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BIOLOGICAL CONTROL STRATEGIES FOR ALMOND PESTS: GLOBAL PERSPECTIVES AND CHALLENGES

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ABSTRACT

Almond production worldwide faces persistent threats from a diverse complex of insect pests, including lepidopterans, coleopterans and hemipterans, which significantly reduce yield and quality. Conventional reliance on chemical pesticides has raised concerns over resistance development, environmental contamination and non-target effects, underscoring the urgent need for sustainable alternatives. Biological control, through the use of parasitoids, predators, entomopathogenic fungi and microbial agents, offers eco-friendly solutions that align with integrated pest management (IPM) principles. This review synthesizes global advances in biological control of almond pests, highlighting successful case studies, regional variations and emerging biocontrol technologies. Key challenges such as climatic influences, orchard management practices and limited commercialization of biopesticides are critically examined. Future directions emphasize the integration of biological control with cultural and ecological approaches to ensure resilient, sustainable almond production systems worldwide.
***Keywords* :** Biological control, Almond pests.

Introduction

The almond *[Prunus dulcis* (Mill.); syn.*P. amygdalus* Batsch] is a commercially produced *Prunus* spp. and *Amygdalus* spp. (Rosaceae, subfamily Prunoideae). The cultivated almond is assumed to have evolved in Central Asia's dry mountainous regions (Martínez-Gómez, 2007; Kumar, 2016). *Prunus fenzliana* (Fritsch) Lipsky, *P. bucharica* Korschinsky and *P. kuramica* Korschinsky (of the Section Euamygdalus) are the wild species most closely related to almond (Browick and Zohary,1996) and may be the ancestral species of the modern cultivated almond (Kester *et al.*, 1991).

The fruit contains nutritious components such fatty acids, lipids, amino acids, proteins, carbs, vitamins and minerals (Barreca *et al.*, 2020). Almond's chemical and physical makeup offer antidepressant, antioxidant, memory enhancing and anti-aging properties (Barreca *et al.*, 2020; Martínez-Gómez *et al.*, 2017; Aires *et al.*, 2018; Mushtaq *et al.*, 2015). It can be consumed as fresh fruits or processed goods (such as milk and wheat). Furthermore, fruit byproducts (skin) can be used for various reasons, such as biopreservation of food and pharmaceutical items (Badalamenti *et al.*, 2023). Over the centuries, through seed propagation, grafting and cloning reproduction, the species has expanded throughout the world (Hamadeh *et al.*, 2018). This spread has compelled the species to evolve physiological, ecological and genetic traits in order to adapt to the various soil, water availability and climate conditions (Wang *et al.,* 2021). As a result, there exist various almond tree kinds, each with distinct characteristics, including phenological timings, sexual compatibility, vigor and growth, ease of pruning, resistance to pests and diseases, productivity and fruit attributes.

Almond orchards emphasize numerous main insect and mite pests that were previously controlled with dormant season organophosphate sprays. The most significant pests are the peach twig borer *(Anarsia lineatella*), which destroys shoots and fruit and the San Jose scale (*Quadraspidiotus perniciosus*), a dangerous armored scale insect that attacks branches and fruit. Dormant oil sprays were also employed to suffocate the overwintering eggs of spider mites, specifically the European red mite (*Panonychus ulmi*) and the brown mite *(Bryobia rubrioculus*) (Epstein *et al.*, 2001). Hemipteran pests, particularly leaffooted bugs (*Leptoglossus zonatus*, L. clypealis), cause nut drop, gummosis and kernel necrosis in almonds. Several native stink bugs (*Chlorochroa uhleri*, *Thyanta pallidovirens, Chinavia hilaris* and *Euschistus conspersus*) consume developing nuts, resulting in abortion and malformations. The invasive brown marmorated stink bug (*Halyomorpha halys*) has emerged as a significant threat, causing kernel damage throughout the season. Occasional pests include *Lygus hesperus*, *Calocoris norvegicus*, *Phytocoris* spp. and the western boxelder bug (*Boisea rubrolineata*), which attack young fruits but are less economically significant. Leaf-feeding insects like the false chinch bug (*Nysius raphanus*) and almond lace bug (*Monosteira unicostata*) cause intermittent or regional threats. Collectively, these hemipterans reduce yield and quality, highlighting the need for integrated pest management in almond systems (Rijal *et al.,* 2021).

Almond trees and fruits are attacked worldwide by a variety of pests, including many Hemiptera (Hill, 1987). These insects can harm crops directly or indirectly by feeding on fruits, leaves, or other plant parts. For feeding, hemipteran insects insert their stylets into host plant tissues and some of them may inject toxic saliva that spreads into the surrounding tissue. One of the four feeding mechanisms stylet sheath, lacerate and flush, macerate and flush, or osmotic pump can be used to describe how they feed on plant tissues (Hori, 2000). Phytophagous heteropteran feeding causes complex damage symptoms in host plants, including mechanical injury, hormonal and physiological imbalances and salivary enzymes (Hori, 2000).

Biological control has emerged as a cornerstone of sustainable almond pest management, offering a viable alternative to the long standing reliance on chemical pesticides. Historically, organophosphate sprays were the primary tool against key pests such as the navel orangeworm and hemipteran species, but increasing concerns over environmental contamination, non-target impacts and regulatory restrictions have accelerated the shift toward integrated pest management (IPM). Within this framework, biological strategies including the use of parasitoids like *Trichogramma* spp., predators such as lacewings and lady beetles and habitat diversification through cover crops and orchard floor vegetation have demonstrated significant potential in suppressing pest populations while enhancing ecosystem services. These approaches not only reduce chemical inputs but also promote biodiversity, improve soil health and align with consumer demand for residue free produce. When combined with cultural practices such as orchard sanitation and early harvest, biological control provides long-term resilience and economic sustainability, positioning it as a superior strategy compared to chemical interventions in modern almond production systems.

Major pest of Almond and their Biological control

Leaf footed bugs, *Leptoglossus* spp

Studies have demonstrated that *Gryon pennsylvanicum* parasitizes *Leptoglossus zonatus* eggs in almonds (Zalom *et al.,* 2012), while parasitism of *L. clypealis* eggs by *Gryon* spp. has also been reported in pistachios in California. Beyond almonds, biological control of *L. zonatus* has been extensively investigated in other crops, where egg parasitism has been attributed to hymenopterans such as *Trissolcus* spp. (Marchiori, 2002), *Anastus* spp., *Gryon* spp., (Mahendiran *et al.,* 2022) and tachinid flies like *Trichopoda pennipes* (Duarte-Sanchez *et al.,* 2008). The suppression of leaffooted bug populations relies on a diverse assemblage of natural enemies acting across life stages. Egg parasitoids, particularly *Gryon pennsylvanicum*, play a key role in reducing egg survival, while predators such as lacewings (*Chrysoperla* spp.), assassin bugs (*Zelus* spp.) (Mitchell, 2000; Schaefer *et al.*, 2000) and damsel bugs (*Nabis* spp.) target nymphs and adults. Additional mortality is contributed by ants (*Solenopsis* spp.), earwigs (*Forficula auricularis*) and generalist predators including spiders. Although these natural enemies seldom achieve complete control independently, they are integral to integrated pest management programs, where their collective impact reduces pest pressure and supports sustainable crop protection (Daane *et al.,* 2016).

Brown marmorated stink bug, *Halyomorpha halys* (Stål)

Biological control services are provided by generalist arthropod predators and parasitoids that attack *H. halys* and its egg masses in agroecosystems (Morrison *et al.,* 2016, Abram *et al.,* 2017, Jones *et al.,* 2017). Natural enemies in California include assassin bugs, ground beetles, lady beetles, jumping spiders, praying mantis, earwigs, big-eyed bugs, damsel bugs and various crickets and katydids (Dreistadt, 2014; Lara *et al.,* 2016). While these predators have been observed attacking other hemipteran bugs including *H. halys* in the U.S., their impact on population reduction is negligible. *Anastatus pearsalli* Ashmead, a generalist egg parasitoid, was found in sentinel egg masses of H. halys in California's metropolitan environments (Lara *et al.,* 2016). However, parasitism is minimal. *Trissolcus japonicus* (Ashmead), often known as the samurai wasp, is a specialist *H. halys* egg parasitoid with a high parasitism rate (up to 70%) in its natural habitat (Yang *et al.,* 2009). *T. japonicus* can be found in states from east to west where *H. halys* is established (McIntosh *et al.,* 2019). The samurai wasp was recently discovered in an urban habitat in southern California (Lara *et al.,* 2019).

Green stink bug, *Chinavia hilaris* Say

Biological control is primarily achieved through natural enemies. Egg parasitoids such as *Trissolcus, Anastatus* and *Telenomus* spp. have been documented (Kamminga *et al.,* 2012), along with the tachinid fly *Trichopoda pennipes*, which parasitizes adults (Gomez and Mizell, 2019). These natural enemies can significantly reduce populations under favorable conditions, though their effectiveness in almonds specifically remains under studied. Cultural practices like weed management around orchards also help limit early season infestations by reducing overwintering sites and alternative hosts (Rijal *et al.,* 2021).

Stink bugs, such as the green stink bug (*Chinavia hilaris* Say), are biologically controlled by a variety of egg parasitoids and generalist predators. Eleven parasitoid species, including *Anastatus pearsalli* (Eupelmidae), Ooencyrtus californicus and *O. johnsoni* (Encyrtidae), *Gryon obesum*, *Telenomus podisi* and *Psix tunetanus* (Platygastridae), as well as a number of *Trissolcus* spp., including *T. euschisti*, *T. hullensis*, *T. utahensis*, *T. cosmopeplae* and *T. basalis* (Scelionidae). Another significant cause of death was predation, with mice (*Mus musculus*) targeting *Nezara viridula* eggs and Argentine ants (*Linepithema humile*) and pillbugs (*Armadillidium vulgare*) heavily feeding on sentinel egg masses in riparian and roadside vegetation (Ehler, 2000).

Navel orange worm, *Amyelois transitella* (Walker)

Early descriptions of *A. transitella* in California found native natural enemies, including the larval parasitoids *Parasierola breviceps* (Krombein) (Hymenoptera: Bethylidae). *Mesostenus gracilis* Cresson (Hymenoptera: Ichneumonidae), *Microbracon hebetor* (Say) (Hymenoptera: Braconidae) and the predaceous mite *Blattisocius tarsalis* (=tineivorus). Berlese (Oudemans) (Acari: Ascidae) and the beetle *Cymatodera ovipennis* LeConte (Coleoptera: Cleridae) feed on the eggs (Wade,1961). Foreign exploration efforts were made to seek better natural enemies, as none of these were considered acceptable for adequate control.

Foreign exploration efforts were launched in the early 1960s in Israel and Mexico (Caltagirone *et al.,* 1964; Caltagirone, 1966). *Copidosoma* (=Pentalitomastix) *plethorica* (Caltagirone) (Hymenoptera: Braconidae), a polyembryonic egg larval parasitoid, was first discovered in the *E. ceratoniae*.

In the 1970s, efforts to explore Texas, Uruguay and Argentina resulted in the introduction of *Goniozus emigratus* Rohwer (Hymenoptera: Bethlyidae) and *G. legneri* Gordh (Gordh & Hawkins, 1981; Gordh, 1982; Legner *et al.,* 1982; Legner and Silveira-Guido, 1983). The biology and life tables of *G. legneri* were based on *A. transitella* and the pink bollworm, *Pectinophora gossypiella* (Lepidoptera: Gelechiidae) (Gordh *et al.,* 1983). While all three parasitoids have established in California and may help manage *A. transitella* numbers, they are not sufficient to maintain infestation levels below 2% (Legner and Warkentin, 1988; Legner and Gordh, 1992). Some commercial insectaries sell and release *Goniozus legneri* as part of a natural enemy augmentation program, however the effectiveness of this approach has not been properly examined. *Goniozus* spp. show brood guarding behavior (Hardy and Blackburn, 1991). In low host availability settings, parasitoids may prioritize defending their eggs above searching for new hosts to attack (Sreenivas and Hardy, 2015). *Goniozus legneri* may only have a substantial influence if *A. transitella* numbers are large (Hardy *et al.,* 2000; Wang *et al.,* 2014), which many farmers cannot tolerate.

Transitella spp. eggs are preyed upon by *Blattisocius keegani* foxes (Acari: Ascidae) has also been assessed. The authors point out the possibility of an augmentative control program despite the lack of a commercial program, particularly considering that these mites seem to be phoretic on adult moths (Thomas *et al.*, 2011). Growers may be able to manage these tiny insects because *Phytocoris relativus* Knight (Hempitera: Miridae) and *P. californicus* Knight are known to kill *A. transitella* eggs in pistachios (Rice and Jones 1988), albeit they can also attack pistachio nuts. (Haviland *et al.*, 2020).

To control *A. transitella* larvae, a spray solution containing *Steinernema feltiae* (Filipjev, 1934) (=Neoaplectana carpocapsae) (Rhabditida: Steinernematidae) was used to almonds in season (Lindegren *et al.*, 1978, 1987). Later research concentrated on using *Steinernema carpocapsae* (Weiser, 1955) (Rhabditida: Steinernematidae) to treat overwintering mummy almonds (Agudelo-Silva *et al.*, 1995) and pistachios (Siegel *et al.*, 2004, 2006). Due of unsatisfactory results, no commercial *A. transitella* control programs have been developed using entomopathogenic nematodes.

Carob moth, *Ectomyelois ceratoniae*

Ectomyelois ceratoniae (carob moth) in almonds demonstrates that biological control in this system is limited. Field observations revealed that the carob moth's natural parasitism was low, implying that parasitoids and other natural enemies had little impact on population reduction. The moth's life cycle was strongly related to orchard conditions, with larvae overwintering in unharvested nuts, pupating in late winter and adults emerging in spring. Egg laying was concentrated on defective or unused nuts. Because natural enemies were ineffective, the study highlights that cultural activities such as early harvest and orchard cleaning (removal of mummified nuts) are the most effective ways to reduce damage. Biological control alone was unable to prevent almond outbreaks (Gothilf, 1984). Biological control options include egg parasitoids such as *Trichogramma cacoeciae*, microbial agents like *Bacillus thuringiensis* and pheromone-based mating disruption for monitoring and suppression (Mamay, 2025).

Almond bark beetle, *Scolytus amygdali*

Beauveria bassiana, an entomopathogenic fungus, can be used to successfully manage the almond bark beetle (*Scolytus amygdali*). The fungus, when formulated in an inversion emulsion, achieved up to 100% adult mortality in laboratory testing and 81-86% in field studies, while retaining conidial viability and allowing secondary cycling in beetle galleries. This demonstrates its promise as a sustainable and environmentally acceptable biocontrol agent (Batta, 2008).

Biological control of the almond bark beetle (*Scolytus amygdali*) focuses on disrupting fungal symbioses and lowering beetle survival. Key fungal companions like *Geosmithia*, *Paecilomyces* and *Quambalaria* cause necrosis and tree decline, but they also provide options for antagonistic control. Beneficial fungi, such as *Trichoderma* spp., can inhabit beetle galleries and control pathogenic strains, whereas entomopathogenic fungus (*Beauveria bassiana*, *Metarhizium anisopliae*) attack adult beetles during emergence. These eco-friendly measures, when combined with orchard cleanliness (the removal of infested wood) and natural enemy conservation, reduce beetle pressure and fungal disease spread. Such integrated biological techniques are increasingly being recognized as long-term alternatives to chemical control in Mediterranean almond orchards (Costanzo *et al.*, 2026).

The almond bark beetle (*Scolytus amygdali*) in Tunisia is naturally regulated by a complex of hymenopteran parasitoids and mites. Dominant species included *Cerocephala eccoptogastri* (53.26%), *Cheiropachus quadrum* (14.88%) and *Rhaphitelus maculatus* (10.44%), all belonging to Pteromalidae. Notably, *Eusandalum merceti* (Eupelmidae) was recorded for the first time in Tunisia, acting as an ectoparasitoid of mature larvae and pupae. In addition, *Pyemotes* sp. mites attacked all developmental stages of the beetle and its parasitoids, underscoring the diverse natural enemy complex that contributes to biological control of *S. amygdali* (Zeiri *et al.*, 2013).

Table 1 : Almond Pests: Description, Damage and Biological Control

Pest	Description	Damage	Biological Control
Poplar lace bug (*Corythucha ciliata*)	Small hemipteran with lace-like wings; nymphs spiny and dark.	Leaf chlorosis, stippling, premature leaf drop; reduced photosynthesis and tree vigor.	Predatory bugs (*Orius* spp.), lacewing larvae (*Chrysoperla* spp.), parasitoid wasps; habitat management to conserve natural enemies.
Longhorn beetle (*Capnodis tenebrionis*)	Large beetle; larvae bore into roots and trunk.	Root and collar girdling, tree decline, mortality.	Entomopathogenic nematodes (*Steinernema* & *Heterorhabditis* spp.), fungi (*Beauveria bassiana*), orchard sanitation.

Peach twig borer moth (*Anarsia lineatella*)	Small moth; larvae tunnel shoots and nuts.	Shoot dieback, nut boring, yield loss.	*Bacillus thuringiensis* sprays, pheromone mating disruption, predators (lacewings, lady beetles).
San Jose scale (*Quadraspidiotus perniciosus*)	Armored scale insect; sessile on bark and fruit.	Sap removal, branch dieback, nut drop, tree decline.	Parasitoid wasps (*Encarsia* spp.), lady beetles, horticultural oils.
Almond fruit wasp (*Eurytoma amygdali*)	Small hymenopteran; larvae develop inside almond fruits.	Nut abortion, kernel destruction, yield reduction.	Egg parasitoids (Braconidae), orchard sanitation (removal of infested nuts), promoting natural enemies.

(Baspinar *et al.*, 2017).

Table 2 : Biology and Damage of Hemipteran Pests in Almonds

Feature	Leaffooted Bug (*Leptoglossus* spp.)	Brown Marmorated Stink Bug (*Halyomorpha halys*)	Green Stink Bug (*Chinavia hilaris*)
Origin/Status	Native to the Americas; occasional but sometimes severe pest	Invasive from East Asia	Native to North America
Size/Appearance	Large (19–25 mm); brown with zig-zag band; leaf-like tibiae	12–17 mm; marbled brown; black & white abdominal edges; white antennal bands	12–20 mm; bright green; yellow margins; black dash-like markings
Generations/Seasonality	2–3 generations/year; active April–June; overwinter in aggregations	2 overlapping generations/year in California; active spring–summer	1–2 generations/year; overwinter in orchards under debris
Feeding Damage	Early-season: almond drop; late-season: kernel necrosis, shriveled kernels	Early-season: nut abortion/drop; late-season: gumming, dark kernel spots	Adults cause blemishes, deformities, necrotic lesions; nut abortion less common
Distinct Damage Symptoms	1–2 thread-like gumming spots per nut; common nut drop	Multiple "glob-like" gumming spots; nut abortion frequent	Multiple thread-like gumming spots; late-season feeding may not damage kernel
Hosts Beyond Almonds	Pistachio, pomegranate, corn, soybean, citrus	>170 crops including apple, peach, grape, tomato, soybean	Almond, pistachio, cotton, tomato, soybean, peach, apple, cherry
Biological Control	Egg parasitism by *Gryon* spp., *Trissolcus* spp.; tachinid flies (Trichopoda)	Samurai wasp (*Trissolcus japonicus*) promising; generalist predator minimal impact	Egg parasitoids (*Trissolcus*, *Anastatus*,); tachinid flies (Trichopoda)

(Rijal *et al.*, 2021)

Conclusion

Biological control represents a pivotal shift in global almond pest management, moving beyond the limitations of chemical reliance toward resilient, eco-friendly solutions. Case studies across diverse regions demonstrate that parasitoids, predators, entomopathogenic fungi and microbial agents can effectively suppress lepidopteran, coleopteran and hemipteran pests while safeguarding environmental health and consumer safety. Yet, challenges such as climatic variability, orchard practices and the slow pace of biopesticide commercialization remain barriers to widespread adoption. The future of almond production lies in integrated strategies where biological control is harmonized with cultural, ecological and technological innovations to build sustainable, climate-resilient systems. By embracing these approaches, almond growers worldwide can ensure long-term productivity, ecological balance and economic viability, positioning biological control as the cornerstone of modern almond IPM.

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