

Field effectiveness of biorational insecticides against *Dactylopius opuntiae* (Cockerell) in commercial *Opuntia ficus-indica* (L.) Mill. production in Morelos, Mexico

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Abstract. Mexico is the world's leading producer and consumer of *Opuntia ficus-indica*. However, production of this crop is constantly affected by the wild cochineal (*Dactylopius opuntiae* Cockerell), which is the most economically important pest of prickly pear. The objective of this study was to evaluate the biological effectiveness of several biorational insecticides for controlling wild cochineal populations on nopal cactus and to reduce the use of conventional pesticides. The study was conducted in a seven-year-old commercial nopal plantation located in Tlalnepantla, Morelos, Mexico. Seven biorational insecticides each applied at two doses (low and high) were evaluated: Cinnacar®, Blinem®, Asphix®, Mass derrive, Prowet Ovi-Die®, Roma® soap + Bemix®, and potassium soap, in addition to a regional conventional control based on Malathion 1000 CE at two doses (low and high). The experimental design was a completely randomized design with four replicates per treatment. Applications were performed using a motorized sprayer. Results showed that potassium soap achieved >50% control in third-level cladodes and up to 49.2% on the fourth-level cladodes, even under high infestation pressure. Likewise, some products such as Roma soap, Prowet Ovi-Die, and Mass derrive may be effective against initial infestations of less than 30%, depending on the structural area of application. Furthermore, since female nymphs tend to migrate vertically to areas with lower cellulose content within the plant structure to insert their mouthparts and establish their sessile stage, it is important to maintain control of the mealybug on the third level; otherwise, the cladodes on the fourth level will also be affected. These results indicate that biorational insecticides are a viable and environmentally safe component of integrated pest management strategies for controlling wild cochineal in open-field production systems for nopal as a vegetable crop.

Keywords: Integrated pest management, *Opuntia ficus-indica*, wild cochineal.

Introduction

In Mexico, *Opuntia ficus-indica* (L.) Mill. (Cactaceae) is a crop of major economic, social, and nutritional importance. It supplies both domestic markets and international niches, particularly in North America, Europe, and recently Asia (SADER, 2025). In 2024, more than 12,400 ha were harvested, with a total produ-

ction exceeding 844,000 t and a value of more than 3 billion Mexican pesos. The state of Morelos is the main producer of nopal vegetable (nopalitos), with Tlalnepantla municipality contributing more than one-third of national production (SIAP, 2024). Nopal cladodes are widely consumed due to their nutritional and functional properties, including high soluble fiber content, which contributes to the prevention of metabolic diseases (De Albuquerque *et al.*, 2019; Hernández-Becerra *et al.*, 2022). Per capita consumption in Mexico is approximately 6.72 kg person⁻¹ year⁻¹, with a stable demand throughout most of the year (SADER, 2020).

Nopal production is severely affected by the wild cochineal, one of the most destructive pests of this crop. Its high reproductive capacity and gregarious behavior make control difficult. Both nymphs and adults feed on plant sap, causing chlorosis, weakening, and even plant death under severe infestations (Vanegas-Rico *et al.*, 2010). The pest is particularly problematic during the dry season (February-May), when population levels peak (Chávez-Moreno *et al.*, 2011). In recent decades, *Dactylopius opuntiae* has emerged as one of the most aggressive and economically important pests affecting *Opuntia* spp. worldwide. Bibliometric analyses indicate that more than 80% of the scientific literature on this species has been generated in the last two decades, reflecting its increasing relevance as a global phytosanitary threat (Méndez-Gallegos and Bravo-Vinaja, 2022). Its rapid geographical expansion, currently reported in more than 20 countries, highlights its invasive potential and the urgent need to develop effective and sustainable management strategies under different production systems.

The global threat posed by cochineal insects to cactus pear production has been widely documented in different regions of the world. For example, in Ethiopia, the introduction and uncontrolled spread of cochineal resulted in the loss of more than 75% of cactus pear production areas, severely affecting food security, livestock feeding, and rural livelihoods (Ayimut, 2025). Conventional pest control in nopal relies heavily on synthetic insecticides such as Malathion and Fipronil (Bonfil-Sanders *et al.*, 2017; COFEPRIS, 2024). However, their use poses environmental and health risks, including residues in fresh produce and the reduction of beneficial organisms (Gutiérrez-Ramírez *et al.*, 2013; Angeles-Núñez *et al.*, 2014). In addition, repeated use of the same active ingredients promotes insect resistance and increases production costs. In Mexico, the inappropriate use of pesticides in nopal production has been widely documented, including the application of non-authorized active ingredients, inadequate handling practices, and limited compliance with Good Use and Management of Pesticides (BUMP) regulations. These practices pose significant risks to farm workers, consumers, and the environment (Ramírez-Bustos *et al.*, 2023).

Given this scenario, biorational insecticides with physical or mechanical action, such as potassium salts of fatty acids and vegetable oils, are emerging as crucial tools for integrated pest management. Unlike synthetic neurotoxins, these compounds cause physicochemical disruption of the insect's lipid cuticle and protective waxy coating, minimizing the likelihood of cross-resistance (Isman, 2006; Sahito *et al.*, 2022). However, the technical feasibility of these alternatives under scenarios of seasonal hydrological stress and critical pest densities has been scarcely quantified under field conditions. Based on the above, the objective of this study was to evaluate the dynamics of population suppression and the biological effectiveness of a gradient of biorational insecticides against the wild cochineal, analyzing their differential performance according to the structural architecture of the prickly pear cactus under conditions of high infestation pressure.

Materials and Methods

Study site

The experiment was conducted in Tlalnepantla, Morelos, Mexico (18.996480 N, 98.978842 W; 1856 m.a.s.l.), in a seven-year-old commercial plantation of nopal vegetable (cv. Milpa Alta) with a density of 14,705 plants ha⁻¹. The experimental area covered 3,500 m², and no insecticides had been applied prior to the trial. Evaluations were conducted in April 2022, corresponding to the month of highest natural infestation (Vigueras *et al.*, 2009).

Experimental design

The experimental area was flat and completely uniform; therefore, a completely randomized design with 17 treatments and four replicates was used, with each cladode at each level serving as the experimental unit. The experimental plot covered a central area of 700 m² within the commercial plantation, isolating the edge effect to mitigate spatial variability in the initial dispersal of the nymphs.

Treatments

The selection of the 17 treatments was based on the need to evaluate a diverse range of biorational modes of action (botanical extracts, vegetable oils, terpenes, and surfactants) using a comparative dose-response approach, rigorously testing them against the regional synthetic standard and the pest's natural population dynamics.

The experimental relevance of the design lies in its matrix structure: eight distinct active ingredients were selected, each evaluated at two concentration levels (Low Dose, LD, and High Dose, HD; Treatments 1 through 16) corresponding to the recommended commercial and industrial thresholds for managing sessile phytophagous insects. This dose-response stratification is methodologically essential for determining whether an increase in concentration optimizes mechanical or biochemical disruption of the waxy matrix of *D. opuntiae*. Based on this, the removal or degradation of the waxy layer is the critical factor determining the penetration and biological effectiveness of any biorational treatment (Palacios-Mendoza *et al.*, 2004).

Finally, a control (Treatment 17, based exclusively on the application of pure distilled water) was included, which served as the negative baseline control for the experiment. The inclusion of this control is scientifically relevant for distinguishing and isolating the possible effect of physical detachment or mechanical washing caused by the hydrodynamic pressure of the motorized spraying equipment on the cochineal colonies, thereby ensuring that the suppression observed in the remaining treatments is attributable solely to the toxicological and physicochemical properties of the active ingredients evaluated (Table 1).

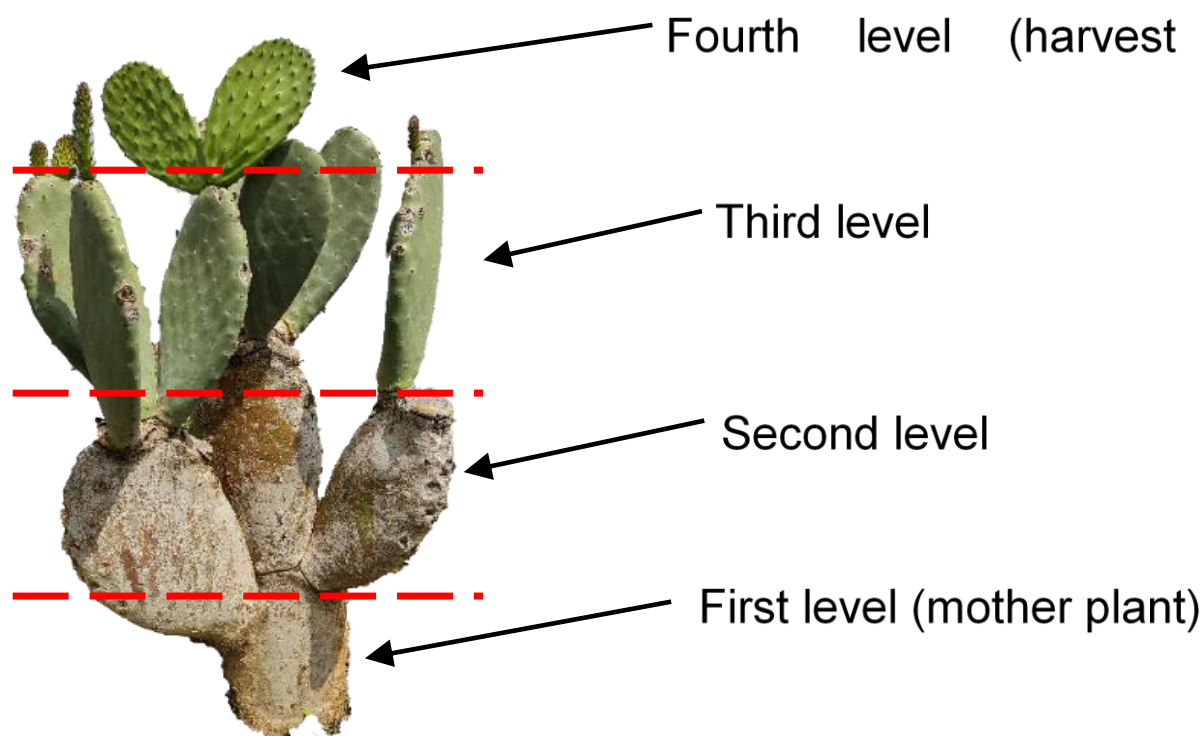
Application of treatments

The nopal plants were stratified into four structural levels according to their physiological maturity (Figure 1): the first level consisted of the woody trunk or mother plant; the second level comprised mature intermediate cladodes that provide structural support; the third level included young apical cladodes from which new shoots emerge; and the fourth level consisted of tender cladodes (nopalitos) harvested for human consumption. Evaluations focused on the third- and fourth-level cladodes because of their commercial importance and susceptibility to cochineal infestation.

Table 1. Products used to control the prickly pear cactus wild cochineal (*Dactylopius opuntiae* Cockerell) in Tlalnepantla, Morelos, Mexico (April 2022).

Treatment	Product name	Active ingredient	Dose
1	Cinnacar®	Cinnamon extract (15%)	1.0 L*
2	Cinnacar®	Cinnamon extract (15%)	2.0 L**
3	Blinem®	Neem extract (30%) and Garlic (5%)	1.0 L*
4	Blinem®	Neem extract (30%) and Garlic (5%)	2.0 L**
5	Asphix®	Soybean vegetable oil (90%)	1.5 L*
6	Asphix®	Soybean vegetable oil (90%)	3.0 L**
7	Mass derrive	Citrus terpenes (20%)	400 mL*
8	Mass derrive	Citrus terpenes (20%)	600 mL**
9	Prowet® ovi-die	Sodium dioctyl sulfosuccinate (70%)	2.0 L*
10	Prowet® ovi-die	Sodium dioctyl sulfosuccinate (70%)	3.0 L**
11	Potassium soap	Potassium hydroxide (90%)	2.700 kg*
12	Potassium soap	Potassium hydroxide (90%)	3.240 kg**
13	Roma soap® + Bemix®	Roma liquid detergent + Soybean oil	3 L*
14	Roma soap® + Bemix®	Roma liquid detergent + Soybean oil	5 L**
15	Malathion® 1000 CE	Malathion (83.80%)	1.0 L*
16	Malathion® 1000 CE	Malathion (83.80%)	2.0 L**
17	Control (distilled water)	---	500 L

*Low dose. **High dose.

**Figure 1.** Structure of the *Opuntia ficus-indica* plant and stratification.

Four weekly applications were made, covering each plant completely. The applications were carried out using an Echo® Shp-800-2 motorized sprayer (Polígono Industrial Congost, Barcelona, Spain) with

a capacity of 25 L, a maximum pressure of 356 psi, and a kawashima JO318 double fan nozzle. A preliminary calibration was performed for a water flow rate of 600 L ha⁻¹.

Study variables

A preliminary evaluation was conducted, followed by four weekly evaluations, one each week after each application. Only the results of the fourth evaluation are reported, as this was when the evident effect of the treatments was observed. Given the high initial infestation level, as mentioned by Hernández *et al.* (2019), due to the insects' thick waxy coating, one or two applications prove ineffective, and three or more consecutive applications are required as part of a pre-established management program, generally spaced 7 to 14 days apart depending on the severity of infestation between applications, in order to damage the protective layer, dehydrate the sessile adult stages, and control the pest in a technically acceptable manner under field conditions. The severity of wild cochineal infestation was assessed using the six-category logarithmic infestation scale described by Vanegas-Rico *et al.* (2010). The scale was defined as follows: 1 = 1-5 colonies, 2 = 6-15 colonies, 3 = 16 colonies and up to 25% coverage of the cladode surface, 4 = 26 to 50% of the cladode surface colonized, 5 = 51 to 75% of the cladode surface colonized, and 6 = 76 to 100% of the cladode surface colonized.

To assess the severity of infestation, 10 cladodes were selected from each block corresponding to the third level, where cladodes emerge for consumption, and 5 cladodes in a consumable state, giving a total of 40 and 20 cladodes per treatment, respectively. The experimental unit was one cladode.

The percentage of damage (disease severity) was estimated based on the level of infestation using the formula adapted from Townsend and Heuberger (1943).

$$DS = \left[\frac{\sum(n \cdot v)}{N \cdot C} \right] \times 100 \quad [1]$$

Where: DS = disease severity rating in %; n = number of samples per category; v = numerical value of each category; N = Total number of samples; C = Highest category.

Biological effectiveness (efficacy) was calculated using the formula adapted from Abbott (1925).

$$E = \frac{C - T}{C} \times 100 \quad [2]$$

Where: E = Efficacy (%); C = Severity in the control; T = Severity of the replicate in each treatment.

Statistical analysis

The percentage data on infestation and effectiveness were transformed using the arcsine of the square root to improve compliance with the assumptions of analysis of variance. They were then subjected to analysis of variance and comparison of means using Tukey's test ($\alpha \leq 0.05$), with the SAS® statistical program, version 9.0.

Results and Discussion

Percentage of damage to cladodes in two levels of the plant

In the preliminary evaluation, the crop showed uniform percentage damage from prickly pear cochineal, falling into categories 5 and 6 on the scale and corresponding to 94.7% in the third level cladodes, while in fourth-level cladodes, categories 3 to 6 were observed, corresponding to 73.9% damage.

Reduction in infestation of third-level cladodes based on the percentage damaged

Treatments with potassium soap at low and high doses on the third level showed the lowest percentage of damage compared to the control (91.3%), with reductions of 43.3% and 50.4% for the low and high doses, respectively. The other treatments, meanwhile, showed reductions in infestation ranging from 18.3% to 32.1%, with the products Prowet Ovi-Die and Asphix at their high doses (Figure 2).

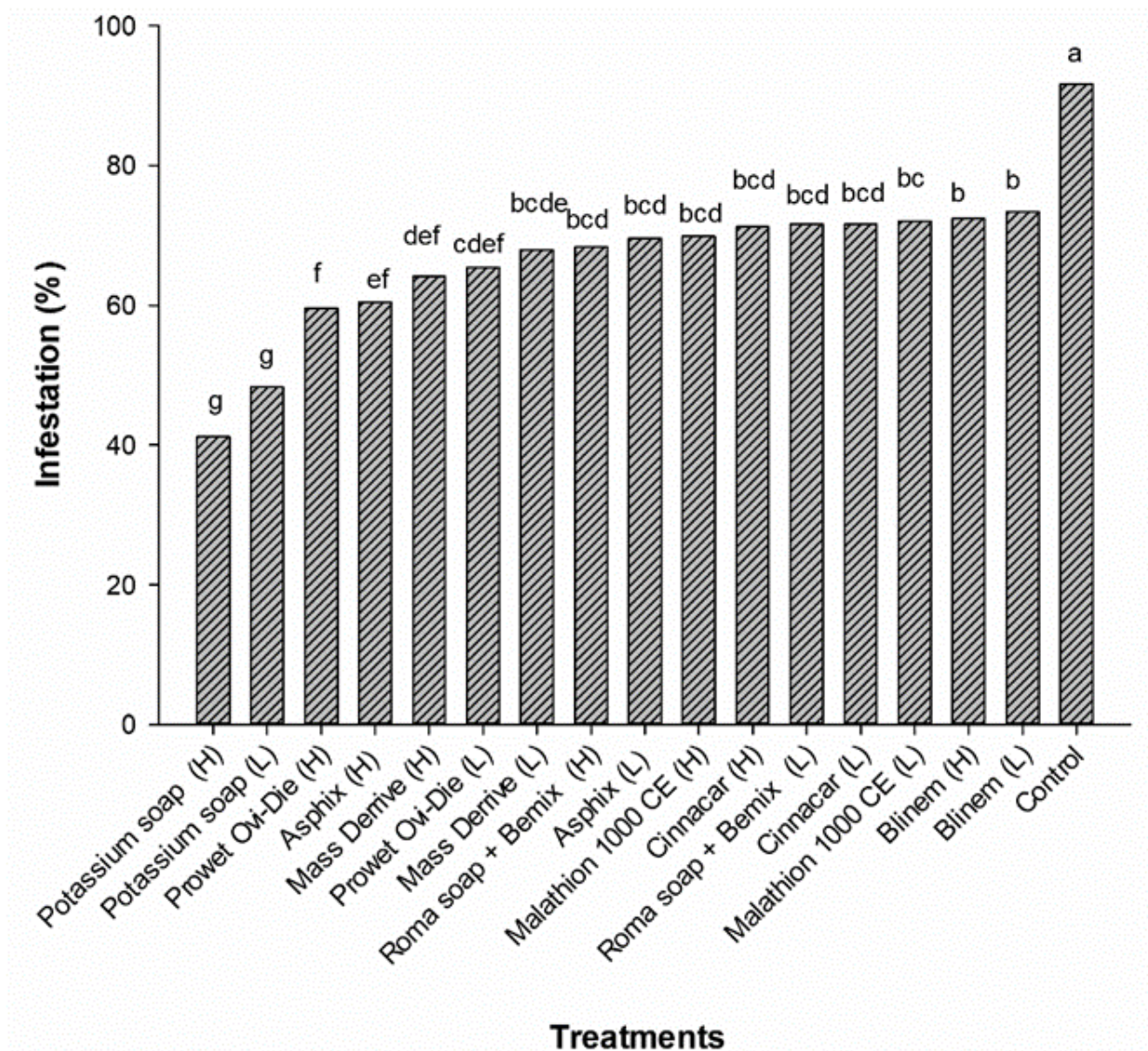


Figure 2. Percentage of damage to third-level nopal cladodes at high (H) and low (L) doses. Bars with the same letters are not statistically different according to Tukey's test ($P \leq 0.05$).

Reduction in infestation of fourth-level cladodes based on the percentage damaged

In this section, the percentages of infestation reduction were similar for the potassium soap treatments, at 48.8% and 38.8%, compared to the control (82.5%), while Mass derrieve, Roma soap + Bemix, Prowet Ovi-Die, and Malathion 1000 CE achieved a reduction in infestation of between 22 and 25% (Figure 3).

In contrast, the synthetic regional control (Malathion 1000 CE) showed a critical failure in control. At the third level (Figure 2), damage levels remained severe at both doses H: 69.9% and L: 72.1% and were statistically similar to those of the absolute control. Although cladodes at the fourth level (Figure 3) showed a slight decrease in residual infestation (H: 60.0%), this is attributed solely to a lower initial pest density in that basal zone, which facilitated better temporal coverage of less dense colonies. However, in both scenarios, the organophosphate insecticide was decisively outperformed by potassium soap. These findings suggest that the limited effectiveness of malathion under high infestation pressure may be associated with reduced insecticide penetration through the protective waxy coating. However, the potential contribution of insecticide resistance requires further investigation.

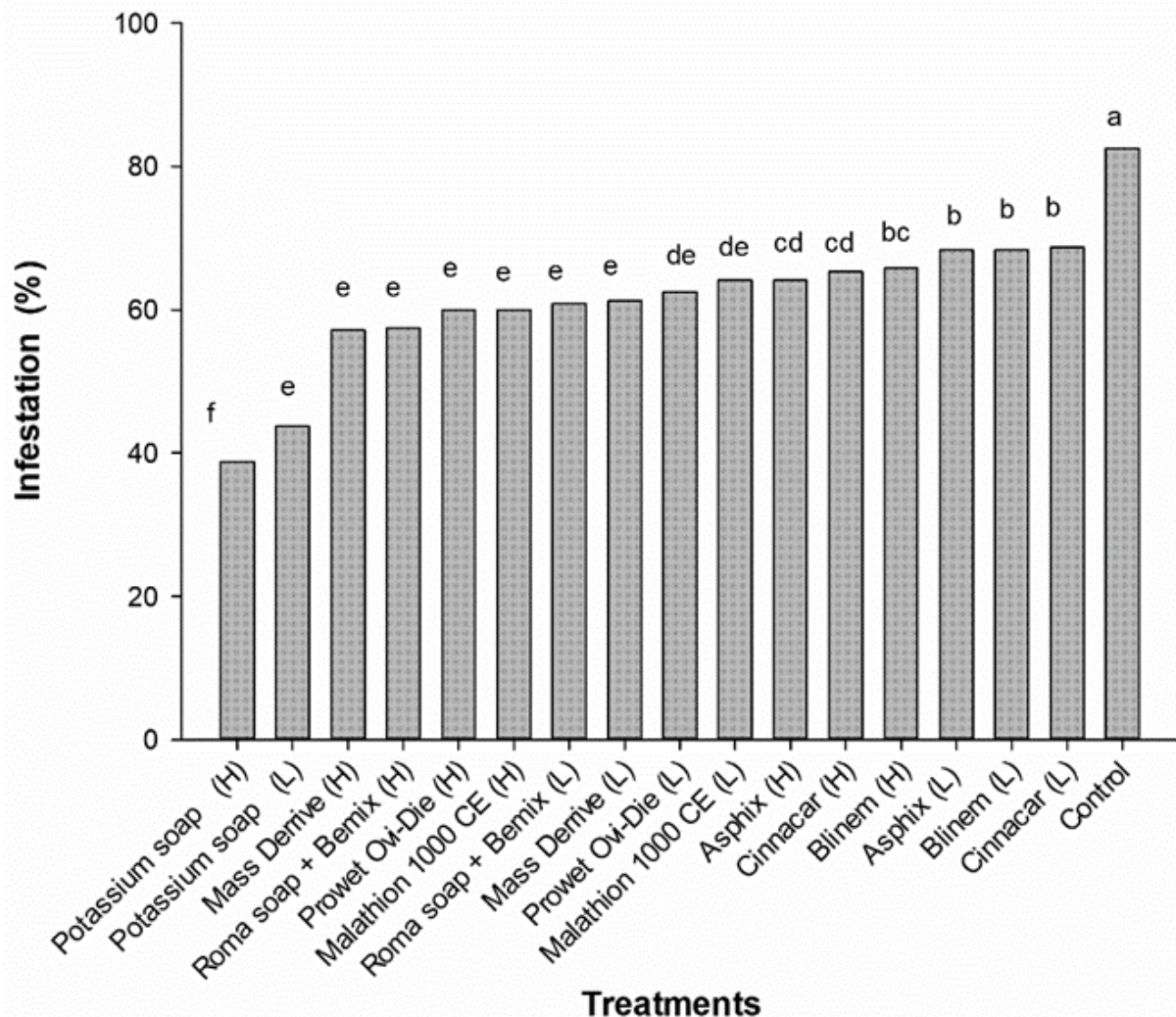


Figure 3. Percentage of damage to fourth-level cladodes at high (H) and low (L) doses. Bars with the same letters are not statistically different according to Tukey's test ($P \leq 0.05$).

The results in these two sections of the plant also align with those obtained by Hernández *et al.* (2019), who reported between 1 and 4 damage categories after three applications on nopal cacti, as this study observed between 2 and 4 categories after the third and fourth applications. This is due to the high degree of infestation present in the crop. These same authors found that good results can be obtained with three applications of Roma soap and commercial potassium soap. Furthermore, Palacios *et al.* (2004) reported a 50% nymph mortality rate with Roma soap, results far superior to ours, perhaps due to field conditions and the high population density of the insect. The results obtained in this study are consistent with international reports indicating that conventional chemical control is often ineffective under high infestation pressure. In Ethiopia, repeated insecticide applications failed to suppress cochineal populations due to reinfestation, difficult terrain, and the lack of natural enemies (Ayimut, 2025). This highlights the importance of exploring alternative approaches such as biorational products and integrated pest management strategies.

Effectiveness of treatments at the third level

The efficacy of the treatments confirms the results obtained in the post-application infestation assessment, since potassium soap applied to third-level cladodes remained the most effective product, while the other treatments achieved efficacy rates ranging from 32.5 to 5.4%. The results indicate that Prowet Ovi-Die and Roma Soap + Bemix showed percentages above 25% but below 35% at their high doses and under high infestation rates.

The low biological effectiveness shown by the commercial control Malathion at the third structural level (Figure 4) highlights a critical issue: The low biological effectiveness of malathion at the third structural level (Figure 4) suggests limited insecticide performance under high infestation pressure, although potential resistance in local *D. opuntiae* populations cannot be confirmed without specific susceptibility tests. This poor performance is attributed to the dense waxy secretion that coats gregarious mealybug colonies during stages of high infestation (>80% initial severity). The hydrophobic wax acts as a physical barrier that prevents Malathion (a contact and stomach insecticide) from effectively penetrating the insect's cuticle (Mwanauta *et al.*, 2022).

The superiority of potassium soap lies in its purely physicochemical mode of action. Saponified fatty acids reduce the surface tension of the solution, allowing for the solubilization and disruption of the insect's epicuticular waxes (Wafula *et al.*, 2017). This leaves the integument unprotected, causing cellular lysis of the membranes due to the infiltration of their lipophilic chains into the cellular matrix and subsequent lethal osmotic dehydration (NPIC, 2001), in addition to mechanical asphyxiation caused by the direct blockage of the respiratory spiracles (Cloyd, 2020).

Effectiveness of treatments at the fourth level

Treatments with potassium soap were largely effective (Figure 5), just as they were at the previous level, whereas Roma Soap + Bemix and Mass derrive showed efficacy levels comparable to those of the regional control (Malathion 1000 CE), since this treatment was outperformed on third-level cladodes (Figure 4) and, in this section, managed to match only Prowet Ovi-Die at high doses; the other treatments exhibited efficacy ranging from 26 to 15% at both doses. This consistency across strata demonstrates that the physical action of potassium soap is not affected by the subtle cuticular or biochemical variations that exist between a young third-level cladode and one in the consumption phase (fourth level).

This slight increase in the response to Malathion on fourth-order cladodes is attributed to the lower initial pest density in this area (73.9%). Because there was less accumulation of gregarious wax layers on the cladodes at harvest, the contact insecticide achieved better coverage of the insect's integument. However, even under this lower pest pressure, Malathion continued to be significantly less effective than both doses of potassium soap, confirming that mechanical disruption far exceeds the efficacy of the insecticide's traditional neurotoxic mechanism, a finding that corroborates the similarity observed in third-level treatments.

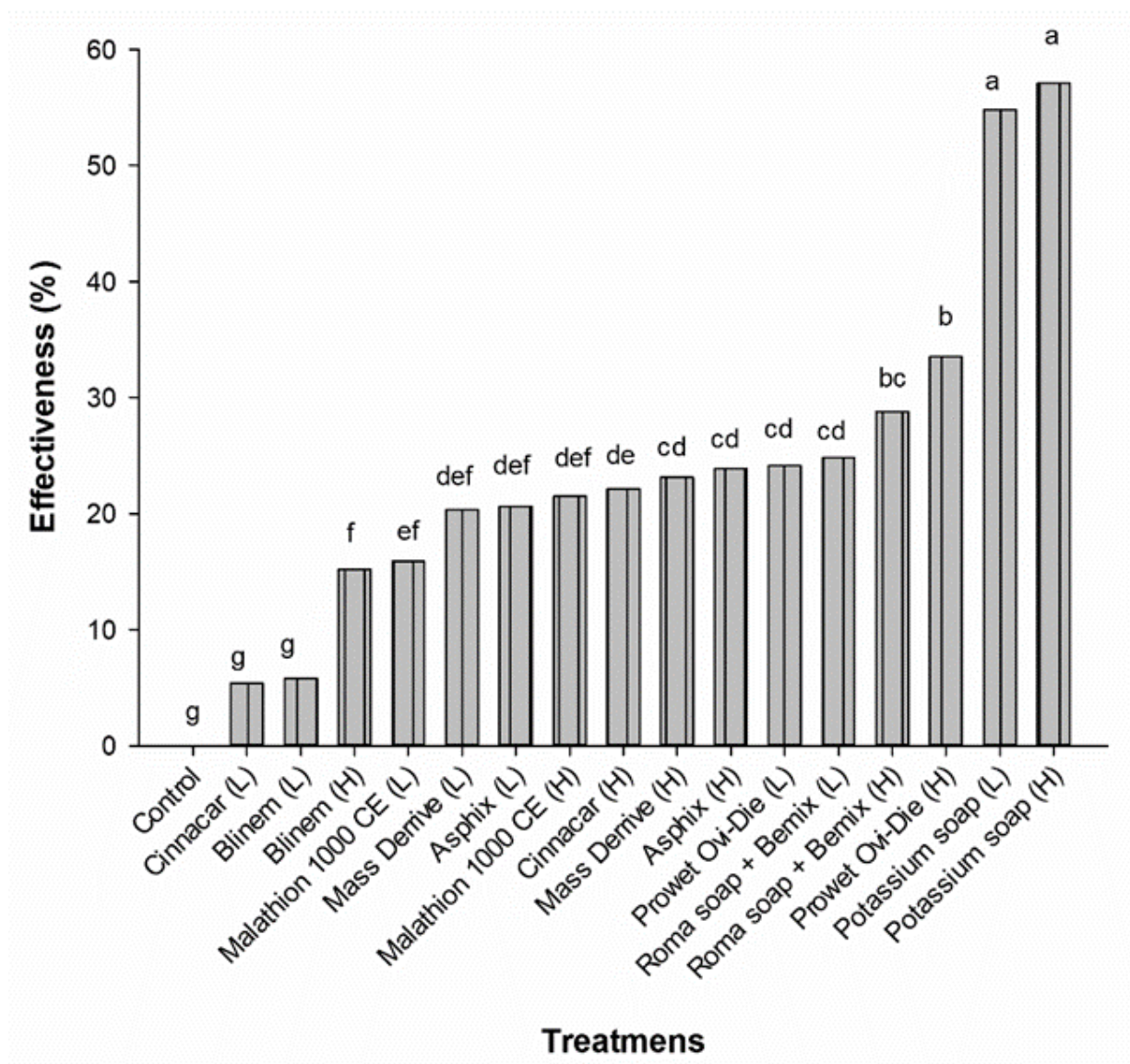


Figure 4. Percentage effectiveness of biorational pesticides in controlling the prickly pear cactus scale on third-order cladodes at low (L) and high (H) doses. Bars with the same letter are not statistically different according to Tukey's test at $P \leq 0.05$.

The results of this study using Roma + Bemix soap (adherent) on both parts of the plant showed lower efficacy than that reported by Perales-Rosas et al. (2024), who achieved 87% effectiveness with Percil soap. This could be because, in their study, the soap was mixed with conventional insecticides, which

may have improved treatment efficacy. Similarly, Ramdani *et al.* (2021) obtained results with an efficacy greater than 80% using black soap, which was also enhanced with *Capsicum annum* extract.

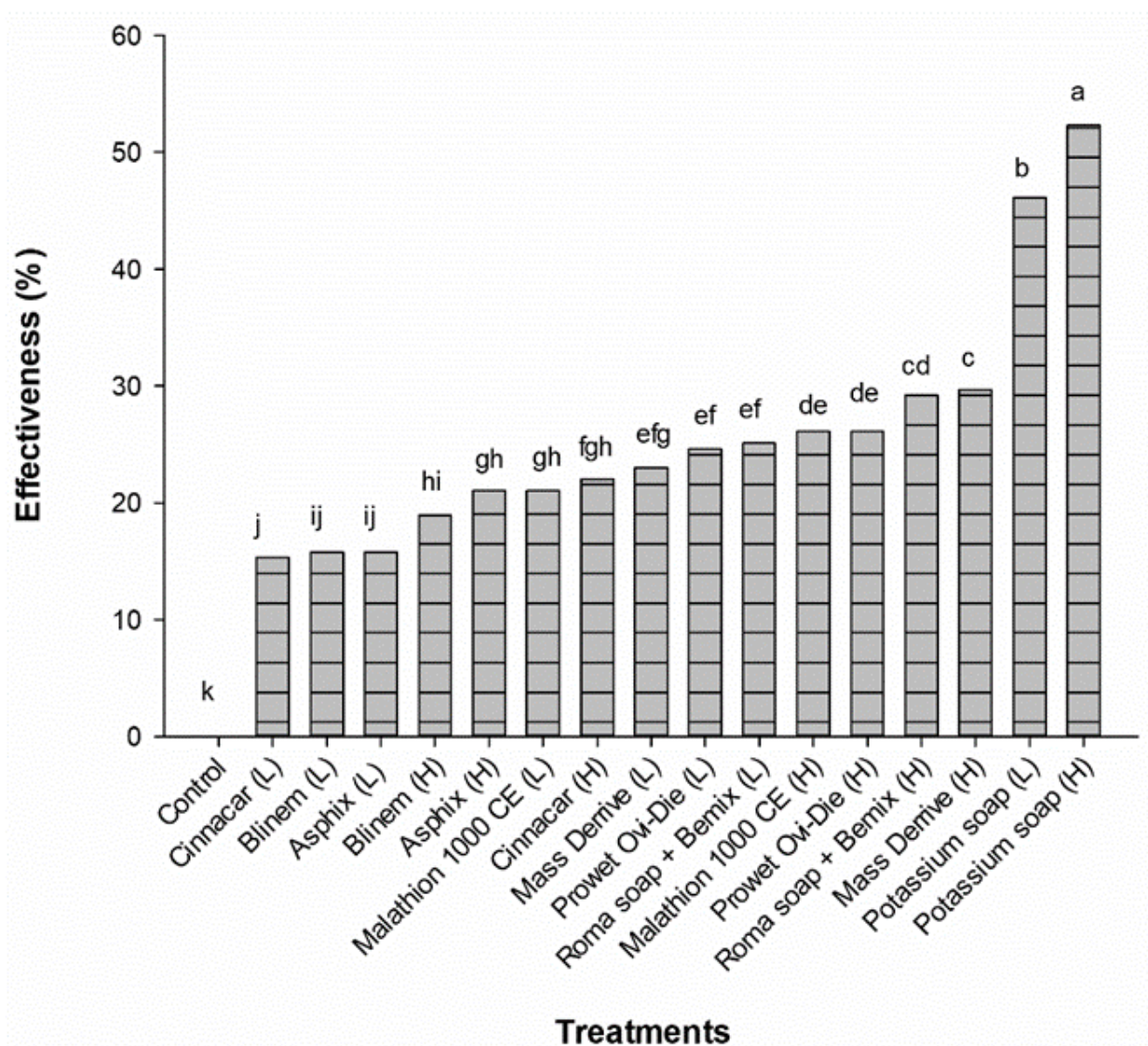


Figure 5. Percentage effectiveness of biorational pesticides in controlling the prickly pear cactus scale on harvest-stage cladodes at low (L) and high (H) doses. Bars with the same letter are not statistically different according to Tukey's test at $P \leq 0.05$.

On the other hand, Hernández *et al.* (2019) achieved results of around 62% using the commercially available GreenSoap® potassium soap, enhanced with the insecticide Mark 1000 (malathion), whereas, in our study, the artisanal potassium soap achieved efficiencies of between 45-53% on fourth-order cladodes and between 55 and 57% on third-order cladodes, without mixing it with any other enhancer, results that were only slightly lower. It should be noted that the crop in which this study was conducted exhibited a high degree of prior damage, exceeding 80%, whereas in the research by the aforementioned authors, the damage did not exceed 30% and ranged from mild to moderate. Palacios-Mendoza *et al.* (2004) noted that the recovery of wild cochineal and the progressive degradation of their waxy coating at different stages of the insect's life cycle are of utmost

importance for the implementation of product application and use programs, which typically occurs five days after the first application, suggesting that the insect should not be given the opportunity to recover completely and that consecutive applications should be spaced no more than 7 days apart.

Figure 6 shows images of third- and fourth-order cladodes. The illustrations of cladodes treated with low and high doses of potassium soap show a greater reduction in the pest population than the other treatments. A positive effect is also observed in the treatments with Prowet Ovi-Die (sulfonic acid) and with Roma soap + Bemix. In contrast, the regional control (Malathion 1000 EC) shows an area that is still covered by more than half of the insect population.

Mwanauta *et al.* (2022), as well as Sahito *et al.* (2022), noted that wild cochineal insects are very difficult to control because their bodies have a waxy coating that protects them from chemical treatments throughout most of their life cycle, while Lobos *et al.* (2013) suggest a two-stage application: one to prevent nymphs and another to control those already on the plant, as demonstrated in our study, since the control measures resulted in a gradual decline in the insect population with each application.

The infestation pressure factor and architectural synergy

When comparing these results with the literature, it is observed that the efficacies obtained in this study (46.1-57.1%) are numerically lower than the upper limits of 80 to 87% reported by Perales-Rosas *et al.* (2024) and Ramdani *et al.* (2021). However, the true contribution of this study lies in demonstrating the consistency of potassium soap under conditions of extreme epidemiological saturation (initial severity >80% in categories 5 and 6). The cited authors evaluated controlled scenarios or incipient infestations (<30%), where the absence of multilayered colonies facilitates coverage. Achieving more than 50% net suppression in a well-established infestation during April (the dry season and peak reproductive rate) validates potassium soap as a viable, low-cost shock treatment.

Furthermore, the spatial selectivity observed between the third instar of the insect and young cactus pads at harvest stage corroborates Mann's (1969) hypothesis. Young apical tissues possess chemical gradients and lower cellulose deposits that attract wandering nymphs. By achieving a greater population reduction on the third level (the immediate support for the shoots), potassium soap mitigates the rate of vertical dispersal of nymphs toward the marketable zone, thereby indirectly protecting the aesthetic quality of the fourth-level cladodes.

The results obtained in this study should be interpreted within the broader context of the global spread of *D. opuntiae*, as recent bibliometric evidence indicates that research efforts have shifted significantly from biological control applications toward the development of management strategies, due to its growing impact as a pest (Méndez-Gallegos and Bravo-Vinaja, 2022). This shift reflects the urgent need for effective and environmentally safe alternatives, particularly in scenarios of high infestation such as those evaluated in the present study. In this context, the effectiveness of potassium soap observed here is consistent with current research trends that emphasize the use of biorational products, including botanical extracts, biodegradable compounds, and low-impact control strategies. Potassium soap may represent an affordable and potentially lower-impact alternative for managing wild cochineal infestations. However, its safe preparation and application should follow appropriate handling recommendations. Integrated approaches combining resistant varieties, cultural practices,

and low-impact pest control methods have been proposed as the most sustainable strategy for managing scale outbreaks in prickly pear systems (Ayimut, 2025). The efficacy of potassium soap observed in this study indicates the feasibility of incorporating biorational products into such integrated pest management (IPM) schemes.

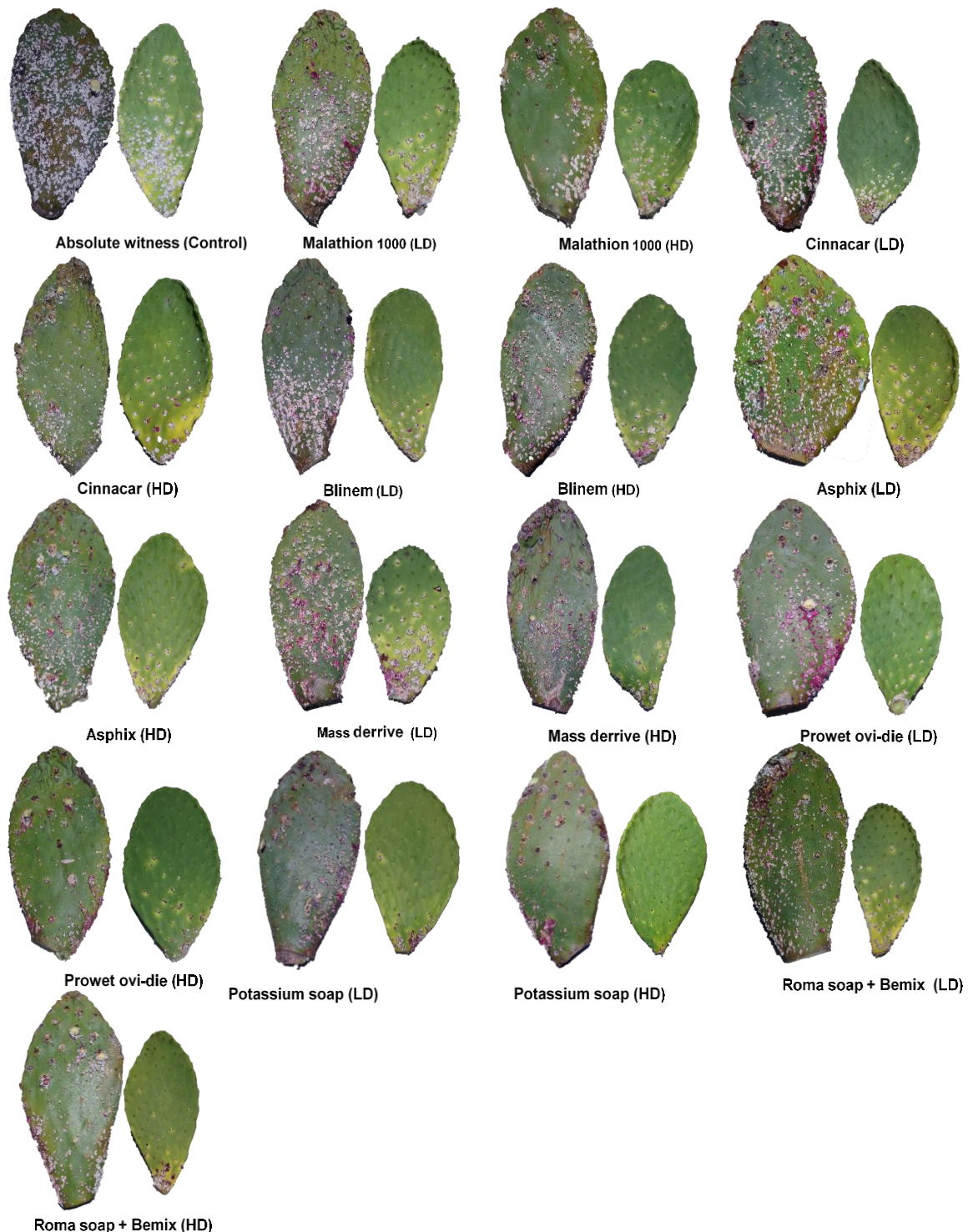


Figure 6. Representative images of third-level (left) and fourth-level (right) cladodes showing cochineal infestation after the final application of each treatment at low (L) and high (H) doses.

Conclusions

Potassium soap, applied at doses of 2.7 and 3.24 kg ha⁻¹, was the most effective biorational treatment against *Dactylopius opuntiae*, significantly outperforming the conventional insecticide malathion under the conditions evaluated. The limited effectiveness of malathion may be associated with the protective waxy coating of the insect, although other factors, including potential insecticide resistance, cannot be ruled out.

The effectiveness of potassium soap does not depend on a biochemical target site, but rather on the physicochemical disruption of the cochineal's protective wax, demonstrating its ability to suppress infestations even under conditions of critical infestation pressure (initial severity greater than 80%).

The aqueous plant extracts evaluated (Cinnacar and Blinem) showed limited effectiveness (efficacy rates below 22%), which rules out their use as sole emergency measures during population peaks in the dry season.

The stratification of phytosanitary control at the third level of the plant is a strategic component of agroecological management: suppressing populations at this level slows the vertical migration of sessile nymphs toward the fourth-level cladodes, or young cacti in the consumption phase, thereby safeguarding the commercial value of the fresh product without leaving chemical residues that are harmful to consumers.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

Not applicable.

AUTHOR CONTRIBUTIONS

Conceptualization, investigation, writing—original draft preparation A.G.H.; supervision, writing—review and editing, P.J.L.; formal analysis, I.A.T. and E.M.F.; validation, V.L.M. and N.A.V.

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