Bulletin of Entomological Research

cambridge.org/ber

Orange peel soil amendments affect *Brassica rapa* growth and aphid development without disrupting parasitoid foraging behaviour

Zhao Jianye[1,†], Huan Xia[1,†], Jamin Ali[1,†], Wang Jingyu[1], Li Yang[1], Yuhan Zhang[1], Xiyao Xue[1], Jiyun Liang[1], Han Xiao[1], Mohammad Mahamood[2], Habib Ali[3], Adil Tonga[4], Qiyun Li[1] and Rizhao Chen[1]

[1]College of Plant Protection, Jilin Agricultural University, Changchun, PR China; [2]Department of Plant Protection, College of Agriculture and Food, Qassim University, Buraydah, Saudi Arabia; [3]Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan and [4]Entomology Department, Diyarbakır Plant Protection Research Institute, Diyarbakır, Türkiye

Research Paper

[†]The authors equally share first authorship and are entitled to claim it as first authors on their resumes.

Cite this article: Jianye Z *et al*. (2026) Orange peel soil amendments affect *Brassica rapa* growth and aphid development without disrupting parasitoid foraging behaviour. *Bulletin of Entomological Research* **116**, 346–354. https://doi.org/10.1017/S0007485325100758

Received: 7 July 2025
Revised: 9 December 2025
Accepted: 17 December 2025
First published online: 5 January 2026

Keywords:
crop protection; food security; insect pest management; orange peel; soil amendment; tritrophic interactions

Corresponding author: Rizhao Chen;
Email: rizhaochen@jlau.edu.cn

Abstract

This study tested the effects of soil amendment with orange peel powder (*Citrus sinensis* L.) on *Brassica rapa* growth, the performance of the aphid *Myzus persicae* Sulzer, and the foraging behaviour of its parasitoid *Aphidius gifuensis* Ashmead. Three peel: soil ratios (1:10, 1:15, 1:20 w/w) were compared with an unamended control. The 1:10 amendment significantly reduced seed germination, plant height, leaf size, and fresh weight, while the 1:20 amendment also decreased fresh weight. Aphid nymphal development was significantly delayed in the 1:10 and 1:15 treatments, and adult weight gain was reduced in the 1:15 treatment. Aphid population growth and parasitoid foraging time were unaffected across treatments. The results indicate that orange peel amendments can delay aphid development but also suppress plant growth at higher concentrations, highlighting the need for optimized application rates. This study supports further exploration of orange peel as a sustainable soil amendment in integrated pest management.

Introduction

Soil amendments critically mediate plant-insect interactions through modifications to soil nutrient profiles, microbial communities, and plant secondary metabolism (Barragán-Fonseca *et al.*, 2023; Wantulla *et al.*, 2023). These alterations directly influence plant phenotypic traits – including seed germination efficiency (Solaiman *et al.*, 2012), vegetative growth (Roy *et al.*, 2010), leaf expansion, and biomass accumulation (Agegnehu *et al.*, 2016; Holatko *et al.*, 2022), while concurrently enhancing soil structure, water retention, and nutrient bioavailability (Zhou *et al.*, 2020; Xuan *et al.*, 2022). Organic amendments further modulate plant defence mechanisms, inducing systemic resistance against herbivores through elevated secondary metabolites or nutrient reallocation (Gu *et al.*, 2022; Javed *et al.*, 2025). Crucially, bioactive compounds within amendments (e.g. chitin, neem derivatives) can directly suppress pest performance via antifeedant, repellent, or insecticidal activity (Alyokhin *et al.*, 2013; Rowen, 2020), though efficacy is inherently dose-dependent and context-specific, as demonstrated by the phytotoxicity of high-concentration garlic stalk amendments in eggplant (Ghani *et al.*, 2019).

The functional diversity of soil amendments is evidenced across multiple systems: chitin-rich crustacean shells prime jasmonate-dependent defences against chewing herbivores (Sharp, 2013; van de Zande *et al.*, 2024), while insect exuviae amendments restructure rhizosphere microbiomes to enhance plant tolerance and yield in *Brassica nigra* L. (Barragán-Fonseca *et al.*, 2023; Wantulla *et al.*, 2023). Similarly, composted organics elevate defensive metabolites to reduce herbivory (Jiang *et al.*, 2020), and neem-based formulations disrupt aphid fecundity in brassicaceous crops (Lokanadhan *et al.*, 2012; Gupta, 2022). Despite these advances, the potential of orange peel amendments, a globally abundant agricultural waste, remains underexplored in aboveground pest management, particularly for phloem-feeding insects.

Citrus sinensis L. peels are rich in bioactive compounds, including flavonoids, terpenes (notably limonene), and organic acids, which contribute to their well-documented antimicrobial and allelopathic properties (Saini *et al.*, 2022; da Silva *et al.*, 2023; Maqbool *et al.*, 2023; Fernando *et al.*, 2024). Orange peel is a globally abundant agricultural by-product (Okino Delgado and Fleuri, 2016; Mohsin *et al.*, 2022). Previous studies have investigated its use in soil: for example, orange peel extract enhanced growth and antioxidant capacity in quinoa under

© The Author(s), 2026. Published by Cambridge University Press.

water deficit (El-Bassiouny *et al.*, 2016), and soil amendment with orange peel improved heat tolerance in *Schefflera arboricola* (Hayata) Merr. (El-Serafy *et al.*, 2023). When incorporated into soil, such organic amendments can modify rhizosphere conditions and plant physiology, which may indirectly influence aboveground insect herbivores (Gu *et al.*, 2022; Barragán-Fonseca *et al.*, 2023). Importantly, limonene has also been shown to inhibit insect feeding and oviposition (Fernando *et al.*, 2024). Despite promising evidence for plant protection and plant resilience, the effects of orange peel amendments on aboveground herbivores, especially phloem-feeding insects like aphids, remain largely unexplored. This is a critical gap, as aphids are highly responsive to even subtle changes in host plant chemistry, which can profoundly affect their development, reproduction, and population dynamics.

Aphids such as *Myzus persicae* Sulzer (Hemiptera: Aphididae) pose serious threats to agriculture through direct feeding and virus transmission (Van Emden *et al.*, 1969; Ali, 2023; Ali *et al.*, 2023). Their population dynamics are highly sensitive to host plant quality, particularly factors like nitrogen content, secondary metabolites (e.g. glucosinolates), and stress-induced changes in plant defence signalling (Ahuja *et al.*, 2011; Cao *et al.*, 2016; Ali *et al.*, 2024). Soil amendments that enhance plant defences or alter nutrient profiles have been shown to reduce aphid fecundity or delay development (Sharp, 2013; Gupta, 2022; Barragán-Fonseca *et al.*, 2023; Wantulla *et al.*, 2023). Nevertheless, imbalanced application rates can impose unintended stress on the plant, occasionally rendering it more vulnerable to pests, a paradox noted in allelopathic studies (Noble, 2011; Abdel Ghani *et al.*, 2018; Brtnicky *et al.*, 2021; Adhikari *et al.*, 2024). For instance, Ghani *et al.* (2019) showed that high doses of raw garlic stalk amendment suppressed eggplant biomass and photosynthetic efficiency, increased oxidative stress markers, hydrogen peroxide (H_2O_2), and malondialdehyde (MDA), and reduced chlorophyll content, despite lower doses enhancing antioxidative defences and promoting growth. This trade-off between pest suppression and plant vigour underscores the importance of optimizing amendment dosage. However, how such effects manifest in response to orange peel amendments, particularly in aphid-infested systems, remains unclear.

Despite the dual potential of *C. sinensis* peels as soil enhancers and sources of bioactive limonene, their impact on *Brassica*-aphid-parasitoid systems remains unknown. We applied orange peel powder as a soil amendment (rather than as a foliar spray) to test for plant-mediated, systemic effects on the aphid-parasitoid system. This method simulates a practical agronomic practice for integrating waste into soil and allows for the potential modulation of root-shoot signalling and phloem chemistry. We hypothesize that orange peel soil amendments alter *Brassica rapa* L. (Brassicales: Brassicaceae) physiology and defence profiles, thereby indirectly delaying aphid development via changes in host plant quality, without directly deterring the parasitoid. This study bridges this gap by investigating: (1) Dose-response effects of orange peel powder amendments on *B. rapa* growth traits; (2) Consequences for *M. persicae* developmental dynamics and population growth; and (3) Implications for the foraging efficiency of its parasitoid *Aphidius gifuensis* Ashmead (Hymenoptera: Braconidae). We hypothesize that peel amendments will induce plant defence responses, delaying aphid development without compromising parasitoid behaviour. Our findings will elucidate the viability of orange waste as a sustainable tool for integrated pest management.

Materials and methods

Insect culture

Myzus persicae founders were purchased from Qu Shou Natural (Nanyang, China) then reared on field mustard (*B. rapa*) plants in rearing cages (60 × 60 × 60 cm) under controlled environmental conditions (20 ± 2°C, 45 ± 5% RH, photoperiod 16L: 8D). Adult apterous aphids from this colony were used in all experiments. The initial colony of parasitoid *A. gifuensis* was sourced from aphid mummies provided by Better Life Co. Ltd., Yunnan, China. *A. gifuensis* were reared on *B. rapa* plants infested with *M. persicae* under controlled conditions (20 ± 2°C, 45 ± 5% RH, photoperiod 16L: 8D). After emergence, parasitoid adults were provided with a honey-water solution (1:1) in a small plastic tub (3 × 4 cm) placed in the corner of the rearing cage, which was replaced with fresh solution twice a week. Naïve female parasitoids (3–5 days old) were used in all the experiments.

Plant culture

B. rapa plants were grown from seed (Hebei Dayu Seeds, Cangzhou, China) at 20 ± 3°C, 50 ± 10% RH, 16L: 8D h photoperiod in 7 cm diameter pots filled with soil (Jiangsu Siweibo Biotechnology Co., Ltd., China). Experiments were conducted using four-week-old plants (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [(BBCH]) growth stage 14 (Meier, 2001), which corresponds to plants with four fully expanded true leaves.

Soil amendment

Soil amendment was carried out using dried and pulverized peels of *C. sinensis* (Gannan navel orange), a variety produced in Ganzhou City, Jiangxi Province. Fresh fruits were purchased from the Guoshu Fruit Chain Supermarket in Changchun, China. The peels were rinsed with distilled water and air-dried. The dried peels were first ground using a grinder and then sieved through a mesh with an approximate pore size of 1.2 mm × 0.8 mm to obtain a uniform powder. Soil was purchased from Jiangsu Siweibo Biotechnology Co., Ltd., China, and autoclaved before use. Three amendment treatments were prepared at peel-to-soil ratios of 1:10, 1:15, and 1:20 (w/w). The powdered orange peels were thoroughly mixed into the dry soil by hand to ensure uniform distribution. Control soil underwent the same procedure, but without the addition of orange peel powder.

Seed germination

To evaluate the effect of orange peel soil amendment on seed germination, an experiment was conducted using plastic seedling trays, each containing 50 cells (5 × 4.5 cm per cell). Two seeds were sown in each cell, resulting in 100 seeds per tray. Five trays were used per treatment, totalling 500 seeds per treatment group. Trays were filled with soil corresponding to the respective amendment treatments (1:10, 1:15, and 1:20 peel-to-soil ratios), along with a control treatment without orange peel powder. Seeds were sown directly into the amended soil in each cell. The total number of germinated seeds was recorded on the 15th day after sowing. A seed was considered germinated when the radicle visibly emerged above the soil surface. All trays were maintained under controlled environmental conditions (20 ± 3°C, 45 ± 10% RH, 16L:8D photoperiod).

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

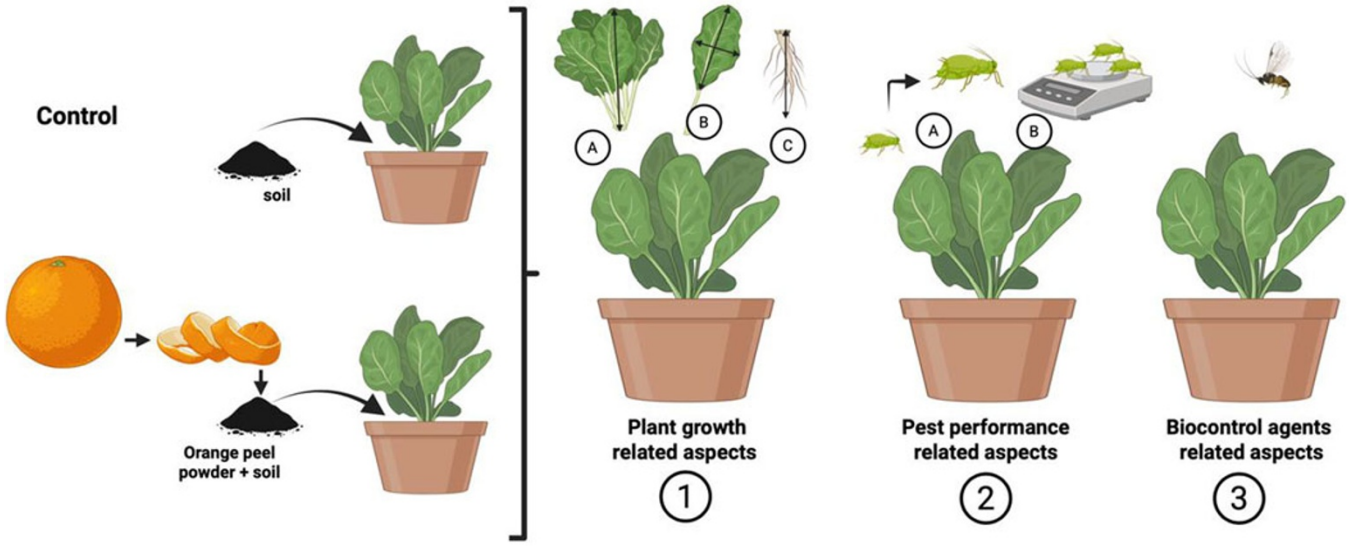


Figure 1. Overview of the experimental design used to assess the effects of orange peel soil amendment on plant growth, pest performance, and biocontrol agent behaviour. Control plants were grown in unamended soil, while treatment plants received soil amended with powdered Citrus sinensis peels. Assessments included: (1) plant growth parameters such as height (A), leaf dimensions (B), and root length (C); (2) aphid development time (A) and weight gain (B); and (3) parasitoid foraging behaviour. All experiments were conducted under controlled environmental conditions.

Effect of orange peel amendment on plant traits

Plant growth parameters were evaluated in *B. rapa* plants grown for 4–5 weeks in amended or unamended soils under controlled environmental conditions. Measurements were performed across four treatments: control (unamended soil), T1 (1:10 w/w peel: soil), T2 (1:15 w/w peel: soil), and T3 (1:20 w/w peel: soil), with ten replicates per treatment. Plant height was quantified by measuring the vertical distance (cm) from the soil surface to the top of the longest leaf using a calibrated ruler (fig. 1, 1A). Leaf dimensions were assessed by recording leaf length as the linear distance from the petiole base to the leaf tip and leaf width as the maximum lateral span perpendicular to the midrib (fig. 1, 1B), with length and width analysed separately. Root length was measured after gently washing root systems under running water to remove soil particles; roots were blotted dry and measured linearly (cm) from the root–shoot junction to the tip of the longest intact root (fig. 1, 1C). Fresh biomass was determined by harvesting entire plants (shoots and roots) and immediately weighing them on a precision balance, with washed roots patted dry to minimize errors from residual moisture.

Aphid development and weight

To assess the effect of soil amendment on the development time and weight gain of *M. persicae*, a single wingless adult aphid was placed on a *Brassica* plant leaf in a Petri dish lined with moist filter paper. After 24 h, the adult aphid and all other nymphs were removed, leaving only one neonate nymph. This remaining nymph was then transferred to a fresh plant leaf and enclosed in a clip cage (25 mm diameter) using a camel hair brush. The nymphs were allowed to develop on the plant until they reached adulthood. Development time was recorded as the number of days from birth to reproductive maturity, which was defined by the appearance of the first offspring. For weight measurements, groups of five neonate nymphs were weighed in 1.5 mL Eppendorf tubes using an electronic microbalance (Sartorius Technology Instruments Company, Ltd., Beijing, China) on the first day and again upon reaching adulthood. Average weight gain was calculated by subtracting the initial weight from the final weight measured after 7 days. Twenty replicates were conducted for the development assay, and ten replicates were used for the weight gain bioassay.

Aphid population

In this experiment, we assessed the population growth of *M. persicae*. Three newly emerged wingless adult aphids were transferred onto each plant, which was then enclosed in a vented bag (30 cm × 40 cm). The plants were left undisturbed for 7 days. After this period, the total number of aphids, including adults and nymphs, was recorded for each plant. Ten replicates were conducted for each treatment.

Parasitoid foraging bioassay

This experiment was designed to evaluate the effect of soil amendment on the foraging behaviour of the parasitoid *A. gifuensis*. The total time female parasitoids spent on plants grown under different soil amendment treatments was compared with that on control plants. For each trial, a single female parasitoid was released from a vial onto a plant leaf placed inside an open-fronted cage. The total time the parasitoid remained on the plant was recorded using a timer. Observation ended when the parasitoid flew away from the plant, which was considered as leaving the foraging 'patch'. If the parasitoid remained on the plant for longer than 25 minutes, the observation was terminated at that point. Sixteen replicates were conducted for each treatment, alternating between treated and control plants. All experiments were performed between 10:00 AM and 2:00 PM.

Statistical analysis

Count, binomial, and continuous data were modelled with generalized linear models with Poisson, Binomial, and Gaussian distributions. However, when over- or under-dispersion was

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

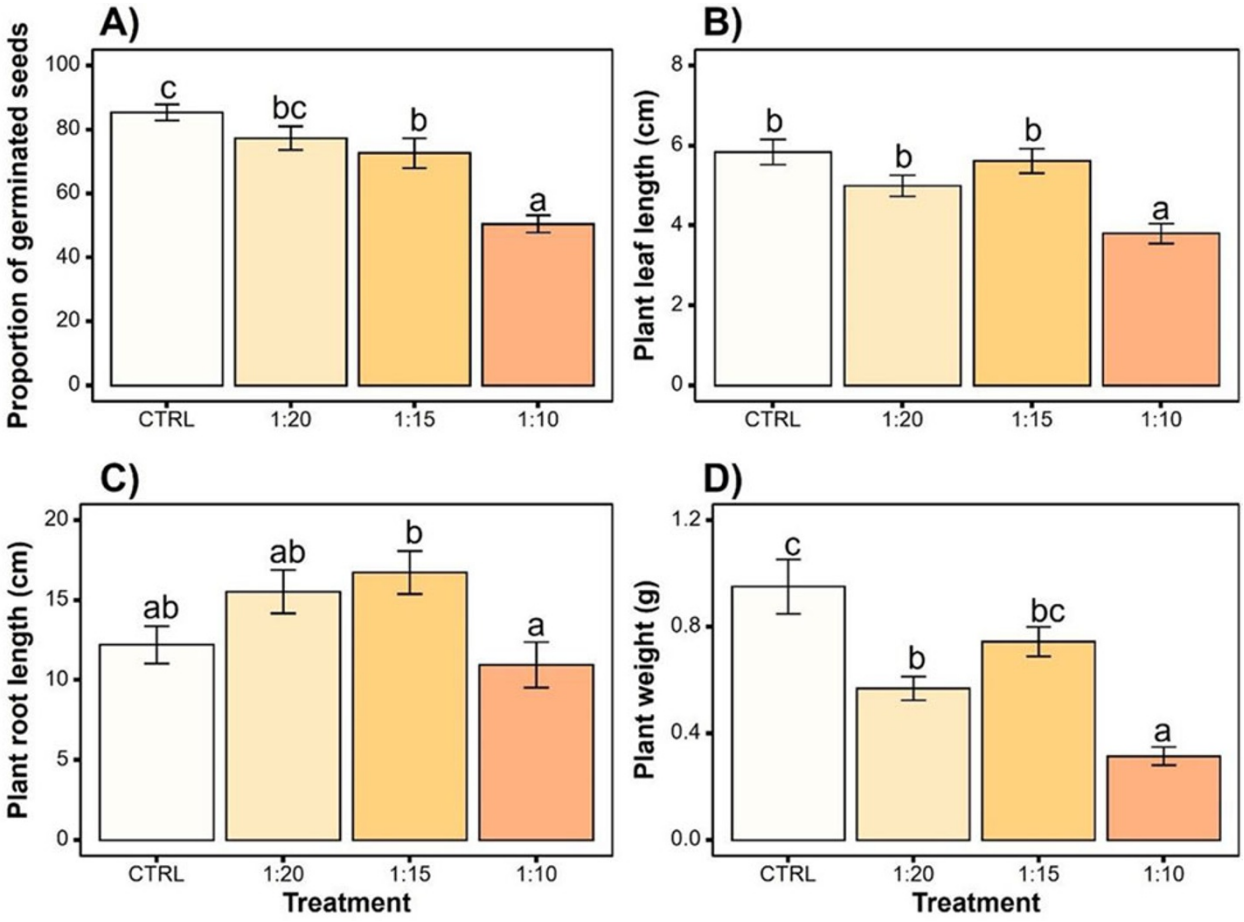


Figure 2. Proportion of germinated seeds (A), total height (B), root length (C), and fresh weight (D) of *Brassica rapa* plants under different orange peel amendment treatments with a respective ratio to soil (1:20, 1:15, 1:10 compared with control) as in the axis *x* for each subplot. Different lower cases depict the differences between treatments.

observed, the models were converted to quasi versions to avoid dispersion-associated issues (Faraway, 2016; Dunn and Smyth, 2018). Anova() function from car package helped generate likelihood ratio test results. Multiple comparison tests were performed based on Tukey's approach, using emmeans package. All figures except fig. 1 were generated with ggplot2 package (Wickham *et al.*, 2023). Data underwent statistical procedures in R statistical software (R Development Core Team, 2024).

Results

Effect of orange peel amendment on plant traits

Orange peel amendment treatments significantly affected seed germination success ($\chi^2_{df=3} = 48.00$, $P < 0.001$), plant total height ($\chi^2_{df=3} = 30.71$, $P < 0.001$), plant root length ($\chi^2_{df=3} = 12.58$, $P = 0.006$) and plant fresh weight ($\chi^2_{df=3} = 47.94$, $P < 0.001$), and leaf dimensions (leaf length ($\chi^2_{df=3} = 37.74$, $P < 0.001$); leaf width ($\chi^2_{df=3} = 66.96$, $P < 0.001$). Seed germination success was significantly lower in soils with the 1:15 and 1:10 (w/w) orange peel amendments (fig. 2A). Plant height was significantly reduced in soil with the 1:10 amendment (fig. 2B). Although a significant overall effect on root length was detected ($\chi^2_{df=3} = 12.58$, $P = 0.006$), none of the amended treatments differed significantly from the control; differences occurred only among the amendment treatments themselves (fig. 2C). Plant fresh weight was significantly lower in soils amended at the 1:10 and 1:20 (w/w) ratios compared with the control (fig. 2D). Leaf traits were also affected, with the 1:10 (w/w) amendment significantly reducing both leaf length and leaf width (fig. 3A, B).

Aphid performance (development, weight, and population increase)

Aphid performance parameters such as nymphal duration ($\chi^2_{df=3} = 172.43$, $P < 0.001$) and adult weight gain ($\chi^2_{df=3} = 25.86$, $P < 0.001$) were significantly affected by orange peel amendments in the soil. The 1:15 and 1:10 (w/w) orange peel amendments delayed nymphal developmental duration (fig. 4A) while the 1:15 amendment reduced adult weight gain (fig. 4B). Aphid population increase was not significantly affected by the treatments ($\chi^2_{df=3} = 2.42$, $P = 0.490$, fig. 4C).

Parasitoid foraging behaviour

The foraging behaviour of *A. gifuensis* was not significantly affected by the soil amendments containing *C. sinensis* peel powder ($\chi^2_{df=3} = 3.20$, $P = 0.362$, fig. 5). Parasitoids showed similar host-searching durations across all treatments and the control.

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

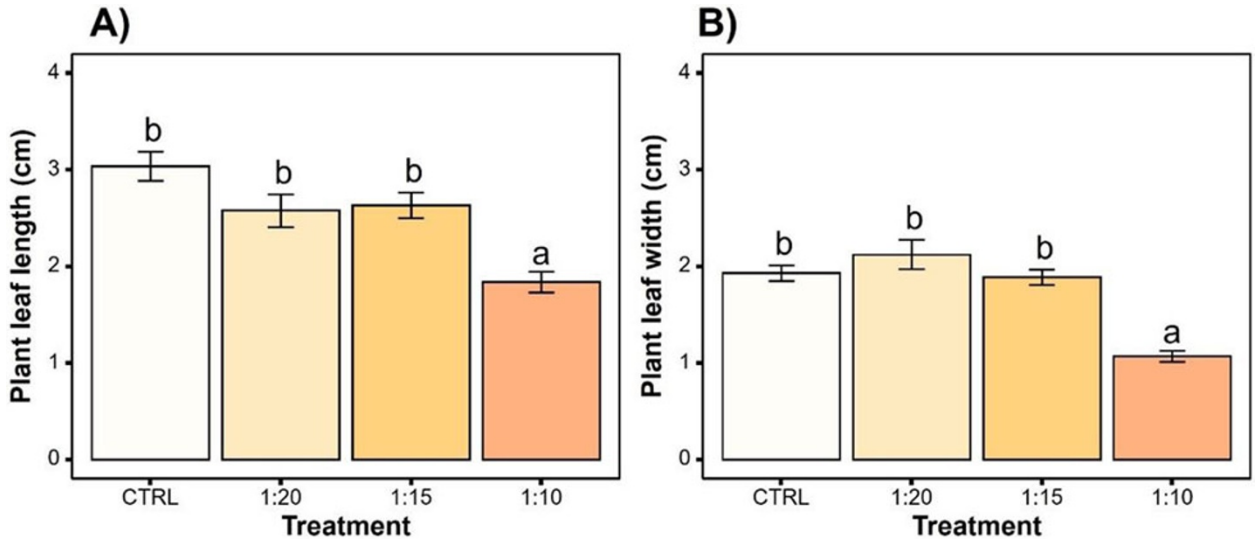


Figure 3. Leaf length (A) and width (B) of *Brassica rapa* plants under different orange peel amendment treatments with a respective ratio to soil (1:20, 1:15, 1:10 compared with control) as in the axis *x* for each subplot. Different lower cases depict the differences between treatments.

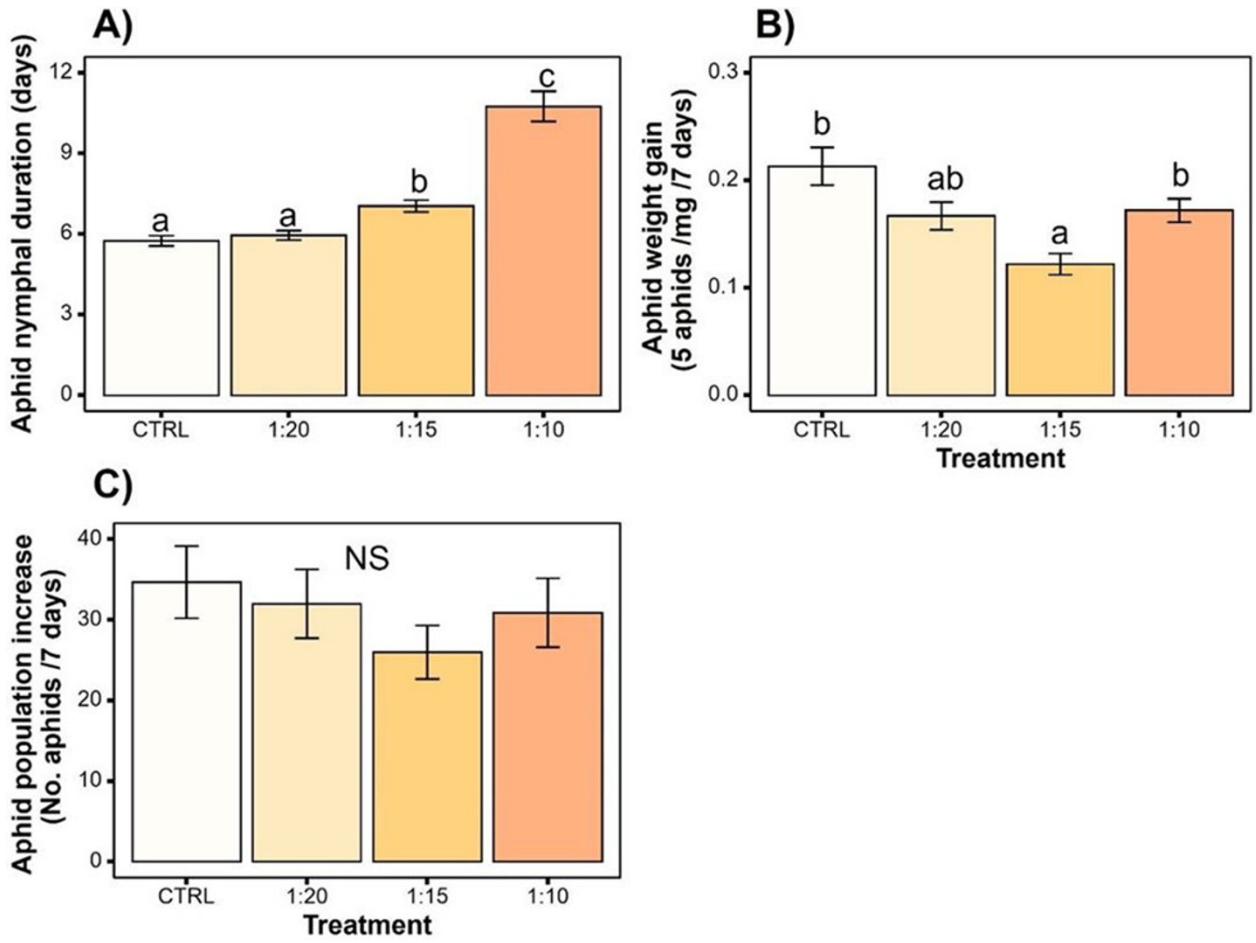


Figure 4. Nymphal developmental duration (A), weight (B), and population increase of *Myzus persicae* reared on *Brassica rapa* plants under different orange peel amendment treatments with a respective ratio to soil (1:20, 1:15, 1:10 compared with control) as in the axis *x* for each subplot. Different lower cases depict the differences between treatments, while the annotation 'NS' refers to a non-significant treatment effect.

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

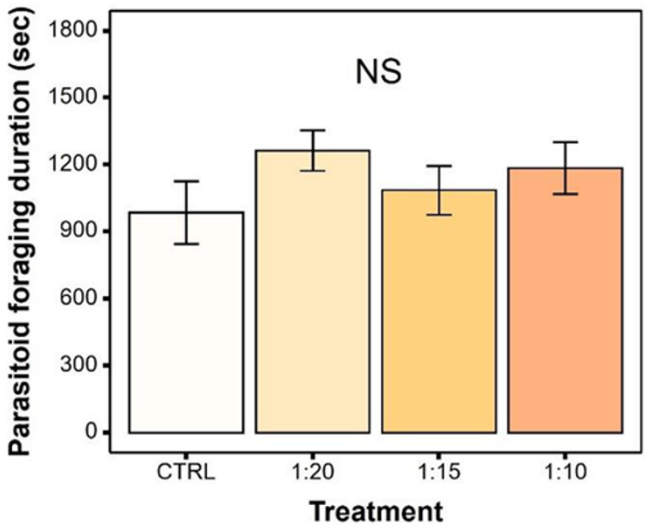


Figure 5. Foraging duration (sec, mean ± sem) of *Aphidius gifuensis* under different orange peel amendment treatments with a respective ratio to soil (1:20, 1:15, 1:10 compared with control) as in the axis *x*. The annotation 'NS' refers to a non-significant treatment effect.

Discussion

The valorization of agricultural by-products as soil amendments represents a promising strategy for sustainable pest management. Orange peel, a globally abundant citrus waste rich in bioactive compounds, offers potential to modulate plant-soil-insect interactions. This study demonstrates that soil amendment with orange peel powder at specific ratios can influence *B. rapa* growth and *M. persicae* development, without disrupting the foraging behaviour of its parasitoid *A. gifuensis*. These findings highlight both the promise and the practical challenges of utilizing citrus waste in integrated pest management.

We observed clear concentration-dependent effects on plant performance. The 1:10 amendment significantly reduced seed germination, plant height, leaf dimensions, and fresh biomass, while the 1:20 amendment also decreased fresh weight. These phytotoxic effects are consistent with prior research on citrus-based amendments. Ribeiro and Lima (2012) reported that volatile compounds in orange peel oil suppressed seedling growth and caused morphological changes in weeds. Similarly, Nath *et al.* (2016) found that lemon peel extracts reduced germination and growth in lettuce and cabbage, effects attributed mainly to limonene, a dominant compound in orange peels (Shafique *et al.*, 2013; Mahmoud, 2017). Ugolini *et al.* (2024) further showed that orange *pastazzo* extracts rich in limonene inhibited germination in *Chenopodium album* L. and delayed *Lactuca sativa* L. germination. Supporting this, Sahoo *et al.* (2015) demonstrated that *Citrus reticulata* leaf extracts inhibited germination and shoot/root growth in various crops in a dose-dependent manner. Allelopathic activity varies among citrus species and tissues. Fujihara and Shimizu (2003) found strong inhibitory effects from *Citrus junos* peel but minimal effects from navel orange and lemon, emphasizing the importance of species-specific phytochemical profiles. Furthermore, Tsai (2008) showed that stored pulpified orange peels enhanced nematostatic and egg hatch inhibition effects, likely due to the release of essential oils during storage. This suggests that the method of orange residue preparation could significantly influence biological activity, an aspect worth exploring in future work.

Reduced plant height and fresh weight may also be linked to nutrient immobilization during microbial decomposition of high-carbon organic matter (Bonanomi *et al.*, 2006, 2011). Interestingly, even the low-concentration amendment (1:20) reduced plant weight, indicating that minor doses can influence soil nutrient availability or plant physiology. This contrasts with positive results reported from orange pulp amendments (Mahmoud *et al.*, 2019), underscoring the different impacts of various citrus tissues. The pattern is consistent with dose-dependent effects seen in other amendments, such as garlic stalk, where moderate doses enhance growth but higher concentrations induce stress (Ghani *et al.*, 2019). Leaf size reduction in the 1:10 treatment aligns with reports of phytotoxic effects on leaf development. For instance, terpenes such as limonene have been suggested to interfere with hormonal signalling in other plant systems (Rodriguez *et al.*, 2011; Qasim *et al.*, 2024), which could theoretically contribute to reduced leaf expansion. This indicates a trade-off between pest suppression and plant vigour, which could be attributed to phytotoxic effects of peel compounds and/or to nutrient immobilization during decomposition of the high-carbon amendment. These effects highlight the need for optimized application rates.

Also reported dose-dependent effects of garlic stalk amendments: moderate doses enhanced plant growth, while higher concentrations induced stress, a pattern consistent with our findings. Although we did not observe changes in root length, previous studies reported root suppression with orange peel extracts (Nath *et al.,* 2016), again pointing to species-specific sensitivity. Leaf size reduction in Treatment 1 is consistent with reports of phytotoxic effects on leaf development. For instance, terpenes such as limonene have been suggested to interfere with hormonal signalling in other plant systems (Rodriguez *et al.*, 2011; Qasim *et al.*, 2024), which could theoretically contribute to reduced leaf expansion. Nevertheless, this did not translate into population-level effects on *M. persicae*, possibly due to the aphid's ability to adjust feeding behaviour and reproduction under stress (Goggin and Fischer, 2022; Ali *et al.*, 2025a, 2025b)

The impact on aphid performance was similarly dose-dependent. The 1:10 and 1:15 amendments significantly delayed nymphal development, and the 1:15 amendment reduced adult weight gain. This aligns with studies linking plant secondary metabolites to extended insect development. Hollingsworth (2005) demonstrated that 1% aqueous limonene solutions effectively controlled various sap-feeding insects, suggesting that limonene, a major component of orange peel oils, has potential as a natural insecticide. The reduction in adult weight at moderate amendment levels (1:15) suggests a possible induction of plant defence responses. In *Brassica* species, similar abiotic or biotic stresses can lead to increased glucosinolate production (Mewis *et al.*, 2012), which is known to influence aphid performance. However, aphid population growth remained unchanged, contrasting with findings that compounds like sinigrin reduce fecundity (Gabrys and Tjallingii, 2002). This suggests *M. persicae* may possess metabolic adaptations to cope with moderate chemical defences (Farhan *et al.*, 2024). The absence of population-level effects may also reflect spatial limitations of the experiment. Gfeller *et al.* (2023) demonstrated that root-exuded benzoxazinoids suppressed herbivore abundance only under field conditions. Similarly, Gu *et al.* (2022) reported that aphid suppression by organic amendments depended on widespread application. Our pot-scale setup may not have provided sufficient spatial heterogeneity to amplify sublethal stress into population-level control (Gu *et al.*, 2022; Gfeller *et al.*, 2023, 2024).

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

Importantly, orange peel amendments did not affect *A. gifuensis* foraging behaviour, suggesting that changes in plant traits or volatiles did not interfere with parasitoid host-searching. This aligns with Gu *et al.* (2022), who found that maize straw amendments increased parasitism rates without altering parasitoid foraging, likely due to altered amino acid profiles rather than volatiles. Thus, orange peel amendments appear compatible with this aspect of biological control, though further research on other parasitoid life-history traits is needed for a comprehensive assessment. Beyond direct pest management, orange peel residues offer wider ecological benefits, such as their potential use in creating bioactive, sustainable materials (Selvaraj *et al.*, 2025).

In conclusion, this study demonstrates that soil amendment with orange peel powder can influence plant-insect interactions by modifying plant physiology and impairing aphid development. The amendments delayed *M. persicae* nymphal development and reduced adult weight gain, suggesting potential for pest suppression. However, these effects were accompanied by reductions in plant performance at higher amendment levels. The lack of effect on parasitoid foraging is encouraging for integrated strategies. These findings highlight the promise of orange peel residues as a sustainable tool while emphasizing the need to calibrate application rates. Future studies incorporating soil property analyses (e.g. pH, EC, and organic matter) would help elucidate whether plant responses are driven primarily by phytochemical activity or by shifts in nutrient availability. Research across different cultivars and field conditions, with quantification of active compounds, would support broader agricultural application of this approach to waste valorization.

Acknowledgements. The authors acknowledge BioRender.com for providing the platform used to create fig. 1.

Author contributions. **Zhao Jianye:** methodology, experimentation, data curation. **Huan Xia:** methodology, experiments. **Jamin Ali:** conceptualisation, methodology, experimentation, writing – original draft; writing – reviewing and editing, data analysis, visualization. **Wang Jingyu:** methodology, experimentation, data collection. **Li Yang:** experimentation. **Yuhan Zhang:** experimentation. **Xiyao Xue:** methodology, experimentation. **Jiyun Liang:** experimentation, resources. **Han Xiao**: writing – reviewing and editing. **Mohammad Mahamood:** writing – original draft; writing – reviewing and editing. **Habib Ali:** writing – original draft; writing – reviewing and editing, critical reading, and visualization. **Adil Tonga:** conceptualisation, original draft; writing – reviewing and editing; data analysis, visualization. **Qiyun Li:** conceptualisation, supervision, funding acquisition, project administration, resources, writing – review and editing. **Rizhao Chen:** conceptualisation, supervision, funding acquisition, project administration, resources, writing – review and editing.

Financial support. This work was supported by the People's Government of Jilin (Grant No. 20220203198SF) and the Ministry of Science and Technology of China (Grant No. 2022YFD1500701).

Competing interests. The authors declare no competing interests.

Consent for publication. All authors agree to and provide their approval for the publication of this article.

Ethics approval and consent to participate. Not applicable.

Data availability statement. The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdel Ghani SB, Al-Rehiayani S, El Agamy M and Lucini L (2018) Effects of biochar amendment on sorption, dissipation, and uptake of fenamiphos and cadusafos nematicides in sandy soil. *Pest Management Science* **74**(11), 2652–2659.

Adhikari A, Kwon E-H, Khan MA, Shaffique S, Kang SM and Lee IJ (2024) Enhanced use of chemical fertilizers and mitigation of heavy metal toxicity using biochar and the soil fungus Bipolaris maydis AF7 in rice: Genomic and metabolomic perspectives. *Ecotoxicology & Environmental Safety* **271**, 115938.

Agegnehu G, Nelson PN and Bird MI (2016) Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. *Soil and Tillage Research* **160**, 1–13.

Ahuja I, Rohloff J and Bones AM (2011) Defence mechanisms of Brassicaceae: implications for plant-insect interactions and potential for integrated pest management. *Sustainable Agriculture* **2**, 623–670.

Ali J (2023) The Peach Potato Aphid (*Myzus persicae*. Ecology and Management' **1**, 132. https://doi.org/10.1201/9781003400974

Ali J, Alam SS, Abdel Hafez MM, Abbas S, Alam A, Ji Y, Ghramh HA, Khan KA, Saddam B, Tonğa A and Chen R (2025a) Signals from aphid-infested neighboring plants modify aphid performance and host plant biochemistry. *Journal of Economic Entomology* toaf134.

Ali J, Bayram A, Mukarram M, Zhou F, Karim MF, Hafez MM, Mahamood M, Yusuf AA, King PJ, Adil MF and Ma Z (2023) Peach–potato aphid *myzus persicae*: current management strategies, challenges, and proposed solutions. *Sustainability* **15**(14), 11150.

Ali J, Munawar A, Abbas S, Khan KA, Ghramh HA, Li Q, Chen R and Bayram A (2025b) Host adaptation in model aphid pest *Myzus persicae* (Hemiptera: Aphididae): genetic, physiological, and behavioral perspectives. *Journal of Economic Entomology* Edited by R. Medina, (XX). 1–14. https://doi.org/10.1093/jee/toaf116

Ali J, Tonğa A, Islam T, Mir S, Mukarram M, Konôpková AS and Chen R (2024) Defense strategies and associated phytohormonal regulation in *brassica* plants in response to chewing and sap-sucking insects. *Frontiers in Plant Science* **15**, 1376917.

Alyokhin A, Gross S, Vincent C and Giordanengo P (2013) Interactions among organic soil amendments, plants, and insect herbivores. *Insect Pests of Potato: Global Perspectives on Biology and Management* 291–309.

Barragán-Fonseca KY, Greenberg LO, Gort G, Dicke M and Van Loon JJ (2023) Amending soil with insect exuviae improves herbivore tolerance, pollinator attraction and seed yield of Brassica nigra plants. *Agriculture Ecosystems and Environment* **342**, 108219.

Bonanomi G, Incerti G, Barile E, Capodilupo M, Antignani V, Mingo A, Lanzotti V, Scala F and Mazzoleni S (2011) 'Phytotoxicity, not nitrogen immobilization, explains plant litter inhibitory effects: evidence from solid-state 13C NMR spectroscopy.' *New Phytologist* **191**(4), 1018–1030.

Bonanomi G, Sicurezza MG, Caporaso S, Esposito A and Mazzoleni S (2006) Phytotoxicity dynamics of decaying plant materials. *New Phytologist* **169**(3), 571–578.

Brtnicky M, Datta R, Holatko J, Bielska L, Gusiatin ZM, Kucerik J, Hammerschmiedt T, Danish S, Radziemska M, Mravcova L and Fahad S (2021) A critical review of the possible adverse effects of biochar in the soil environment. *Science of the Total Environment* **796**, 148756.

Cao -H-H, *et al.* (2016) The green peach aphid *Myzus persicae* perform better on pre-infested Chinese cabbage *Brassica pekinensis* by enhancing host plant nutritional quality. *Scientific Reports* **6**(1), 1–12.

da Silva VHN, Trindade ÍT, Vicente ME, de Souza GS, Maia PJ, Ávila MD, da Silva IR, de Lima BR and Do Carmo DF (2023) 'Chemical Composition, Allelopathic Potential, and Antimicrobial and Anticholinesterase Activity of *Citrus sinensis* (L.) Peel Oil.'

Dunn PK and Smyth GK, *Generalized linear models with examples in R*, Springer (2018). *Generalized linear models with examples in R* Ed, Chapman and Hall/CRC.

El-Bassiouny HMS, Abdallah MM, Bakry BA and Ibrahim FM (2016) Effect of orange peel extract or ascorbic acid on growth, yield and some biochemical aspects of quinoa plants under water deficit. *International Journal of Pharmaceutical Technology Research* **9**, 86–96.

El-Serafy RS, El-Sheshtawy A-NA and Dahab AA (2023) Fruit peel soil supplementation induces physiological and biochemical tolerance in *Schefflera arboricola* L. grown under heat conditions. *Journal of Soil Science and Plant Nutrition* **23**(1), 1046–1059.

Faraway JJ, 2016. *Extending the linear model with R: generalized linear, mixed effects and nonparametric regression models*. Chapman and Hall/CRC.

Farhan M, Pan J, Hussain H, Zhao J, Yang H, Ahmad I and Zhang S (2024) Aphid-Resistant plant secondary metabolites: Types, insecticidal mechanisms, and prospects for utilization. *Plants* **13**(16), 2332.

Fernando S, Jayasooriya RGPT, Samarakoon KW, Wijegunawardana NA and Alahakoon SB (2024) Citrus-based bio-insect repellents—a review on historical and emerging trends in utilizing phytochemicals of citrus plants. *Journal of Toxicology* **2024**(1), 6179226.

Fujihara S and Shimizu T (2003) Growth inhibitory effect of peel extract from *Citrus junos*. *Plant Growth Regulation* **39**(3), 223–233.

Gabrys B and Tjallingii WF (2002) The role of sinigrin in host plant recognition by aphids during initial plant penetration. *Entomologia Experimentalis et Applicata* **104**(1), 89–93.

Gfeller V, Thoenen L and Erb M (2024) Root-exuded benzoxazinoids can alleviate negative plant–soil feedbacks. *New Phytologist* **241**(6), 2575–2588.

Gfeller V, Waelchli J, Pfister S, Deslandes-Hérold G, Mascher F, Glauser G, Aeby Y, Mestrot A, Robert CA, Schlaeppi K and Erb M (2023) Plant secondary metabolite-dependent plant-soil feedbacks can improve crop yield in the field. *Elife* **12**, e84988.

Ghani MI, Ali A, Atif MJ, Ali M, Amin B, Anees M and Cheng Z (2019) Soil amendment with raw garlic stalk: A novel strategy to stimulate growth and the antioxidative defense system in monocropped eggplant in the north of China. *Agronomy* **9**(2), 89.

Goggin FL and Fischer HD (2022) Reactive oxygen species in plant interactions with aphids. *Frontiers in Plant Science* **12**, 811105.

Gu S, Zalucki MP, Men X, Li J, Hou R, Zhang Q, Ge F and Ouyang F (2022) Organic fertilizer amendment promotes wheat resistance to herbivory and biocontrol services via bottom-up effects in agroecosystems. *Journal of Pest Science* **95**, 339–350.

Gupta AK (2022) Use of neem and neem based products in organic farming. *Indian Farming* **72**(1).

Holatko J, Hammerschmiedt T, Mustafa A, Kintl A, Radziemska M, Baltazar T, Jaskulska I, Malicek O, Latal O and Brtnicky M (2022) Carbon-enriched organic amendments differently affect the soil chemical, biological properties and plant biomass in a cultivation time-dependent manner. *Chemical and Biological Technologies in Agriculture* **9**(1), 1–13.

Hollingsworth RG (2005) Limonene, a citrus extract, for control of mealybugs and scale insects. *Journal of Economic Entomology* **98**(3), 772–779.

Javed MW, Hasan MU, Sagheer M, Abbasi A, Hussain M, Arshad M, Hussain D, Sarfaraz RA, Riaz R and Rebouh NY (2025) Soil amendment-mediated herbivory resistance, crop improvement, and phytoremediation in canola: physiological defense mechanism and health risk assessment. *Plants* **14**(7), 1110.

Jiang L, Bonkowski M, Luo L, Kardol P, Zhang Y, Chen X, Li D, Xiao Z, Hu F and Liu M (2020) Combined addition of chemical and organic amendments enhances plant resistance to aboveground herbivores through increasing microbial abundance and diversity. *Biology and Fertility of Soils* **56**, 1007–1022.

Lokanadhan S, Muthukrishnan P and Jeyaraman S (2012) Neem products and their agricultural applications. *Journal of Biopesticides* **5**, 72.

Mahmoud AM, Hernández Bautista RJ, Sandhu MA and Hussein OE (2019) Beneficial effects of citrus flavonoids on cardiovascular and metabolic health. *Oxidative Medicine and Cellular Longevity* **2019**(1), 5484138.

Mahmoud EA (2017) Essential oils of Citrus fruit peels antioxidant, antibacterial and additive value as food preservative. *Journal of Food and Dairy Sciences* **8**(2), 111–116.

Maqbool Z, Khalid W, Atiq HT, Koraqi H, Javaid Z, Alhag SK, Al-Shuraym LA, Bader DM, Almarzuq M, Afifi M and Al-Farga A (2023) Citrus waste as source of bioactive compounds: Extraction and utilization in health and food industry. *Molecules* **28**(4), 1636.

Meier U (2001) 'Growth Stages of Mono and Dicotyledonous Plants; BBCH Monograph; Federal Biological Research Centre for Agriculture and Forestry: Bonn, Germany, 2001'.

Mewis I, Khan MAM, Glawischnig E, Schreiner M and Ulrichs C (2012) Water stress and aphid feeding differentially influence metabolite composition in Arabidopsis thaliana (L.). *PLoS One* **7**(11), e48661.

Mohsin A, Hussain MH, Zaman WQ, Mohsin MZ, Zhang J, Liu Z, Tian X, Salim-Ur-Rehman KIM, Niazi S and Zhuang Y (2022) Advances in sustainable approaches utilizing orange peel waste to produce highly value-added bioproducts. *Critical Reviews in Biotechnology* **42**(8), 1284–1303.

Nath S, Yumnam P and Deb B (2016) Allelopathic effect of lemon plant parts on the seedling germination and growth of lettuce and cabbage. *International Journal of Plant Biology and Research* **4**, 1054.

Noble R (2011) Risks and benefits of soil amendment with composts in relation to plant pathogens. *Australasian Plant Pathology* **40**, 157–167.

Okino Delgado CH and Fleuri LF (2016) Orange and mango by-products: Agro-industrial waste as source of bioactive compounds and botanical versus commercial description—A review. *Food Reviews International* **32**(1), 1–14.

Qasim M, Islam W, Rizwan M, Hussain D, Noman A, Khan KA, Ghramh HA and Han X (2024) Impact of plant monoterpenes on insect pest management and insect-associated microbes. *Heliyon* **10**(20).

R Development Core Team, R: A language and environment for statistical computing (version 4.4.1). The R foundation for statistical computing. Vienna, Austria, R Foundation for Statistical Computing, Vienna, Austria (2024).

Ribeiro JPN and Lima MIS (2012) Allelopathic effects of orange (*Citrus sinensis* L.) peel essential oil. *Acta Botanica Brasilica* **26**, 256–259.

Rodriguez A, San Andrés V, Cervera M, Redondo A, Alquézar B, Shimada T, Gadea J, Rodrigo MJ, Zacarías L, Palou L and López MM (2011) Terpene down-regulation in orange reveals the role of fruit aromas in mediating interactions with insect herbivores and pathogens. *Plant Physiology* **156**(2), 793–802.

Rowen E (2020) Soil management changes biological control and plant resistance to insect herbivores.

Roy S, Arunachalam K, Dutta BK and Arunachalam A (2010) Effect of organic amendments of soil on growth and productivity of three common crops viz. Zea mays, Phaseolus vulgaris and Abelmoschus esculentus. *Applied Soil Ecology* **45**(2), 78–84.

Sahoo UK, Jeeceelee L, Lallinrawna S and Muthukumaran RB (2015) 'Effect of *Citrus reticulata* Blanco leaf extract on seed germination and initial seedling growth parameters of five home garden food crops.'

Saini RK, Ranjit A, Sharma K, Prasad P, Shang X, Gowda KG and Keum YS (2022) Bioactive compounds of citrus fruits: A review of composition and health benefits of carotenoids, flavonoids, limonoids, and terpenes. *Antioxidants* **11**(2), 239.

Selvaraj RCA, Kanagaraj A, Karuppiah P, Ravindran S, Raj MM, Senthamaraikannan P and Suyambulingam I (2025) Leveraging citrus extract to enhance antioxidant properties of mung bean (*Vigna radiata*) protein edible films. *Biomass Conversion and Biorefinery* 1–16.

Shafique S, Shafique S and Aqeel A (2013) Ecofriendly response of citrus peels to Alternaria leaf spots of tomato: exclusive role of peel phenolics. *International Journal of Agriculture and Biology* **15**(6).

Sharp RG (2013) A review of the applications of chitin and its derivatives in agriculture to modify plant-microbial interactions and improve crop yields. *Agronomy* **3**(4), 757–793.

Solaiman ZM, Murphy DV and Abbott LK (2012) Biochars influence seed germination and early growth of seedlings. *Plant & Soil* **353**, 273–287.

Tsai BY (2008) Effect of peels of lemon, orange, and grapefruit against Meloidogyne incognita. *Plant Pathology Bulletin* **17**(3), 195–201.

Ugolini F, Crisci A, Baronti S, Cencetti G, Dal Prà A, Albanese L, Michelozzi M, Zabini F and Meneguzzo F (2024) Effects of orange waste extract produced by hydrodynamic cavitation on the Germination of *Chenopodium album* L. and *Lactuca sativa* L. *Sustainability* **16**(7), 3039.

van de Zande EM, Wantulla M, van Loon JJA and Dicke M (2024) Soil amendment with insect frass and exuviae affects rhizosphere bacterial community, shoot growth and carbon/nitrogen ratio of a brassicaceous plant. *Plant & Soil* **495**(1), 631–648.

Van Emden HF, Eastop VF, Hughes RD and Way MJ (1969) The ecology of *Myzus persicae*. *Annual Review of Entomology* **14**(1), 197–270.

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press

Wantulla M, van Loon JJA and Dicke M (2023) Soil amendment with insect exuviae causes species-specific changes in the rhizosphere bacterial community of cabbage plants. *Applied Soil Ecology* **188**, 104854.

Wickham H, Chang W, Henry L, Pedersen TL, Takahashi K, Wilke C *et al*.,. Create Elegant Data Visualisations Using the Grammar of Graphics (ggplot2 v3.4.4) (2023).

Xuan K, Li X, Yu X, Jiang Y, Ji J, Jia R, Wang C and Liu J (2022) Effects of different organic amendments on soil pore structure acquired by three-dimensional investigation. *European Journal of Soil Science* **73**(4), e13264.

Zhou H, Chen C, Wang D, Arthur E, Zhang Z, Guo Z, Peng X and Mooney SJ (2020) Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. *Soil and Tillage Research* **202**, 104663.

https://doi.org/10.1017/S0007485325100758 Published online by Cambridge University Press