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# Efficacy of Zeolite and Kaolin in the Control of *Cacopsylla pyri* (L.) (Hemiptera: Psyllidae) and Compatibility With Its Natural Antagonist *Anthocoris nemoralis* (Fabricius) (Hemiptera: Anthocoridae)

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## ABSTRACT

The pear psyllid *Cacopsylla pyri* is a major pest of European pear orchards, responsible for significant yield losses. Its management is increasingly challenged by restrictions on synthetic active ingredients, resistance development, and the shift towards sustainable production systems. Therefore, in order to ensure the ecological and economic sustainability of pear cultivation, psyllid control requires innovative and selective approaches compatible with biological control agents, as the predator *Anthocoris nemoralis*. This study evaluated the efficacy of kaolin and zeolite, applied in both liquid and powder formulations, for the control of *C. pyri* and their compatibility towards the natural antagonist *A. nemoralis*. Laboratory assays, conducted under controlled conditions (24°C ± 2°C, 65% ± 5% RH, 16:8L:D photoperiod), examined the effects on nymphs and eggs of the psyllid (acute mortality, ovicidal activity and oviposition deterrence) and potential side effects on the predator *A. nemoralis*, assessing acute mortality resulting from direct and indirect exposure to both particles. Results showed that powdered zeolite caused the highest mortality in nymphs, reaching approximately 48% at 10 days after treatment (DAT), compared with about 10% in the untreated control, whereas liquid zeolite exhibited the strongest ovicidal activity, with 21.2% of eggs remaining unhatched at 7 DAT, significantly higher than the control (3.8%). All treatments reduced oviposition compared to the control, indicating a deterrent effect: the mean number of eggs per plant decreased from 27.2 in the control to 3.7, 7.1 and 4.4 in ZEO-L, ZEO-P and KAO-L treatments, respectively. Regarding *A. nemoralis*, powder applications (both kaolin and zeolite) caused higher mortality, while liquid formulations proved more selective and therefore more compatible with biological control (< 15% at 6 DAT). Overall, kaolin showed lower efficacy than zeolite, although still yielding meaningful results. This study demonstrates that these geomaterials, particularly liquid zeolite, have significant potential as non-toxic physical tools to be integrated into sustainable pear pest management programs. Future research should investigate the persistence and field performance of these materials under different environmental conditions and evaluate their optimal integration with other biological and integrated pest control strategies.

## 1 | Introduction

Pear (*Pyrus* spp.) is one of the key crops in Italy and worldwide. In 2024, global pear production reached 27.6 million tons harvested from 1.36 million hectares. Italy ranks as the 6th biggest

pear producer, with 436,000 tons harvested from 20,500 hectares (FAOSTAT 2026).

It therefore represents a crop of fundamental importance, whose protection against pathogens and pests has steadily increased

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in complexity in recent years. However, the sustainability of pear production is increasingly challenged by biotic pressures, climate change and limitations in varietal innovation (Modesti et al. 2020; Musacchi et al. 2021).

A major phytosanitary concern is the pear psyllid, *Cacopsylla pyri* (Linnaeus, 1758) (Hemiptera: Psyllidae), considered the primary pest in southern Europe (Civolani 2012; Civolani et al. 2023). Both nymphs and adults damage the crop: immature stages excrete copious honeydew, promoting sooty mould growth, reducing photosynthesis (Horton 1999) and affecting fruit quality and harvestability; adults vector “Candidatus *Phytoplasma pyri*,” the causal agent of pear decline, which can devastate orchards within a few years (Carraro et al. 1998). The control of this pest is complicated by its high reproductive potential and by the favourable conditions for its proliferation in modern intensive orchards (Daugherty et al. 2007; Kocourek et al. 2021).

Chemical control has traditionally played a central role in psyllid management; however, widespread resistance to organophosphates, pyrethroids and chitin synthesis inhibitors has emerged (Nin et al. 2012; Ali 2020). Recent regulatory withdrawals of widely used active ingredients in Europe have further limited options (Shaw et al. 2021), emphasising the need for integrated pest management (IPM) approaches and non-chemical alternatives (Kocourek et al. 2021; Reeves et al. 2024). Climatic shifts and altered phenology may also cause temporal mismatches between psyllids and their natural enemies, further complicating control (Musacchi et al. 2021). The use of broad-spectrum insecticides further compromises biological control (Civolani 2012) by reducing predator and parasitoid populations (Berrada et al. 1995; Souliotis and Moschos 2008), thereby making selective or non-toxic approaches a priority for sustainable production.

*Anthocoris nemoralis* (Fabricius, 1794) (Hemiptera: Anthocoridae) is a key predator of *C. pyri* (Sigsgaard et al. 2006; Reeves et al. 2023), this generalist predator is highly voracious and efficient in prey search, consuming thousands of psyllid eggs over its lifespan (Yanik and Ugur 2004). *A. nemoralis* is multivoltine and overwinters as an adult, allowing early-season predation (Krndija et al. 2024). However, broad-spectrum insecticides severely reduce predator populations, undermining its efficacy (Berrada et al. 1995; Souliotis and Moschos 2008).

Particle films based on materials such as kaolin and zeolite are emerging as selective, low-risk tools compatible with IPM and organic farming (Glenn and Puterka 2010; De Smedt et al. 2015, 2016). These films act primarily through physical mechanisms, deterring settling, feeding and oviposition while sometimes causing direct mortality via abrasion and desiccation (Erler and Cetin 2007; Saour et al. 2010). Tianna DuPont et al. (2021) recommend kaolin applications before bloom, when psylla adults recolonise orchards, effects on natural enemies are reduced and photosynthesis is not altered because leaf coverage has not yet developed.

Zeolites are crystalline aluminosilicates with high cation-exchange capacity and water absorption, which confer

physical pest control effects and enhance adhesion of other formulations (De Smedt et al. 2015; Prisa 2024). Evidence suggests zeolites can reduce oviposition of the pistachio psyllid *Agonoscena pistaciae* Burckhardt and Lauterer (Hemiptera: Psyllidae) (Baghodrat et al. 2021), and other pests such as *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) larvae (De Smedt et al. 2016), but data on *C. pyri* and potential impacts on predators remain limited.

The efficacy and safety of particle films depend on mineral type, particle size, formulation and application method (Puterka et al. 2000; Glenn and Puterka 2004). Powder and liquid formulations differ in surface coverage, persistence and exposure pathways, with direct contact representing a worst-case scenario for non-target organisms, while indirect exposure better approximates field conditions (Sackett et al. 2007). Non-target impacts are context-dependent; kaolin, for example, may alter predator assemblages under certain conditions (Glenn and Puterka 2010; Pascual et al. 2010), emphasising the need for careful timing, coverage and integration with biological control.

This study evaluates particle films for *C. pyri* management within an IPM framework, focusing on: (i) direct effects on eggs and nymphs, (ii) deterrent and repellent effects on adult oviposition and (iii) impacts on the predator *A. nemoralis*. We also investigate the influence of application method (liquid vs. powder) on efficacy and non-target effects, aiming to clarify the trade-offs between pest suppression and ecological safety and to provide practical guidance for integrating geomaterials into sustainable pear protection strategies.

## 2 | Materials and Methods

All experiments were conducted under controlled laboratory conditions; bioassays were carried out in a climatic chamber under controlled environmental conditions (24°C ± 2°C, 65% ± 5% RH, 16:8 L:D photoperiod).

### 2.1 | Insects

Individuals of *C. pyri* were collected by beating (frappage) them from foliage in a pear orchard located in Malborghetto di Boara (FE) in November 2024. Adult psyllids were reared in BugDorm cages (60 × 60 × 60 cm), each containing four 1-year-old pear plants, and maintained at 24°C ± 2°C, 65% ± 5% relative humidity, and 16:8 (L:D) h photoperiod. Adults were transferred weekly onto healthy plants using an aspirator. Individuals of *A. nemoralis* were purchased from Bioplanet s.r.l.

### 2.2 | Tested Products

Individuals of *C. pyri* and *A. nemoralis* were exposed to the same concentrations of Zeolite Cubana by Bioagrotech and Kaolin Surround WP by Serbios geomaterials, both in powder and liquid formulations and compared to an untreated control. Field application rates (kg/ha) were converted to equivalent

**TABLE 1** | Products and application rates tested.

Treatment	Commercial name	Dosage (kg/ha)	Water volume (L/ha)	Solution concentration (g/L)	Equivalent rate (g/m <sup>2</sup> )	Amount applied (g/plant)
UTC	N/A	N/A	N/A	N/A	N/A	N/A
ZEO-L	Zeolite Cubana	30	1000	30	N/A	N/A
KAO-L	Kaolin Surround WP	30	1000	30	N/A	N/A
ZEO-P	Zeolite Cubana	30	N/A	N/A	3	0.8
KAO-P	Kaolin Surround WP	30	N/A	N/A	3	0.8

Abbreviations: KAO-L, kaolin liquid formulation; KAO-P, kaolin powder formulation; N/A, not applicable; UTC = untreated control; ZEO-L, zeolite liquid formulation; ZEO-P, zeolite powder formulation.

laboratory doses expressed as g/m<sup>2</sup> and g/plant based on the surface area treated for each plant. The concentrations used in the experiments are reported in Table 1.

### 2.3 | Bioassays on *C. pyri* Nymphs

Acute mortality bioassays by direct application were conducted on second- and third-instar nymphs on potted, micropropagated pear plants approximately 30 cm in height. Each plant represented one replicate, and each leaf was considered a sub-replicate in order to obtain more effective counts.

Before trials, four pear plants were isolated in BugDorm cages and infested with 25 adult psyllids each. Adults were allowed to oviposit for 4 days, after which they were removed and plants were inspected to identify five leaves bearing at least 30 eggs each. The remaining leaves on the plants were not included in the bioassay and were pruned.

When approximately 60% of the eggs had hatched, that is, approximately 10 days, plants were removed from the cages and randomly assigned to each treatment. The number of nymphs on each plant prior to treatment were counted under a stereoscope, then plants were treated using an airbrush for liquid applications and a powder hand sprayer (Zefir Di Martino) for powder applications.

The number of individuals per replicate varied slightly depending on insect availability, ranging from 60 to 100 individuals per replicate, 3 replicates, each consisting of one plant were carried out per treatment. Nymph mortality was assessed at 1, 2 and 7 days after treatment, directly on the plants using a 10× hand lens, whereas the final assessment (10DAT) was conducted by removing the leaves and counting alive individuals on each leaf under a stereomicroscope.

### 2.4 | Bioassays on *C. pyri* Eggs

Plant treatments were performed using the same procedures and application rates as those adopted in the nymph mortality bioassays. The experiments were carried out on eggs previously

laid on pear plants following the same procedure used to obtain nymphs. Treatments were applied 4 days after adult removal to ensure that eggs had reached a sufficient level of embryonic development while still allowing the treatment time to act before hatching. Preliminary observations showed that hatching at 6 days after oviposition was consistently below 5%, indicating that this timing provided approximately 2 days for the treatment to affect the eggs before hatching began. This schedule also allowed the final assessment to be performed 7 days after treatment, ensuring nearly complete hatching in the untreated control while maintaining the excised leaves in good physiological condition, as leaves showed clear signs of deterioration after 10–11 days.

Treated leaves with eggs were transferred onto Petri dishes containing 15 mL of a 3% agar solution, into which the petiole was inserted to prevent leaf desiccation. From each group of plants, 12 leaves were randomly selected. To facilitate counting, eggs on the abaxial leaf surface were removed using a mounted needle, and eggs on the adaxial surface were then counted again under a stereomicroscope. Assessments were performed at 2, 5 and 7 days after treatment.

### 2.5 | Repellence Bioassays on *C. pyri* Adults

For repellence bioassays, four potted micropropagated pear plants approximately 30 cm in height were placed in a plexiglass cage (100 × 100 × 100 cm) and assigned to the four different treatments listed in Table 1. Plants treated with kaolin powder were lost as a result of an irrigation malfunction; therefore, in this case, only data from the remaining three treatments were considered for analysis. Each cage contained one plant per treatment (four plants per cage), so that all treatments were represented within each cage. Measurements were taken at the individual plant level, and plants were treated as experimental units in the statistical analyses.

Two adult pairs with a 1:1 sex ratio were placed on each plant. In total, 16 adults were present in each cage. Adults were maintained on the plants for 4 days, after which all individuals were removed and the number of eggs laid on five randomly selected leaves per plant was recorded.

## 2.6 | Bioassays on *A. nemoralis*

Acute toxicity of the tested products on *A. nemoralis* was assessed through both direct and indirect application methods, using the concentrations listed in Table 1.

**Direct application:** four replicates per treatment were performed, each consisting of 10 adults. Adults were placed in an organza bag, through which the treatment was applied, ensuring direct contact with the predators. After treatment, individuals were transferred to 100 mL plastic boxes and fed with *Ephesthia kuehniella* eggs provided *ad libitum* every 2 days. Mortality was recorded at 6 h and 5 days after treatment. Vitality was assessed by stimulating individuals with a mounted needle to avoid confounding effects of thanatosis.

**Indirect application:** acute toxicity via indirect exposure was tested by treating pear plants according to the concentrations in Table 1 and subsequently introducing *A. nemoralis* adults. For each treatment, four replicates were performed, each consisting of one plant with 15 adults; six replicates were used for the control, as extra individuals and plants were available. Prior to treatment, each plant was infested with *C. pyri* to ensure sufficient prey for the predators throughout the experiment. Plants were grouped in BugDorm cages (three plants per cage) and infested with 20 adult psyllids (sex ratio 1:1), which were removed after 4 days. Plants containing at least 100 eggs were selected for the assay and treated. When approximately 60% of *C. pyri* eggs had hatched, each plant was placed in a plexiglass cylinder and adults of *A. nemoralis* were introduced. In order to facilitate check of live and dead individuals, non-woven fabric was placed at the base of the plants to isolate the soil. The status of psyllid nymphs was checked prior to predator release to ensure the treatment did not cause excessive prey mortality. Fifteen adult *A. nemoralis* were released per cylinder, and mortality was assessed at 1, 3 and 6 days after treatment. During the first two intervals, mortality was evaluated by counting dead individuals at the base of the plant to avoid bad handling. At 6 days, cylinders were opened and vitality was verified by stimulating individuals with a mounted needle. Final destructive counts confirmed the accuracy of previous assessments.

## 3 | Statistical Analysis

Differences in *C. pyri* nymph mortality and egg hatching, as well as *A. nemoralis* adults mortality among treatments over time, were analysed using a generalised linear mixed model (GLMM) with a binomial distribution, implemented with the `glmer()` function of the `lme4` package in RStudio. The response variable was a binomial variable constructed from counts of dead and live individuals, including treatment, time and their interaction as fixed effects, while the experimental replicate was considered as a random effect. To correct for potential overdispersion, an additional random effect was included for each observation. The significance of fixed effects was assessed using an analysis of deviance based on Type II Wald chi-square tests with the `emmeans` package in RStudio.

Differences in the number of *C. pyri* eggs laid among treatments were analysed using a randomised complete block ANOVA, followed by Tukey's post hoc test ( $p < 0.05$ ), with treatment as the fixed factor and cage included as a blocking factor. Each cage contained one plant per treatment, and individual plants were considered as replicates.

## 4 | Results

### 4.1 | Bioassays on *C. pyri* Nymphs

Statistical analysis showed significant differences both among treatments ( $\chi^2 = 31.78$ ,  $df = 16$ ,  $p = 0.01$ ) and over time ( $\chi^2 = 34.14$ ,  $df = 16$ ,  $p = 0.01$ ), while the treatment  $\times$  time interaction was not significant. No differences between treatments were observed the first and the second day after application, with generally low mortality levels. From the seventh day onward, mortality increased, particularly in the zeolite-based treatments, although differences were not statistically significant (Table 2). At 10 days post-treatment, powdered zeolite (ZEO-P) caused the highest mortality, showing statistically significant differences compared to the control and KAO-L. Liquid zeolite (ZEO-L) and powdered kaolin (KAO-P) exhibited intermediate efficacy, whereas liquid kaolin (KAO-L) did not produce effects statistically different from the control (Figure 1).

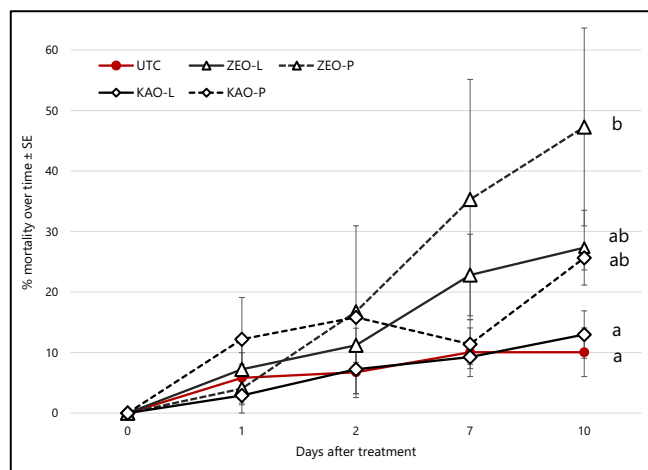
**TABLE 2** | Mortality percentage of *C. pyri* nymphs at 1, 2, 7 and 10 days after direct exposure to geomaterials.

Mortality % $\pm$ SE				
Days after treatment	1	2	7	10
UTC	5.8 $\pm$ 4.1 a A	6.7 $\pm$ 3.6 a A	10.0 $\pm$ 4.0 a B	9.8 $\pm$ 3.5 a B
ZEO-L	7.2 $\pm$ 4.6 a A	11.2 $\pm$ 2.8 a A	22.8 $\pm$ 6.7 a B	27.3 $\pm$ 6.2 ab B
ZEO-P	4.0 $\pm$ 4.0 a A	16.8 $\pm$ 14.2 a A	35.3 $\pm$ 19.8 a B	47.3 $\pm$ 16.4 b B
KAO-L	2.9 $\pm$ 1.5 a A	7.2 $\pm$ 4.0 a A	9.3 $\pm$ 1.2 a B	13.0 $\pm$ 3.9 a B
KAO-P	12.2 $\pm$ 9.6 a A	15.8 $\pm$ 0.5 a A	10.0 $\pm$ 3.7 a B	25.7 $\pm$ 2.0 ab B

Note: Different lowercase letters within the same column indicate significant differences among treatments at each sampling date, whereas different uppercase letters within the same row indicate significant differences over time ( $p < 0.05$ ; GLMM, Tukey post hoc test).

## 4.2 | Bioassays on *C. pyri* Eggs

Statistical analysis showed significant differences attributable to both treatment ( $\chi^2 = 29.25$ ,  $df = 4$ ,  $p < 0.01$ ) and time ( $\chi^2 = 358.9$ ,  $df = 2$ ,  $p < 0.001$ ), while no interaction between the two factors was observed. Two days after treatment, powdered zeolite reduced egg hatching compared to the liquid formulations, but no significance was detected in comparison with the control and the powdered kaolin (Table 3), whereas liquid formulations of kaolin and zeolite had a more moderate effect. At 5 days, all treatments caused a reduction in hatching relative to the control, although no statistically significant differences were detected among them. Seven days after treatment,



**FIGURE 1** | Mean mortality percentage at 1, 2, 7 and 10 days after treatment of *C. pyri* second- and third-instar nymphs directly exposed to geomaterials. Points carrying different letters differ significantly from each other ( $p < 0.01$ ; GLMM, Tukey post hoc test). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

**TABLE 3** | Mean percentage  $\pm$  SE of unhatched eggs at 2, 5 and 7 days after treatment of *C. pyri* eggs directly exposed to geomaterials.

% of unhatched eggs				
Days after treatment	2	5	7	
UTC	100 $\pm$ 0.0 ab A	25.3 $\pm$ 7.1 a B	3.8 $\pm$ 2.1 a C	
ZEO-L	97.7 $\pm$ 1.0 b A	46.9 $\pm$ 7.8 a B	21.2 $\pm$ 5.4 b C	
ZEO-P	87.8 $\pm$ 3.8 a A	25.4 $\pm$ 6.3 a B	14.7 $\pm$ 4.3 ab C	
KAO-L	97.1 $\pm$ 1.2 b A	35.6 $\pm$ 7.1 a B	12.7 $\pm$ 3.7 ab C	
KAO-P	97.7 $\pm$ 1.4 ab A	31.6 $\pm$ 7.2 a B	10.2 $\pm$ 3.4 ab C	

Note: Different lowercase letters within the same column indicate significant differences among treatments at each sampling date, whereas different uppercase letters within the same row indicate significant differences over time (GLMM, Tukey post hoc test,  $p < 0.05$ ).

**TABLE 4** | Mean number of eggs per plant laid by *C. pyri*.

	Treatment			
	UTC	ZEO-L	ZEO-P	KAO-L
Number (mean $\pm$ SE) of eggs laid per plant	27.2 $\pm$ 3.6 b	3.7 $\pm$ 3.1 a	7.1 $\pm$ 3.9 a	4.4 $\pm$ 1.8 a

Note: Data carrying different letters differ significantly from each other (randomised complete block ANOVA, Tukey post hoc test,  $p < 0.001$ ).

liquid zeolite exhibited the strongest ovicidal activity, being significantly more effective than the control and superior to the other treatments (Table 3).

## 4.3 | Repellence Bioassays on *C. pyri* Adults

All treatments reduced oviposition to varying degrees; however, no significant differences were detected in the mean number of eggs laid on five randomly selected leaves among treatments, whereas all treatments differed significantly from the control ( $F = 12.417$ ,  $df = 3$ ,  $p < 0.001$ ) (Table 4). The block effect (cage) was not significant.

## 4.4 | Bioassays on *A. nemoralis*, Direct Exposure

Statistical analysis revealed significant differences both among treatments ( $\chi^2 = 291.795$ ,  $df = 27$ ,  $p < 0.001$ ) and over time ( $\chi^2 = 120.823$ ,  $df = 27$ ,  $p < 0.001$ ), whereas the treatment  $\times$  time interaction was not significant. From 6 h onward, a progressive increase in mortality was observed; in particular, powdered kaolin and powdered zeolite (Table 5) showed higher values than the control. At this stage, liquid treatments (KAO-L, ZEO-L) did not differ statistically from the control. This pattern was confirmed in subsequent assessments, with higher mortality in powder treatments, while liquid formulations maintained a more limited impact.

## 4.5 | Bioassays on *A. nemoralis*, Indirect Exposure

Statistical analysis revealed significant differences among treatments ( $\chi^2 = 68.59$ ,  $df = 12$ ,  $p < 0.001$ ), and over time ( $\chi^2 = 18.45$ ,  $df = 10$ ,  $p < 0.05$ ), whereas the treatment  $\times$  time interaction was not significant (Table 6). Overall mortality

**TABLE 5** | Mortality percentage of *A. nemoralis* adults at 6 h, 1, 2, 3, 4 and 5 days after direct exposure to geomaterials.

Mortality % ± SE						
Days after treatment	6h	1	2	3	4	5
UTC	2.4 ± 2.4 a A	9.8 ± 4.7 a B	9.8 ± 4.7 a CD	14.6 ± 5.7 a D	22.0 ± 6.8 a D	24.4 ± 7.1 a D
ZEO-L	7.7 ± 4.3 a A	23.1 ± 7.0 a B	43.6 ± 8.5 b CD	51.3 ± 8.7 b D	56.4 ± 8.6 b D	61.5 ± 8.4 b D
ZEO-P	92.9 ± 3.9 c A	95.2 ± 3.2 b B	100.0 abc CD	100.0 abc D	100.0 ab D	100.0 ab D
KAO-L	2.6 ± 2.5 a A	39.5 ± 8.5 a B	57.9 ± 8.7 b CD	57.9 ± 8.7 b D	65.8 ± 8.3 b D	71.1 ± 7.9 b D
KAO-P	60.0 ± 8.3 b A	90.0 ± 4.8 b B	90.0 ± 4.8 c CD	100.0 abc D	100.0 ab D	100.0 ab D

Note: Different lowercase letters within the same column indicate significant differences among treatments at each sampling date, whereas different uppercase letters within the same row indicate significant differences over time ( $p < 0.05$ ; GLMM, Tukey post hoc test).

**TABLE 6** | Mortality percentage of *A. nemoralis* adults at 1, 3 and 6 days after direct exposure to geomaterials.

Days after treatment	1	3	6
UTC	1.0 ± 1.0 a A	4.1 ± 1.3 a AB	5.0 ± 1.7 a B
ZEO-L	3.3 ± 1.9 a A	5.0 ± 1.7 ab AB	8.3 ± 1.7 ab B
ZEO-P	10.0 ± 3.3 ab A	18.3 ± 5.7 ab AB	30.0 ± 10.0 ab B
KAO-L	6.7 ± 4.7 b A	11.7 ± 5.7 b AB	15.0 ± 5.0 b B
KAO-P	18.3 ± 5.7 b A	23.3 ± 10.4 b AB	33.3 ± 20.2 b B

Note: Different lowercase letters within the same column indicate significant differences among treatments at each sampling date, whereas different uppercase letters within the same row indicate significant differences over time ( $p < 0.05$ ; GLMM, Tukey post hoc test).

levels were low; however, some statistically significant differences among treatments were detected. Mortality remained low in the control treatment. Pairwise comparisons revealed significantly higher mortality in the ZEO-P treatment compared with UTC and KAO-L, and in KAO-P compared with the control.

## 5 | Discussion

The present work shows that geomaterials can significantly affect both *C. pyri* and its key predator *A. nemoralis*, and that formulation is as important as the active ingredient.

Zeolite-based products were consistently more effective against *C. pyri* than kaolin: ZEO-L exerted strong ovicidal activity, anticipatorily reducing egg hatch, whereas ZEO-P and KAO-P produced rapid knockdown of adults.

The higher efficacy of zeolite is consistent with particle film theory: sorptive, angular minerals remove epicuticular wax and absorb cuticular lipids, leading to desiccation, with toxicity scaling with particle adhesion and surface area (De Smedt et al. 2015). Zeolites also exhibit higher cation exchange capacity and water affinity than kaolin, which may enhance both their desiccating and abrasive effects on soft-bodied psyllids (De Smedt et al. 2015; Prisa 2024). In general, few studies are available on the efficacy of zeolite in psyllid control. A superior efficacy of zeolite relative to other mineral materials has been reported against the common pistachio psyllid, with liquid zeolite suspensions significantly reducing oviposition at high application rates (Baghodrat et al. 2021).

Previous studies on kaolin report that particle film caused reductions of psyllid nymph in pear orchards (Daniel et al. 2005; Saour et al. 2010) and a reduction of winterform oviposition rates in laboratory trials (Erlar and Cetin 2007), while in one case kaolin achieved up to 100% deterrence on pistachio psyllid (Dilmen et al. 2025).

However, the same physicochemical properties that make powder formulations effective against psyllids also make them hazardous to *A. nemoralis*. Both ZEO-P and KAO-P caused near-complete adult mortality within 2–3 days following direct exposure, whereas liquid formulations were considerably less harmful. This contrasts with greenhouse and semi-field studies on zeolite products, where zeolite-based formulations were broadly non-toxic to several predators and pollinators, likely because exposure occurred mainly through indirect contact and per-insect doses were lower (De Smedt et al. 2015).

Kaolin has been shown to be slightly harmful against *A. nemoralis* exposed to residues (Bengochea et al. 2010), while in several studies it proved to be generally safe for parasitoids (Bengochea et al. 2014; Chierici et al. 2025) and coccinellid predators (Skouras et al. 2019).

The discrepancy between direct and indirect exposure highlights the importance of application modality when evaluating non-target effects of mineral products. Under indirect exposure conditions, predator mortality was substantially reduced, indicating that application timing, formulation choice and exposure pathways play a central role in modulating ecological risk. Accordingly, toxicity estimates derived from laboratory assays based on direct application should be regarded as conservative,

representing a worst-case exposure scenario rather than realistic field conditions. Similar exposure-dependent responses have been documented for *A. nemoralis* in studies with conventional insecticides, where mortality was consistently higher under topical or forced-contact assays than under residual exposure or semi-field conditions, underscoring the general relevance of exposure route in non-target risk assessment (Berrada et al. 1996; Souliotis and Moschos 2008).

From an IPM perspective, the central role of *A. nemoralis* in psylla regulation requires careful balancing of efficacy and compatibility. Our findings support a strategy in which ZEO-L is preferentially used as a selective ovicidal tool, particularly in early-season applications, while ZEO-P may be reserved for targeted adult knockdown during periods of low predator activity. Broad, in-season dusting with powder formulations should be avoided, as it may undermine biological control services. This approach is consistent with works showing that early-season particle films or selective insecticides can suppress psyllids while conserving anthocorids, whereas non-selective or poorly timed sprays collapse predator populations and trigger resurgence (Solomon et al. 1989; Souliotis and Moschos 2008). Similar patterns were reported for kaolin and zeolitic films, where targeted liquid applications reduced eggs or oviposition with little impact on natural enemies, but broad dusting disrupted predator assemblages (Pasqualini et al. 2002; De Smedt et al. 2015; Baghodrat et al. 2021).

Some limitations of the present study should be acknowledged. Experiments were conducted under controlled conditions, with standardised exposure and without accounting for environmental factors such as rainfall, wind, UV radiation or canopy structure, all of which may influence particle persistence and efficacy in the field. Moreover, only acute lethal effects were assessed, while sublethal impacts on predator behaviour and reproduction remain to be investigated.

Another limitation of the present study is that only one application rate, corresponding to the recommended field dose, was tested. Although this approach enhances the agronomic relevance of the results, it does not allow the estimation of dose-response relationships or relative toxicity parameters. Future studies should investigate concentration-dependent effects to better quantify selectivity thresholds and optimise application strategies within IPM programs.

Taken together, these results indicate that geomaterials—particularly zeolite-based formulations—represent promising tools for *C. pyri* management, provided that formulation type, application timing and non-target exposure are carefully optimised. Their integration into IPM programs will require targeted use strategies and further field validation to maximise pest suppression while preserving key natural enemies.

#### Author Contributions

**Laura Depalo:** methodology, data curation, validation, formal analysis, writing – review and editing; **Giovanni Biscontin:** investigation, writing – original draft, writing – review and editing; **Antonio Russo:** supervision, funding acquisition, project administration; **Elisa Marchetti:** methodology, investigation, supervision, writing – review and editing.

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#### Conflicts of Interest

The authors declare no conflicts of interest.

#### Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.18282632>.

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