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ORIGINAL ARTICLE

Pre-Bloom Application of Petroleum Spray Oil for the Control of Green Apple Aphid, *Aphis pomi* De Geer in Apple Orchards

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ABSTRACT

The green apple aphid (*Aphis pomi* De Geer) is a major early-season pest in apple orchards. While petroleum spray oils (PSOs) are commonly applied at the delayed dormant stage to control San José scale and European red mite, their effect on *A. pomi* remains unclear. This study assessed the ovicidal and larvicidal efficacy of 2% PSO applications at the delayed dormant/green tip stage. Laboratory and field assays demonstrated substantial suppression of egg hatch, with cumulative hatch reduced to 9.90% ± 0.57% (laboratory assay) and 9.62% ± 0.71% (field evaluation) in treated shoots. Survival analyses revealed significantly higher mortality risk for treated eggs. Direct toxicity trials on nymphs showed mortality rates of 69.9% ± 1.95% in field conditions and > 99% in lab dip assays by 5 days after treatment. Residual toxicity assays indicated cumulative mortality reaching 64.07% ± 2.74% by 2 days post-exposure, confirming efficacy even after drying. Field trials further revealed that PSO significantly reduced bud infestation by *A. pomi* (5.22% ± 0.54%) compared to the untreated control (19.04% ± 2.34%), with enhanced suppression observed when combined with imidacloprid (0.29% ± 0.14%). These findings underscore the potential of PSO as both a standalone and synergistic agent in aphid management. This is the first detailed report on the ovicidal and larvicidal activity of PSOs against *A. pomi*, supporting its inclusion in sustainable, early-season integrated pest management programmes.

1 | Introduction

The green apple aphid (*Aphis pomi* DeGeer) is a major pest in temperate pome orchards across North America, Europe and Asia (Jenser et al. 1999; Blackman and Eastop 2000). Feeding on phloem, it causes leaf curling, reduced photosynthesis and stunted growth, while honeydew fosters sooty mould, compounding damage (Rakauskas et al. 2015; Alford 2016). *A. pomi* exhibits a holocyclic, autoecious life cycle on apple. It reproduces parthenogenetically during the growing season, with multiple asexual generations causing significant damage. In autumn, decreasing temperature and photoperiod induce the sexual phase, producing males and oviparae. Mated females lay overwintering eggs on apple shoots, completing the cycle on a single host species (Blackman and Eastop 2000). Its rapid reproduction and overlapping generations make it especially problematic during early shoot and fruit development (Arbab et al. 2006; Whitaker et al. 2006). In Jammu and Kashmir (India), *A. pomi* has emerged as a significant pest with seasonal outbreaks in recent years (Shah et al. 2025).

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Historically controlled with synthetic insecticides, resistance development in *A. pomi*—via enhanced detoxification and target site insensitivity—has compromised efficacy (Erdogan et al. 2023; Sanches and Wise 2024). Regulatory and environmental concerns have further driven the shift toward safer alternatives (Fernandez et al. 2005; Buteler and Stadler 2011; Simon-Delso et al. 2015). Petroleum spray oils (PSOs), or horticultural mineral oils (HMOs), have reemerged as reduced-risk insecticides with minimal phytotoxicity and environmental impact (Fernandez et al. 2005; Taverner et al. 2011, 2012). Acting through physical means—spiracle blockage, cuticle disruption and sensory interference—they cause suffocation, desiccation and deterrence (Rae et al. 1997; Stadler and Buteler 2009; Buteler and Stadler 2011).

PSOs are mainly used during dormant or delayed dormant periods to control overwintering pests like *Panonychus ulmi*, *Quadraspidiotus perniciosus* and aphids such as *Dysaphis plantaginea*. Typically applied at 1.5%–3% concentrations, their efficacy increases near egg hatch (Chapman and Pearce 1949; Bobb 1968; Fernandez et al. 2006; Marčić et al. 2009; Taverner et al. 2011, 2012; Cranshaw and Baxendale 2013). PSOs may also be tank-mixed with selective insecticides to enhance their performance through synergistic action and improved coverage. However, for maximum efficacy, application equipment must ensure fine droplets and thorough coverage, as field performance tends to drop under suboptimal application conditions (Lawson and Weires 1991; Taverner et al. 2012).

Despite their widespread use in citrus and ornamental systems, PSO efficacy data in pome fruit systems regarding residual action and target-specific response in *A. pomi*, remains limited. Historically, ethion-oil and phostex-oil sprays were used to control rosy apple aphid and other aphid species during the dormant period (Kurtz and Fullmer 1959), and early work by Quaintance and Baker (1917) and others recommended contact insecticides for aphid stem mothers shortly after hatching. The earliest observation on the fact that as the eggs of aphids approach hatching, the greater the mortality caused by sprays was noted by Peterson (1914, 1919). Cutright (1930) did a series of experiments on the efficacy of sprays against the eggs of various apple aphids at the delayed dormant stage, probably among the earliest detailed studies on the application of PSOs for the management of apple aphids at the delayed dormant stage and reported their efficacy on par with lime sulphur, the insecticide of choice at the time. In more recent studies, Fernandez et al. (2006) found that both early and main season oil spray programs suppressed *D. plantaginea* densities, although effects on other aphid species like *A. pomi* were inconclusive due to lower incidence.

As high incidence and outbreaks of the aphids have been noticed on the apple orchards of the main apple producing areas of India (Jammu and Kashmir) where PSOs are regularly sprayed at delayed dormancy against the European red mite and San Jose scale, this study was designed to address key knowledge gaps by evaluating the effect of PSO on the percent egg hatch of overwintering eggs of green apple aphid, direct and residual toxicity of a 2% petroleum spray oil formulation against hatched nymphs of *A. pomi* under controlled laboratory and field conditions. Further, the effect of PSO sprays actually intended and timed against the mites and scale on apple was also evaluated under field conditions either sprayed alone or in combination with synthetic insecticides.

2 | Material and Methods

Field and laboratory experiments were conducted in 2023 and 2024 to evaluate the ovicidal and larvicidal effects of PSO on green apple aphids. A field study also examined the impact of PSO sprays—actually targeted applied against overwintering stages of European red mites and San Jose scale—on early spring aphid incidence.

3 | Effect of PSO on the Egg Hatch of Green Apple Aphid

3.1 | Field Study

To investigate the ovicidal efficacy of PSO against overwintering eggs of the *A. pomi*, a field experiment was conducted in the experimental apple orchard at ICAR-Central Institute of Temperate Horticulture, Srinagar (Jammu and Kashmir, India; 33°59′06.0″ N 74°47′47.0″ E) during 2023. The orchard consisted of multiple apple cultivars on MM106 rootstock, 4–5 years old in early bearing stage, laid out with a spacing of 3 × 2 sq. m. The experiments were conducted on the variety 'Coe Red Fuji' as it sustains high populations of GAA.

A total of 65 apple trees with sufficient overwintering *A. pomi* eggs were selected. On each tree, 1–3 shoots with high egg incidence were marked, and three egg clusters (24–34 eggs each) per shoot were labelled (45 segments total). Remaining eggs on the shoots were removed by scrubbing with coarse fabric.

Two treatments were tested: 30 segments were sprayed with 2% PSO, and 15 with distilled water. Sprays were applied on 19th March at the delayed dormant/green tip stage using a calibrated knapsack sprayer (2.5 L per plant, flat-fan nozzle, 0.55 MPa) for full coverage, based on the methodology suggested by Fernandez et al. (2006). The PSO selected for the studies was Servo Petroleum Derived Spray Oil (PDSO) 97% EC (Indian Oil Corporation Ltd. Mumbai—400051, India) as one of the most popular PSOs used by the growers. This oil is a light paraffinic oil with 97% min. unsulfonated residue, min. paraffinic content (Cp) 64%, max. nepthenic content (Cn) 35%, kinematic viscosity at 40°C 15–19 cSt, min. flash point (COC) 150°C, max. pour point −3°C, density 0.825–0.845 g/mL (at 29.5°C). Egg hatch was monitored daily until 1st April, recording hatch rates, desiccation and first instar emergence.

3.2 | Laboratory Assay

To evaluate the ovicidal efficacy of petroleum spray oil (PSO) against overwintering eggs of *A. pomi*, a laboratory assay was conducted using excised apple shoots as suggested by Cutright (1930) and with slight modifications from David and Horsburgh (1985) and Taverner et al. (2011). Dormant shoots naturally infested with aphid eggs were collected from untreated

apple orchards during late winter. Shoots were pruned to a standard length (25 cm), ensuring similar bark thickness and bud development stages across all samples. On each shoot, three segments of 12–23 eggs (42 in total) were marked with a felt pen depending on closely spaced clusters, and counted prior to treatment application. The remaining eggs from the selected shoots were removed by scrubbing off and cleaning the shoots with rough fabric cloth to keep the field of observation clear and prevent any hatched nymphs from wandering off to the marked segments.

The experiment consisted of two treatments in which 28 shoot segments were sprayed with PSO and the remaining 14 shoot segments were sprayed with distilled water. The PSO (Servo PDSO 97% EC) was sprayed at the recommended field dose (2.0% v/v). Treatments were applied using a precision handheld atomiser to ensure uniform wetting of the shoot surface on 17th March (delayed dormant/green tip stage). After application, shoots were allowed to air-dry and then placed individually in flasks containing distilled water to maintain turgor and prevent desiccation. All treated samples were incubated in a controlled environment chamber (Narang Scientific Works, IGC-325) at 20°C ± 1°C, 60%–70% relative humidity, and a photoperiod of 14:10 h (L:D), simulating early spring field conditions. Post-treatment, egg hatch was monitored daily excluding weekends, assessing parameters including daily hatch, egg desiccation (shrivelled eggs) and emergence of first instar nymphs until 3rd April when no further egg hatch was expected. Egg hatch was monitored under a stereomicroscope (Figure S1).

3.3 | Statistical Analysis

The data from both the assays were analysed separately in two steps each. The percent daily egg hatch was calculated as the ratio of the number of eggs hatching on a particular day to the initial number of intact eggs selected, and the total egg hatch was calculated as the ratio of the cumulative number of eggs hatching at the end of the study period to the original number of intact eggs marked. The data on percent daily egg hatch from both the assays showed significant departure from normality based on the Shapiro–Wilk normality test (Shapiro and Wilk 1965) ($W = 0.38$, $p \leq 0.01$ for the lab assay; $W = 0.78$, $p \leq 0.01$ for the field study); therefore, the data were analysed with the Kruskal-Wallis rank sum test (Kruskal and Wallis 1952). When the Kruskal–Wallis test indicated significant differences among treatments, post hoc pairwise comparisons were conducted using Dunn's test with Bonferroni correction for multiple comparisons (Dunn 1964). All analyses were performed in R 4.3.1 (R Core Team 2023) using the '*dunn. test*' package.

Further, the effect of PSO spray on survival probabilities of eggs was derived by the Kaplan-Meier method and their homogeneities between the treated and untreated groups were tested based on the log-rank statistic. The hatching of eggs was treated as censored and death as the event (shrivelled eggs marked as dead). Multiple comparisons were determined with the Bonferroni correction. The Cox proportional hazards model was fitted to analyse the effect of the treatment on egg survival. All the analyses were performed utilising the 'survival' and 'survminer' packages in R 4.3.1 (R Core Team 2023).

4 | Direct and Residual Toxicity of PSO on Hatched Nymphs of *A. pomi*

In this series of experiments, the direct and residual toxicity of PSO against hatched nymphs of *A. pomi* under both controlled laboratory conditions and natural field environments was investigated based on the methodology adopted by Agnello et al. (1994).

4.1 | Laboratory Assay for Direct Toxicity Evaluation

Immediately after hatch, the ensuing nymphs move to the nearest buds as it is the only green tissue available at the time for feeding. Young apple shoots bearing actively feeding *A. pomi* nymphs on the buds (apical and axillary) were harvested from a pesticide-free orchard block during the early season when bud burst occurred. Uniform shoots (25 cm) carrying similar densities of nymphs and at the same approximate phenological stage (green tip) were selected. Only the aphids on apical buds were allowed to remain and the remaining nymphs were removed.

Each shoot harbouring the nymphs on the apical buds was immersed for 5 s in a 2% (v/v) PSO solution (Servo PDSO), prepared using distilled water. After dipping, excess solution was gently removed by shaking, and the shoots were allowed to air-dry under shade for approximately 30 min. Shoots designated as controls were treated with distilled water using the same dipping and drying protocol. Shoots were placed upright in 150 mL Erlenmeyer flasks filled with distilled water, and the necks were sealed with parafilm to minimise moisture loss and prevent aphid escape. The experiment was run four times independently. In each run, 9–12 shoots with nymphs received the PSO dip treatment designated as 'treated', and 3–4 shoots received the distilled water dip treatment designated as 'control'. Each individual shoot hosted 14–28 nymphs on the apical bud. Mortality was assessed at 1, 2 and 5 days after treatment (DAT) using a stereomicroscope. Nymphs were considered dead if they failed to respond to tactile stimulation with a fine camel-hair brush. Dead nymphs had turned black by the time of assessment. The entire assay was conducted under controlled laboratory conditions (20°C ± 1°C, 65% ± 5% RH, and 14:10 h L:D photoperiod).

4.2 | Field Trial for Direct Toxicity Evaluation

A parallel field trial was established in the same orchard, utilising infested apple plants that had shoots with naturally occurring *A. pomi* populations. The experiment was run simultaneously in three blocks of the orchard. In each block, 6–9 trees with medium to high infestation of GAA nymphs on the buds were selected. In each selected tree, 4–6 shoots with nymphs were tagged. On each shoot, both the mixed buds (1–2) and vegetative buds (1–3) with sufficient infestation of GAA were selected and the number of nymphs was noted

individually on each selected bud. The aphids on remaining buds were removed with a camel hair brush and all the eggs (hatched/unhatched) were removed from the shoots by wiping with a rough fabric cloth to prevent immigration of aphids. In each block, 4–5 trees were designated as 'sprayed' and received the 2% PSO spray as described before; the remaining trees were designated as 'unsprayed' and received a spray of distilled water ensuring complete coverage in both cases. Nymph counts were standardised across shoots prior to application to the possible extent without disturbing to ensure minimal variation. Spray treatments were given on 17th March (green tip) and mortality assessments were performed 3 days after treatment (3 DAT), based on visual examination of nymphal responsiveness. The live nymphs were green and responsive to touch, while the dead ones had turned black (Figure S2).

4.3 | Residual Toxicity of PSO on Hatched Nymphs of Green Apple Aphid

Residual toxicity was evaluated by placing freshly hatched neonate nymphs in contact with PSO-treated surfaces under laboratory conditions. Shoots with vegetative and floral buds at the green tip stage were collected and cleared of all eggs and nymphs using a soft brush. Cleaned shoots were dipped in a 2% PSO solution for 10 s, allowed to drain, and air-dried for 1 h in shaded laboratory conditions. The assay was replicated five times, each with a unique shoot and nymph cohort. Constant environmental conditions were maintained throughout. In each run, 9–10 shoots received the PSO dip treatment designated as 'treated', and 3–5 shoots received the distilled water dip treatment designated as 'control'. Neonate *A. pomi* nymphs (< 24 h old), constituting a synchronised cohort reared under constant temperature (22°C ± 1°C), were gently transferred on to the apical buds of treated and control shoots using a fine brush. Each shoot received 10 (in one run), 12 (in two runs) or 15 (in two runs) nymphs. Shoots were placed upright in 150 mL Erlenmeyer flasks filled with distilled water, and the necks were sealed with parafilm to minimise moisture loss and prevent aphid escape. Measures such as petroleum jelly barriers were employed at the shoot base to prevent aphid dispersal. Mortality was assessed at 1, 2 and 5 days after treatment (DAT) using a stereomicroscope. Nymphs were considered dead if they failed to respond to tactile stimulation with a fine camel-hair brush; the dead nymphs had turned black. The entire assay was conducted under controlled laboratory conditions (20°C ± 1°C, 65% ± 5% RH, and 14:10 h L:D photoperiod).

4.4 | Statistical Analysis

The percent mortality was calculated from the initial number of nymphs and the number of nymphs alive on the day of observation. The initial number of nymphs used varied to some extent across the treatment combinations; therefore, the scaling effect of pre-count was tested on the observed mortality using the linear regression. The effect was found non-significant for all assays and blocks/runs; hence, the corrected mortality was calculated using Abbott's formula (Abbott 1925). The significance of the effect of PSO treatment on the nymphal mortality was tested using Welch's *t*-test for all the blocks and runs independently (Welch 1947). The significance of treatment × block or run interaction was tested using the Analysis of Variance (ANOVA) to check for consistency of treatment effects across replicates. Further, Levene's test was conducted to test the homogeneity of variances (Levene 1960) for the observed mortality and corrected mortality before the data across the blocks/runs were pooled for analysis.

5 | Efficacy of PSO Alone and Mixed With Insecticides

A field experiment was conducted at the experimental farm of ICAR-CITH, Rangreth, Kashmir (India), during the pre-bloom period of the apple growing season, 2024. The study was designed to evaluate the bio-efficacy of PSO, both alone and in combination with selected insecticides, against *A. pomi*. The experiment was laid out in a Randomised Block Design (RBD) comprising six treatments, replicated three times. Each experimental plot consisted of two adjacent apple trees, forming a plot unit. The experiments were conducted on the variety '*Coe Red Fuji*' on MM106 rootstock, 4–5 years old in early bearing stage, laid out with a spacing of 3 × 2 sq. m.

Treatments were applied as a single spray on 17th March 2024 corresponding to the delayed dormant/green tip phenological stage of the crop. The six treatment combinations included two conventional insecticides, PSO alone, and mixtures of PSO with each insecticide. Treatments were chlorpyriphos 20 EC at 0.25%, imidacloprid 17.8 SL at 0.04%, horticultural mineral oil (PSO) at 2%, chlorpyriphos 20 EC at 0.25% + PSO at 2%, imidacloprid 17.8 SL at 0.04% + PSO at 2% and untreated control (water spray). All applications were made using a 15 L battery-operated knapsack sprayer ensuring thorough coverage. The whole plant was sprayed with around 2.5 L of the spray solution or water as a fine spray with a flat-fan nozzle at 0.55 MPa pressure.

The efficacy of the treatments against *A. pomi* was assessed based on percent bud infestation without prior observation or pre-count as per the EEPO guidelines (EPPO 2023). Observations were recorded at weekly intervals, specifically at 4 weeks after treatment (4 WAT) and 5 weeks after treatment (5 WAT). For each plant, either all buds on all shoots or from ten randomly selected shoots per tree were examined for the presence of aphids. The percent infestation was calculated as the number of infested buds divided by the total number of buds examined per plant, multiplied by 100.

5.1 | Statistical Analysis

Percent infestation data were subjected to arcsine transformation as arcsine (sqrt(x ± 0.0001)) to stabilise variance prior to statistical analysis. A two-way Analysis of Variance (ANOVA) was conducted using R 4.3.1 (R Core Team 2023) with treatment and replication as factors. Means were separated using Tukey's Honest Significant Difference (HSD) test at a 5% level of significance. Transformed values were back-referenced to original means (± standard error) for interpretation. Grouping of treatments based on statistical similarity was also conducted using the 'agricolae' package in R 4.3.1.

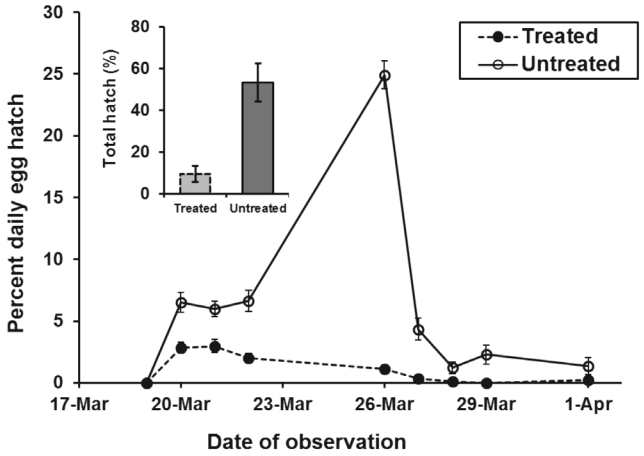

FIGURE 1 | Effect of petroleum spray oil (PSO) on the egg hatch of green apple aphid, *Aphis pomi* under laboratory conditions.

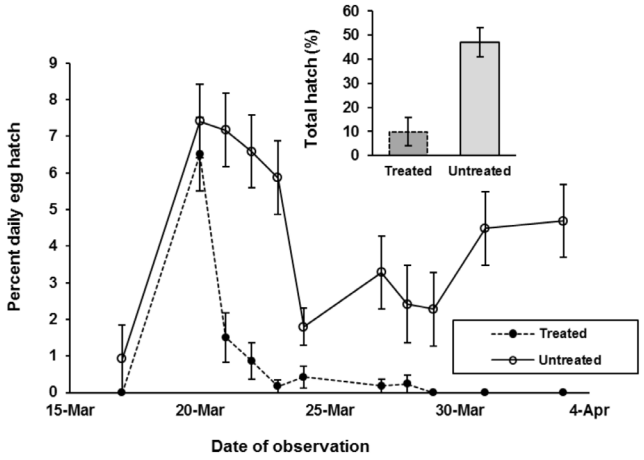

FIGURE 2 | Effect of petroleum spray oil (PSO) on the egg hatch of green apple aphid, *Aphis pomi* under filed conditions.

6 | Results

6.1 | Effect of PSO on the Egg Hatch of Green Apple Aphids

Under controlled laboratory conditions, PSO application significantly reduced hatching of green apple aphid eggs. The mean daily hatch percentage in the treated group was (mean ± SE) 0.93% ± 0.59%, compared to 4.65% ± 2.51% in the untreated control (Figure 1). A Kruskal-Wallis test showed this difference was highly significant ($\chi^2 = 48.16$, $p \leq 0.01$), and Dunn's post hoc test confirmed it with an adjusted $p \leq 0.001$. A peak in hatch was observed on March 20, followed by a sharp decline exhibiting a synchronous hatch pattern for the PSO treated eggs. The cumulative hatch was also substantially reduced in the PSO-treated group. Total egg hatch percentage achieved in the treated shoots was 9.90% ± 0.57% in comparison to untreated shoots 46.91% ± 0.68% (range 38.46–66.67) indicating high efficacy of dormant oil application in preventing egg viability.

In the field trial, petroleum spray oils again suppressed egg hatch, but the temporal dynamics differed markedly. Hatching was spread over 10–12 days, with multiple peaks in hatch observed in untreated shoots. The treated group had a mean daily hatch of 1.06% ± 0.40%, while untreated shoots averaged 5.92% ± 2.51% (Figure 2). This difference was highly significant ($\chi^2 = 29.36$, $p \leq 0.01$; Dunn's *p*.adj. ≤ 0.01). The mean total hatch in treated shoots was 9.62% ± 0.71% in comparison to untreated shoots 53.25% ± 3.25%.

Egg 'survival' analysis—treating hatching as censored and death as the event—showed median survival of 7 days for treated eggs and 8 days for untreated in laboratory assay (Figure 3). The log-rank test was significant ($\chi^2 = 4.28$, $p = 0.039$), and the Cox model estimated a 24% increased hazard of egg death in the treated group (HR = 0.76, $p = 0.0191$). In the field study, the Kaplan–Meier survival analysis showed a median survival of 8 days for both groups, but survival curves were significantly different (log-rank $p = 0.006$) (Figure 4). The Cox model indicated a 17% higher mortality risk for

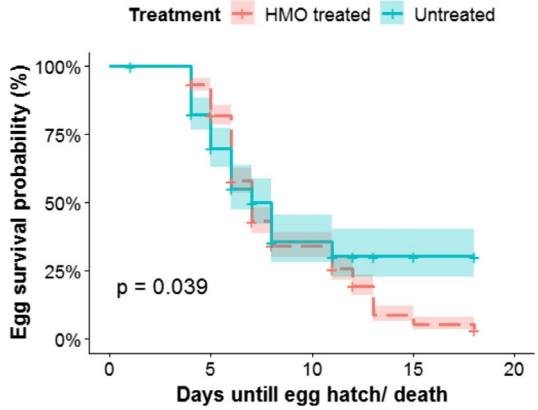

FIGURE 3 | Survivorship analysis of overwintering eggs of green apple aphid, *Aphis pomi* treated with petroleum spray oil (PSO) under laboratory conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

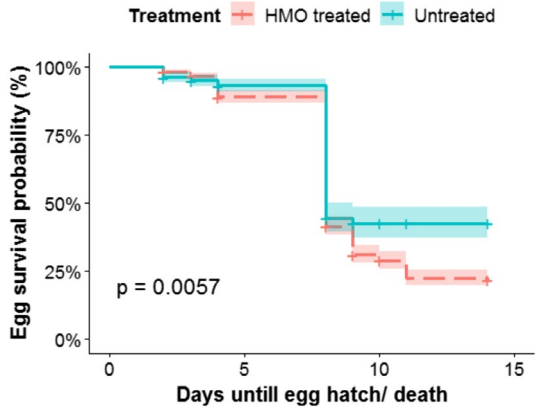

FIGURE 4 | Survivorship analysis of overwintering eggs of green apple aphid, *Aphis pomi* treated with petroleum spray oil (PSO) under field conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

treated eggs (HR = 0.83, $p = 0.0198$). Notably, survival in untreated eggs plateaued more gradually, suggesting a delayed decline due to extended hatching conditions in the field.

6.2 | Direct and Residual Toxicity of PSO to Nymphs of Green Apple Aphid

6.2.1 | Field Evaluation of Direct Toxicity

In the field study of direct toxicity, linear regression modelling was conducted to explore whether total aphid density influenced percent mortality under sprayed conditions. Results indicated no significant effect of aphid density ($\beta = 0.01$, $p = 0.922$), bud type ($\beta = -5.06$, $p = 0.281$) or block (all $p > 0.39$). Hence, the corrected mortality was created using Abbot's formula despite the variable initial number of aphids across the treatments. The application of PSOs resulted in significantly higher nymphal mortality compared to the unsprayed control across all three blocks. Observed mortality rates for sprayed treatments ranged from 68.8% to 74.0%, whereas unsprayed plots consistently showed low mortality rates between 9.2% and 10.5% (Table S1). No significant interaction between treatment and block ($F = 0.239$, $p = 0.788$), nor between bud type and block ($F = 1.836$, $p = 0.167$) was found. Additionally, Levene's test indicated homogeneity of variances for both observed mortality ($p = 0.805$) and corrected mortality ($p = 0.083$), further validating the pooled analyses. Hence, the data were pooled for analyses as well. These differences were statistically significant within each block ($p < 0.001$, Bonferroni-adjusted), and pooled analysis across all blocks reinforced this finding ($t = 29.2$, df = 97.4, $p \leq 0.01$), indicating a robust effect of PSO treatment (Figure 5). Within each block, differences in corrected mortality between bud types (Mixed vs. Vegetative) under the sprayed treatment were not statistically significant ($p > 0.05$). Pooled data also indicated no significant overall difference between bud types (t = 1.20, df = 77.8, $p = 0.23$).

6.2.2 | Laboratory Assay of PSO for Direct Toxicity to Green Apple Aphid Nymphs

Initial aphid density (Precount) on mortality showed no significant relationship ($F = 0.03$, df = 1, 166; $p = 0.85$), suggesting that mortality across all samples was independent of starting population size. Therefore, the corrected mortality was calculated based on Abbot's method (variable initial count). No significant differences were detected among experimental runs ($F = 0.42$; df = 1, 160; $p = 0.51$), along with a non-significant treatment × run interaction that was observed ($F = 4.56$; df = 1, 160; $p = 0.054$), indicating non-significant variability in treatment effect magnitude across runs. Hence, the data across all four experimental runs was pooled and analysed as well. Corrected mortality following PSO treatment was consistently high across all runs, with values exceeding 96% by 1 DAT and reaching near-complete mortality (99%–100%) by 5 DAT. Control mortality remained low throughout the experiment (< 11%) (Figure 6). Mortality differences between treated and control groups were highly significant and consistent across runs. Paired t-tests revealed that mortality in the PSO treatment group was significantly higher than in the control group at all time points ($p < 0.001$ across all runs and days) (Table S2).

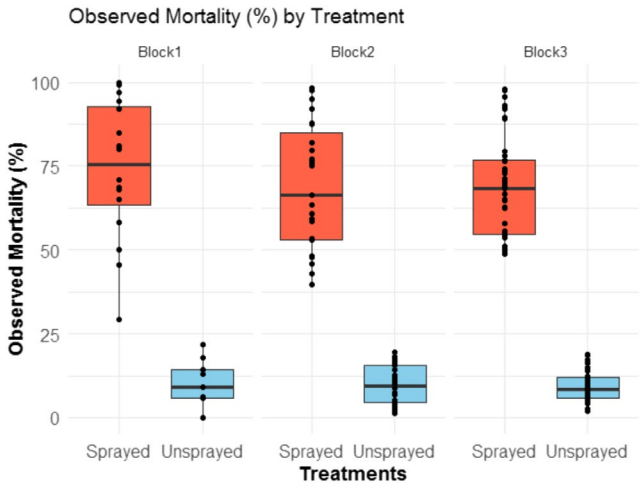

FIGURE 5 | Effect of (PSO) spray on the neonate nymphs of green apple aphid, *Aphis pomi* under filed conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

6.2.3 | Residual Toxicity Assay of PSO Against the Nymphs of Green Apple Aphid

In the residual toxicity assay, the GAA nymphs were introduced onto previously treated shoots for 5 days and nymphal survival was studied after 1, 2 and 5 days of cumulative exposure to the PSO residues. Corrected mortality for the treatment groups was calculated using Abbot's formula as a non-significant effect of initial aphid density on mortality was recorded ($F = 3.65$; df = 1, 205; $p = 0.06$). Analysis of variance showed no significant differences in corrected mortality among experimental runs ($F = 0.67$; df = 4, 139; $p = 0.66$), nor was there a significant treatment × run interaction ($F = 0.37$; df = 4, 252; $p = 0.82$), suggesting consistent treatment effects across replicates. Therefore, the data across the five runs were pooled after individual analyses.

The mean percent mortality at 1 DAT for the control groups was noted as 13.8% ± 4.27% as compared to treatment groups 41.61 ± 3.63 (Figure 7). The mortality in the treated groups for nymphs with 2 days of cumulative exposure was noted as 64.07 ± 2.74 in comparison to control 22.36% ± 6.04%. The percent mortality reached 91.06% ± 1.49% for nymphs with 5 days of cumulative exposure to PSO residues; however, mortality in control groups also increased considerably (46.18% ± 4.65%). Welch's *t*-test for the comparison of corrected mortality across all the runs was statistically significant ($p \leq 0.01$) for residual exposure of 1, 2 and 5 days except for two cases in Run 3 at 2 DAT (t = −2.08, df = 4.86, $p = 0.09$) and 5 DAT ($t = -2.60$, df = 4.42, $p = 0.054$). Although borderline, Levene's test did not indicate homogeneity of variances for the observed mortality across the runs ($F = 1.89$; df = 9, 197; $p = 0.054$). In Run 3, the nymphs with 2 days of cumulative exposure to PSO residues experienced 67.33% ± 3.64% mortality as compared to 42.675 ± 11.27% in control. Nymphs with 5 days of cumulative exposure experienced 90.00% ± 3.02% mortality in comparison to 54.67% ± 13.23% in control. When data were pooled across runs, PSO treatment resulted in significantly higher mortality than control at all intervals ($t = -6.68$, df = 44.8, $p \leq 0.01$ for 1 DAT; $t = -8.02$, df = 31.7, $p \leq 0.01$ for 2 DAT and $t = -8.50$, df = 22.9, $p \leq 0.01$ for 5 DAT). Standard errors were low across all groups, indicating high reproducibility of treatment efficacy except for two occasions in Run 3.

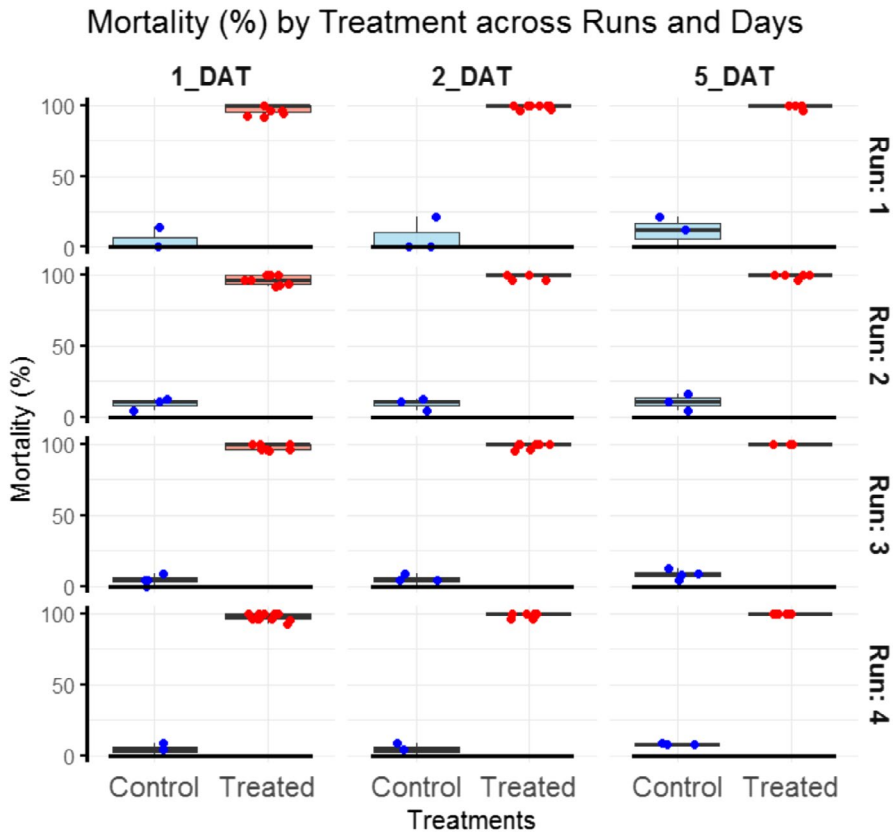

FIGURE 6 | Effect of dip treatment with petroleum spray oil (PSO) on the neonate nymphs of green apple aphid, *Aphis pomi* under laboratory conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

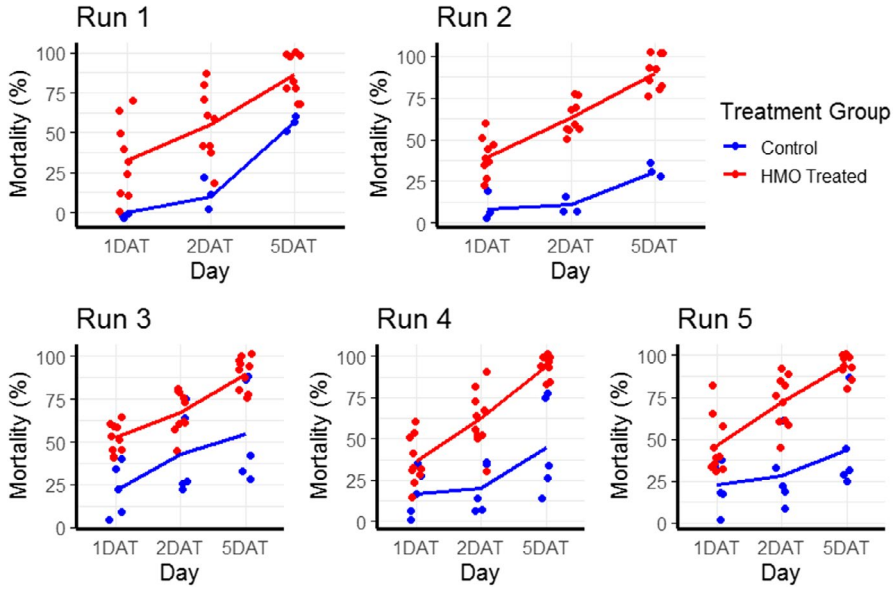

FIGURE 7 | Effect of cumulative residual exposure to petroleum spray oil (PSO) on the survival of neonate nymphs of green apple aphid, *Aphis pomi* under laboratory conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

6.3 | Efficacy of PSO Mixed With Insecticides Against Green Apple Aphid Incidence

The bud infestation remained zero till the 3rd week after treatment application, and significant bud infestation was noticed from the 2nd week of April (4 WAT). After 5 WAT, the production of winged morphs started; hence, the observations were not taken after that. The ANOVA model showed a significant effect of treatment on bud infestation levels ($F(5, 28) = 86.95$, $p \leq 0.01$) with no significant replication effect ($F(2, 28) = 1.16$, $p = 0.32$)

at 4 WAT. The unsprayed control showed the highest infestation, significantly higher than all other treatments ($p \leq 0.01$), while imidacloprid 17.8 SL at 0.04% and imidacloprid 17.8 SL at 0.04% + PSO at 2% showed the lowest infestation rates and did not differ significantly from each other ($p = 0.99$) (Table 1). Similarly, at 5 WAT, the ANOVA again revealed a highly significant effect of treatment ($F(5, 28) = 81.57$, $p \leq 0.01$). Tukey's HSD test confirmed that the untreated control sustained the highest infestation compared to all other treatments. Treatments 2 and 5 again showed the lowest infestation, with no significant difference between them ($p = 0.99$) (Table 1).

7 | Discussion

The PSO sprays at delayed dormant/green tip stage reduced total percent egg hatch by approximately 80%. Historically, petroleum oils have been used for over a century against overwintering pests like San Jose scale and European red mite (Yothers 1922; Chapman 1967). Lawson and Weires (1991) reported strong ovicidal activity of refined oils against the eggs of *P. ulmi* in laboratory settings, with field efficacy depending on coverage and significant reduction in *D. plantaginea* populations with dormant-season sprays. Agnello et al. (1994) reported ovicidal and larvicidal activity with 2%–3% oil sprays post petal fall against *P. ulmi*, further confirmed by Marčić et al. (2009). Significant effects are also reported by Hix et al. (1999) and Pless et al. (1995) for San Jose scale crawlers. Similar efficacy has been reported for *Myzus cerasi* eggs (Jaastad 2007) pear psylla (Schrader et al. 2025) and virus-vectoring aphids in potatoes (Galimberti and Alyokhin 2018; Shah et al. 2022).

Survival analysis showed that while median survival time differences were modest, mortality risk was significantly higher in treated shoots, affirming PSO's population-level impact. Although the time to achieve 50% mortality was similar between treatments, the survival distributions were significantly different. HMO treatment induced more rapid early mortality and maintained a higher hazard of death over time, as shown by the Cox proportional hazards model. In integrated pest management, early suppression is often preferable to prevent feeding injury and reproductive buildup. Moreover, even when median survival times coincide, the eventual level of mortality achieved can be a decisive criterion of efficacy. In our study, the total egg hatch percentage plateaued at markedly lower levels in the treated groups across both trials. Specifically, total hatch in treated shoots was only 9.90% ± 0.57% compared to 46.91% ± 0.68% in untreated shoots during the lab trial, and 9.62% ± 0.71% versus 53.25% ± 3.25% in the field trial. These consistent differences in cumulative hatch underscore the long-lasting suppression provided by petroleum spray oil applications, supporting their value as a reliable control strategy for reducing early-season aphid establishment, even when initial survival dynamics appear superficially similar. It is concluded that median survival time alone does not give a clear picture of the efficacy of the PSO treatment (or any treatment for that matter); the total kill achieved for each treatment as well as the time taken to plateau must also be taken into consideration. Field observations showed asynchronous hatching in untreated plots, reflecting temperature-induced emergence variability across microhabitats. Laboratory hatching was more synchronised, emphasising the value of environmental control in treatment evaluation.

The sharply reduced and compressed hatch in treated groups under both laboratory and field conditions underscores the ovicidal efficacy of PSOs and supports their role in early-season aphid management. Future work should assess physiological traits influencing susceptibility, such as chorion permeability, and use phenological models to optimise application timing, as done for scale insects. Additionally, compatibility with natural enemies and effects on non-targets should be explored to ensure integration into IPM systems. Coverage quality, determined by droplet size and film uniformity, remains critical (Buteler and Stadler 2011).

Direct and residual toxicity of PSOs was also assessed against hatched nymphs. Our examination of residual larvicidal effects was intended to parallel a field situation where the majority of the nymphs hatching from the overwintering eggs hatch onto the leaf and plant surface that has received the PSO spray in the last few days. In field trials of direct toxicity, treated plots showed 68.8%–74.0% nymphal mortality compared to 9.2%–10.5% in controls. No significant effect from aphid density, bud type or block was detected, suggesting treatment robustness, although variation from plant to plant is expected due to non-random distribution of the *A. pomi* colonies and hence the overwintering eggs and ensuing nymphs in spring. Lab dip assays showed near-complete mortality (99%–100%) within 5 days post-treatment; water-dipped controls never exceeded 11.1% mortality. These findings confirm the potent and consistent action of PSOs. However, spray methods are generally less effective than dipping due to coverage limitations (Campbell 1972; Herron and Barchia 2002; Taverner et al. 2012). Thorough coverage to runoff is critical for field efficacy (Buteler and Stadler 2011). Residual toxicity was also evident with 1 and 2 days of cumulative exposure. In Run 3, the mortality of nymphs with 2 and 5 days of cumulative exposure to PSO residues did not differ significantly from the control. Although the percent mortality

TABLE 1 | Effect of petroleum spray oil (PSO) alone and in combination with insecticides on the percent infestation (±SE) of buds by green apple aphid, *Aphis pomi* at pre-bloom and bloom stage.

No.	Treatment details	% Bud infestation	
		4 WAT	5 WAT
1	Chlorpyriphos 20 EC at 0.25%	8.95 ± 0.79 b*	15.52 ± 1.76 b
2	Imidacloprid 17.8 SL at 0.04%	0.19 ± 0.12 d	1.38 ± 0.4 d
3	Petroleum spray oil (PSO) at 2%	5.22 ± 0.54 bc	9.71 ± 0.87 c
4	Chlorpyriphos 20 EC at 0.25% + PSO at 2%	3.51 ± 0.32 c	7.84 ± 0.71 c
5	Imidacloprid 17.8 SL at 0.04% + PSO at 2%	0.29 ± 0.14 d	0.97 ± 0.27 d
6	Control	19.04 ± 2.34 a	25.88 ± 1.15 a

*Figures followed by the same letter in a column are not significantly different.

experienced by the two groups is more or less similar to other runs, the variability in the case of control mortality (SE) for Run 3 was very high (11.27% and 13.23% respectively at 2 and 5 DAT). Non-homogeneity of variances for the observed mortality across the runs further points at field level variation. The fact that the nymphs were exposed to pre-treated buds on shoots, the degree of retention of the spray solution and its extent of drying is likely to vary. Hence, the extent of exposure of the nymphs across buds or similar experimental units is likely to vary. Therefore, we may expect variation across different trees under field conditions as well. Agnello et al. (1994) observed high contact mortality of *P. ulmi* larvae at 0.25%–1.00% oil concentrations, with 79%–95% reductions in motile forms at 0.25%–2% via handgun sprays. However, Potter tower applications of similar rates yielded lower mortality, emphasising application method importance. Moran et al. (2003) showed soybean oil (TNsoy1) at 0.5%–1.5% reduced *P. ulmi* populations by over 94% in airblast applications, with 2% rates achieving >90% reduction. Residual trials by Agnello et al. (1994) mimicked larvae hatching onto oil-treated surfaces. All tested concentrations (0.005%–0.25%) significantly reduced larval survival compared to controls, with minimal differences among higher concentrations. This supports the concept that mineral oil sprays function both via direct contact and residual toxicity.

In our study, imidacloprid 17.8 SL at 0.04% significantly suppressed *A. pomi*, and efficacy improved when tank-mixed with 2% PSO. While PSO alone had a moderate effect, its combination with imidacloprid accelerated aphid mortality. Synergism in similar systems has been reported by Yang et al. (2019) and Shah et al. (2022). The combination enhances active ingredient penetration and coverage, supporting the well-known role of oils in improving insecticide performance. Stadler and Buteler (2009) highlighted the physicochemical interactions of oils with the insect cuticle. Rather than acting purely through spiracle suffocation, PSOs penetrate through altered wax layers and capillary effects, enhancing pesticide transport to lipophilic tissues. De Licastro et al. (1983) and Fontán and Zerba (1987) found cuticular penetration correlated with oil viscosity, supporting the carrier function of PSOs. Historical evidence supports these findings. Madsen and Bailey (1958a, 1958b) documented excellent control of aphids and red mites with ethion-oil and Phostex-oil. Kurtz and Fullmer (1959) confirmed ethion-oil effectiveness during dormant periods. Hough (1939) noted improved aphid egg control with dinitro-oil combinations. Fernandez et al. (2006) found Orchex 796 oil marginally effective alone but more potent when combined with insecticides in codling moth management. Fernandez et al. (2005) similarly emphasised the value of PSOs as adjuvants in IPM, particularly for secondary pests, where complete suppression is not always economically necessary. McLaren and Fraser (2002) described *M. cerasi* control with mineral oil applied during bud movement, combined with pirimicarb or chlorpyrifos. Taverner et al. (2011) showed that oils like All Seasons had ovicidal effects and enhanced insecticide efficacy. Taverner et al. (2012) found UltraPure PSO alone less effective than chlorpyrifos, but equal in efficacy when paired with half rates of the insecticide. Imidacloprid also showed a synergistic response with UltraPure, extending residual efficacy for up to 10 days. Joshi et al. (2023) showed that spring sprays of abamectin or zeta-cypermethrin with just 1% mineral oil provided season-long *P. ulmi* suppression without harming predatory mites.

Despite expectations, chlorpyrifos alone or with PSO in our study did not significantly suppress *A. pomi*, although mineral oils in combination with organophosphates are of common use as dormant or delayed dormant sprays (Alston et al. 2010; Beers et al. 2015). This points to the possible development of resistance in *A. pomi* against the organophosphates. Numerous cases of insecticide resistance in GAA have been reported across multiple countries against organophosphates, carbamates and synthetic pyrethroids (Hogmire et al. 1990, 1992; Qin and Jiucai 2002; Tamaš et al. 2015; Erdogan et al. 2023). The organophosphates have been used in the apple orchards for more than 2 decades (Bhardwaj and Bhardwaj 2005; Anonymous 2024). Therefore, the development of resistance to these chemistries is a possibility.

In conclusion, our findings validate horticultural oils as both ovicidal and larvicidal agents against the green apple aphids, and can act as synergists in IPM. Although complete coverage is necessary, when timed correctly, oil sprays alone effectively suppress pests like aphids and mites; when combined with insecticides, they enhance efficacy and persistence. This dual strategy strengthens selective pest control while aligning with sustainable, ecologically sound orchard practices. Additionally, the development of phenology-based models could refine the timing of oil application to better match local egg development patterns, as has been done for scale insects. The multi-year trials for integration with other IPM tactics are recommended.

Author Contributions

Mohd Abas Shah: conceptualisation, methodology, funding acquisition, project administration, investigation, formal analysis, validation, resources, data curation, writing – original draft, writing – review and editing. **Hafsa Ajaz Tramboo:** investigation, validation, methodology, data curation, writing – original draft, writing – review and editing. **Sheikh Aafreen Rehman:** investigation, validation, methodology, data curation, writing – original draft, writing – review and editing. **Rifat Rasool:** investigation, resources, data curation, writing – review and editing. **Kawsar Rasool:** investigation, resources, data curation, writing – original draft, writing – review and editing. **Shahid Yaqub:** investigation, data curation, writing – original draft, writing – review and editing. **Ronit Jaiswal:** data curation, formal analysis, software, visualisation, writing – review and editing. **Sajad Un Nabi:** conceptualisation, methodology, writing – review and editing.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available at https://doi.org/10.17632/8dvp9jybfz.1.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Left: Experimental setup of the laboratory evaluation of PSO application on the egg hatch of *Aphis pomi* with excised shoots carrying eggs immersed in distilled water in flasks; top right: fate of eggs after receiving PSO treatments with most of the eggs shrivelled, some are intact and some eggs have hatched; bottom right: segments marked on the selected shoots, many

eggs hatched. **Figure S2:** Effect of the direct application of PSO on the neonate nymphs of *Aphis pomi*: (clockwise) neonate nymphs on a mixed bud before treatment; neonate nymphs 1 day after treatment- darkened with oily appearance; neonate nymphs 2 days after treatment- dead with black appearance; neonate nymphs on a vegetative bud that received water treatment (control) - the aphid colony reduced slightly as some of the nymphs were washed away with water spray. **Table S1:** Effect of PSO application on the survival of neonate nymphs of green apple aphid, *Aphis pomi* under field conditions. **Table S2:** Corrected mortality of neonate *Aphis pomi* nymphs in response to PSO treatment under laboratory condition.