that the intercropping of celery (*A. graveolens*),[36] coriander (*C. sativum*),[37] mint (*Mentha arvensis*)[38] and mung bean (*V. radiata*)[25] with other food crops can effectively reduce pest density. This study explored the repellence potential of RPs over the entire growth period for crops in a commercial greenhouse using IPM. Using the same biological chemical spray, we found that the abundance of *M. persicae* varied with RP species and growth period. Mung bean and mint treatment significantly reduced the density of *M. persicae* over the entire growth period of pepper, whereas celery and coriander treatment reduced the *M. persicae* infestation during the main harvest of eggplant.

The division of activity periods is helpful when comparing between-year, between-host or between-habitat dynamics,[27] which consider the numbers of pests over a whole season to analyse trends in population dynamics, when the likelihood of errors is high.[39] For instance, Zhang *et al.*[40] found that different trapping and barrier plants have different effects on the activity periods of pests; the current study found that different RPs have different effects on the activity and density of *M. persicae*. Mung bean

Table 4. Density of *Myzus persicae* (mean number of individuals per plant) on pepper and eggplant crops per aphid activity season with different treatments

	Pepper			Eggplant		
Activity period	Mung bean	Mint	Control	Celery	Coriander	Control
Early	0.45 ± 0.05 b	0.39 ± 0.06 b	5.22 ± 0.12 a	18.69 ± 2.42 a	20.03 ± 1.71 a	22.81 ± 0.10 a
Main	31.33 ± 2.88 a	11.00 ± 4.97 b	9.47 ± 1.04 b	37.97 ± 1.67 b	23.70 ± 0.54 c	46.06 ± 0.43 a
Late	12.33 ± 1.19 b	15.33 ± 0.54 b	58.67 ± 5.00 a	26.05 ± 2.68 ab	21.10 ± 1.94 b	32.48 ± 1.46 a

Lowercase letters indicate significant differences among treatments by the Kruskal–Wallis test followed by LSD multiple comparison test at $P < 0.05$.

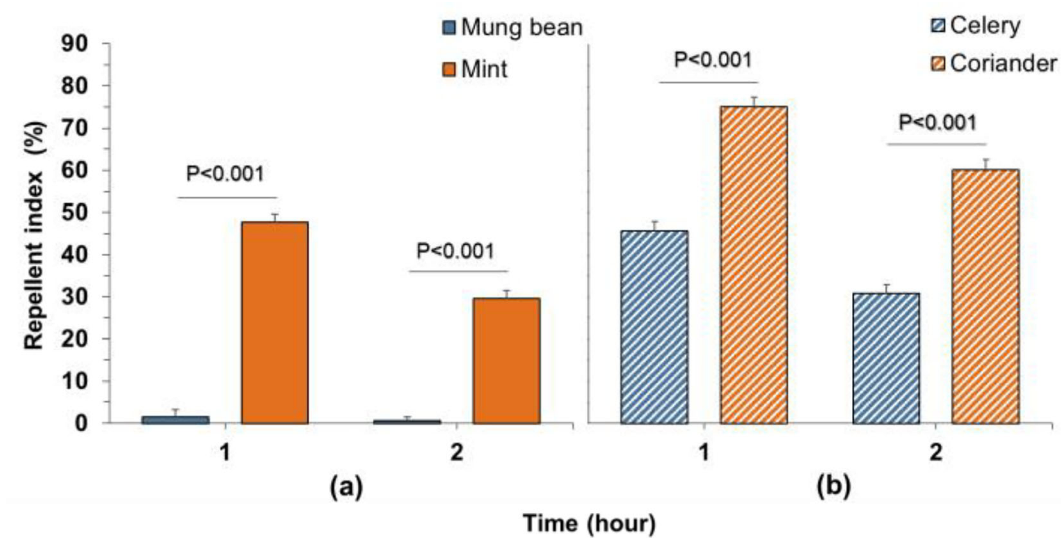

Figure 5. Repellent index (%) of *Myzus persicae* with mung bean and mint on pepper (a), and with celery and coriander on eggplant (b). Differences between the two repellent plants with pepper/eggplant were analyzed using Mann–Whitney *U* tests.

and mint treatments can shorten the active period and reduce injury to pepper, delay the time at which *M. persicae* reaches its peak activity, and reduce aphid densities in the early and late stages of infestation. Although celery and coriander treatment failed to effectively reduce the duration of the main activity of *M. persicae* on eggplant, pest density was significantly lower than on the control, which would reduce the amount of damage to the eggplant plantation. Similar results were found in a previous study in which intercropping tobacco with garlic delayed the occurrence of *M. persicae* and reduced its density at peak activity.[31]

Mung bean is a common species used in intercropping for sustainable pest control. Xie *et al.*[25] investigated the effects of intercropping mung bean with wheat (*Triticum aestivum* L.) on *Sitobion avenae* (F.) populations in field and laboratory experiments, and showed that wheat–mung bean intercropping reduced aphid density, and both apterous and alate aphids showed a significant preference for host plant odour over odour blends of the host and intercrop species. However, our laboratory assays showed that the presence of mung bean had a negligible effect on the orientation and population dynamics of *M. persicae*. The RP biomass in our experiments was too low to release sufficient VOCs to affect *M. persicae* behaviour, which may explain the difference.[20] However, in our field studies, mung bean significantly reduced the density of *M. persicae* during the whole growth period of pepper, which was of a similar magnitude to the aphid density observed by Xie *et al.*[25] in the field.

The repellent and antifeedant properties of mint against agricultural pests have been reported previously.[20,38,41] For example, Sujayanand *et al.*[38] found that the presence of non-host volatiles from mint repelled or confused leafhoppers and whitefly on eggplant, ultimately resulting in a reduced pest population in

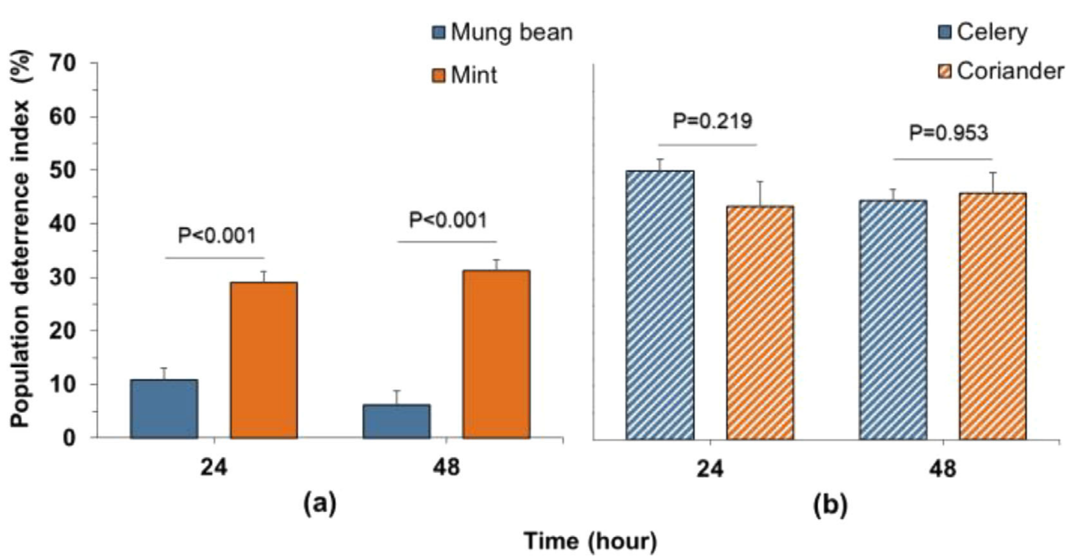

Figure 6. Population deterrence index (%) of *Myzus persicae* with mung bean and mint on pepper (a), and with celery and coriander on eggplant (b). Differences between the two repellent plants with pepper/eggplant were analyzed using Mann–Whitney *U* tests.

polyculture treatments. In our study, mint significantly decreased the density of *M. persicae* over the whole growth period of pepper in the field. Furthermore, in laboratory assays, mint showed repellence against *M. persicae*, which is consistent with the results of Wang *et al*.,[42] who demonstrated that mint VOCs, *in vitro* and *in vivo*, were repellent to *M. persicae*. Moreover, contrary to the effect of peppermint on the settlement and reproduction of *M. persicae* in the study by Ben Issa *et al*.,[20] our results showed that mint negatively affected the population growth of *M. persicae* on pepper leaflets. Dissimilarities in biomass or the phenological stages of RPs may account for these differences.

Celery has previously been reported to significantly reduce whitefly density in tomato, cucumber and pepper plantations.[36,43,44] However, little is known about the repellent effects of celery on *M. persicae*. In our field assays, eggplant intercropped with celery reduced the *M. persicae* population, indicating that intercropping with celery can potentially reduce infestations on eggplant. Celery showed a negative effect on population growth and orientation in *M. persicae* on treated pepper samples in the laboratory, consistent with the findings of Zheng and Chen,[45] namely that celery VOCs had a significant repellence effect on *M. persicae* in a Y-tube olfactometer. Further studies (solid-phase microextraction, GC/MS analysis) are needed to clarify the repellent effects of celery on different pests.

Intercropping of tomato and coriander successfully managed whitefly infestation in the field.[37,38,46] Reductions in the numbers of eggs and adults of the South American tomato pinworm, *Tuta absoluta* (Meyrick) have been reported when tomato is intercropped with coriander.[47] Moreover, tomato intercropped with coriander showed a 37.7% reduction in the density of *B. tabaci* nymphs compared with tomato alone.[34] Our results also showed significantly lower densities of *M. persicae* on coriander-treated plants compared with control plants during the main eggplant harvest period. The results indicate that coriander affected aphid populations in the field by reducing the population growth, performance and settlement of *M. persicae*. Our results showed a similar magnitude of repellence as that reported by Zheng and Chen,[45] who found that the volatiles of coriander repelled *M. persicae* in Y-tube olfactometer behavioural assays.

Furthermore, to optimize field application of RPs, we need to not only confirm the effectiveness of RPs, but also understand the mechanisms involved.[48] At present, there are two known modes of action of volatiles on aphids (direct and indirect effects). The direct effects include VOCs disrupting aphid behaviour directly through repellent activities and/or masking the attractant odour of the host plant to prevent recognition by the pest.[49,50] Another mechanism is the indirect effect via airborne communication between an emitter plant and a receiver plant. VOCs from neighbouring plants can be perceived as biologically relevant information by the receiver plant and consequently modify the biochemical metabolism and/or volatile emission of the receiver plant, thus affecting pest behaviour.[51–53]

Laboratory tests have been carried out to evaluate the performance of RPs and define their mode of action. Tests have shown that the presence of RPs has direct negative effects on aphid fecundity and an indirect repulsion effect on aphid orientation.[20,54] In many cases, the repellent effect of RPs has been used to explain reduced aphid colonization on their host crops.[14] Our laboratory assays allowed us to clearly ascribe changes in aphid behaviour to the presence of RPs. The results showed that coriander, mint and celery exerted a repellent effect on *M. persicae*, whereas mung beans exhibited the weakest effect. The four selected RPs showed a negative effect on the population growth of *M. persicae* on pepper leaflets. The decrease in the population we observed may be attributable to the direct effect of the RPs' VOCs on aphid behaviour. In fact, Tomova *et al*.[55] reported a decrease in *M. persicae* reproduction up to 85% when exposed to *Tagetes* oil. This is also consistent with the findings of Ben Issa *et al*.,[14] who reported a decrease of more than 30% in aphid nymph numbers on pepper in the presence of French marigold (*T. patula*), and of Dardouri *et al*.,[54] who found that the flowers of *T. patula* reduced aphid reproduction significantly in the laboratory.

VOC release is related to abiotic factors (i.e. temperature, humidity and radiation) and the physiological stage of the plant used.[14,54] Dardouri *et al*.[54] found that flower VOCs (but not leaf VOCs) of *T. patula* significantly reduced *M. persicae* reproduction, underlining the need to consider the phenological stages when evaluating the potential of RPs. Our field assays highlighted that the four selected RPs exhibited strong repellence against *M. persicae* during their fast growth periods.

Previous studies have focused mostly on evaluating the impact of RPs on the population dynamics of pests and their natural enemies. Other ecosystem functions, such as nitrogen fixation, soil structure improvement, water infiltration, soil and water conservation, and pollination enhancement have not been considered, but are also likely to influence crop systems.[6] Research has indicated that the agronomic traits (i.e. plant height, stem diameter, single fruit weight and yield) of tomato intercropped with mint have improved.[56] These traits may be comprehensively considered to screen suitable functional plants. Most importantly, intercropping designs preferentially include marketable plants that are useful to farmers. In addition, ease of growth is a fundamental characteristic needed to reduce labour and generate a favourable cost to benefit ratio.[34] Compared with most studies using intercropping with RPs with a high RP–crop ratio,[38,44] we planted the RPs in areas that were not used for growing crops. This intercropping design not only reduced pest density without affecting production, but also promoted the acceptance of RPs for pest control by farmers. The time of planting affects VOC emissions.[57] RPs need to be planted in advance to make full use of the repellence over their entire growth period, and timely replanting is important to ensure the sustainability of the repellent effect in the field.

The enemies hypothesis proposed by Root[58] holds that a mixed cropping system can provide more habitat and food than a single cropping system, thus facilitating the survival of natural enemies in the system and exerting the effect of pest control. Functional plants (i.e. RPs) enhance the activities of natural enemies by providing shelter and food resources.[59] Aromatic plants have been mainly investigated and applied in East Asia to enhance natural enemies in biological control programmes.[24,60] Studies have shown that coriander attracts and/or supports natural enemies (i.e. predatory lady beetles, hover flies and lacewings), promoting pest control of crops.[61–63] Similarly, intercropping mung bean with wheat supports the natural predators of aphids, thus inhibiting the aphid population.[25] It is also important to attract beneficial predators to suppress exponential pest growth.[26,32,64] Furthermore, RPs that not only attract natural enemies, but also repel pests could offer an enhanced alternative for pest control.

Much work is still needed to optimize the services provided by RPs in cropping systems. An RP-alone strategy is unlikely to completely replace a chemical spray or provide satisfactory pest control because of its limited effectiveness, which may be constrained by climatic conditions, and the density and phenology of the RPs.[50] Nevertheless, using RPs with other IPM approaches (i.e. resistant host plants, pest-repellent extracts and essential oils, and early release of natural enemies) would enhance pest control. In addition, the push–pull strategy involves the manipulation of insect behaviour through the integration of stimuli that act to make the protected resource unattractive or unsuitable for the pests (push) while luring them toward an attractive source (pull) from where the pests are subsequently removed.[65,66] This strategy has been used successfully with RPs, reducing pest damage to crops and thus reducing the use of pesticides.[4,67] That is, the pest control efficiency of RPs may be strengthened when combined with trap plants.

To our knowledge, this was the first study to assess the effect of RPs on the population dynamics of *M. persicae* on pepper and eggplant over their entire growth period in a greenhouse. The selected RPs reduced the density of *M. persicae* in *Solanum* vegetables. The repellent effect on *M. persicae* varied with the species and growth periods of the RPs. RPs exhibited strong repellence against *M. persicae* during periods of rapid growth. Mint, celery and coriander repelled *M. persicae* and had a negative influence on its population growth in laboratory assays, revealing the potential of RPs in reducing the density of *M. persicae* in the field. Plants used for habitat manipulation usually need to be established early in the crop calendar for improved pest control.[68] Early planting and timely replanting of RPs can become an effective, sustainable and environmentally friendly pest management strategy against *M. persicae* in greenhouses using IPM.

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