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Studies on the Ecology, Host Interactions, and Management of Papaya Mealybug, *Paracoccus marginatus* Williams and Granara de Willink of Horticultural Ecosystem: A Review

Rudra N. Borkakati [a++*], Mukul K. Deka [b#], Birinchi Kr. Borah [c†], Samiran Pathak [d#], Raju Prasad Paswan [e‡], Naseema Rahman [d^], Snigdha Bhattacharjee [f++] and Bharat Chandra Nath [g++]

[a] AAU-Zonal Research Station, Shillongani, (Assam), India.
[b] Department of Entomology, AAU, Jorhat (Assam), India.
[c] Department of Entomology, BNCA, AAU, Biswanath Chariali (Assam), India.
[d] AAU-Horticultural Research Station, Kahikuchi, (Assam), India.
[e] Department of Agricultural Statistics, AAU, Jorhat, India.
[f] AAU-Sugarcane, Medicinal and Aromatic Plants Research Station, Buralikson, India.
[g] Department of Plant Pathology, AAU, Jorhat (Assam), India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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[++] Scientist;
[#] Pr. Scientist;
[†] Professor;
[‡] Professor & Head;
[^] Sr. Scientist;
**Corresponding author: E-mail: rudra.borkakati@aau.ac.in, rudra.borkakati@aau.ac.in;*

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Review Article

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ABSTRACT

Papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink (Hemiptera: Pseudococcidae) are significant agricultural pests affecting a wide variety of crops, including cotton, papaya, and ornamental plants. Traditionally, chemical insecticides have been employed for mealybug control, but their overuse has led to issues such as pesticide resistance, environmental contamination, and non-target effects on beneficial organisms. In contrast, biological control methods using natural enemies like parasitoids (*Anagyrus loecki*, *Acerophagus papayae*, *Aenasius bambawalei*) and predators (Coccinellidae, Chrysopidae) have shown promise in reducing mealybug populations while maintaining ecological balance. This review compares the effectiveness of biological control agents with chemical control strategies. Studies have demonstrated the high specificity and eco-friendliness of biological agents, although their effectiveness can vary depending on environmental conditions. Conversely, chemical insecticides offer rapid results but pose significant risks to the environment and biodiversity. The integration of both approaches through Integrated Pest Management (IPM) programs emerges as a promising strategy for achieving sustainable, long-term control of mealybugs. This review highlights the importance of combining biological control with selective chemical use, offering a comprehensive overview of mealybug management strategies.

Keywords: Mealybug; biological control; chemical control; Integrated Pest Management (IPM); parasitoids; predators; pesticide resistance; environmental impact.

1. INTRODUCTION

Mealybugs (Pseudococcidae) are notorious for their ability to damage a wide variety of crops and plants by feeding on plant sap. Their infestations lead to weakened plant health, stunted growth, and reduced crop yield, with further complications arising from their secretion of honeydew, which encourages the growth of sooty mold [1]. This combination of direct and indirect damage makes them a significant pest in agricultural systems worldwide. Species such as *Phenacoccus solenopsis*, *Paracoccus marginatus*, and *Maconellicoccus hirsutus* are particularly problematic, with some being invasive and spreading rapidly across various continents [2].

Mealybugs have emerged as a significant threat to agricultural productivity, particularly in tropical and subtropical regions. These invasive sucking pests are notorious for causing extensive damage to a wide range of crops by feeding on plant sap, leading to stunted growth and reduced yields. A comprehensive overview of the ecology and management of mealybugs has been provided, highlighting their impact on agriculture and the various strategies available for their control [3].

Integrated management approaches are essential for effectively tackling the threat posed by mealybugs. Recent research has focused on the identification of mealybug species and the development of integrated pest management (IPM) strategies to mitigate their damage. These strategies include the use of biological control agents, cultural practices, and chemical interventions [4].

Understanding the population dynamics and economic injury levels of mealybugs is critical for implementing effective control measures. Life table studies offer valuable insights into their reproductive potential and population growth under various environmental conditions, which can inform threshold levels for intervention [5].

In the past, chemical control was the primary method used for managing mealybug populations due to its immediate impact. Insecticides such as carbamates, organophosphates, and synthetic pyrethroids have been widely employed for this purpose [6]. However, the repeated use of chemical insecticides has created a number of challenges. These include the development of pesticide resistance in mealybug populations, non-target effects that harm beneficial organisms like pollinators and natural enemies, and the accumulation of toxic residues in the environment [7]. Moreover, the extensive use of chemicals disrupts ecological balance by reducing biodiversity, which can trigger secondary pest outbreaks [1].

Classical biological control [8] has proven effective in some cases by introducing exotic parasitoid species to control invasive mealybug populations. The use of parasitoids like *Anagyrus loecki*, *Acerophagus papayae*, and *Aenasius bambawalei* has shown significant success in controlling species such as *Paracoccus marginatus* and *Phenacoccus solenopsis* in different regions [9]. These biological control agents are highly specific and environmentally friendly, making them ideal candidates for sustainable pest management. Similarly, predators such as ladybird beetles (Coccinellidae) and green lacewings (Chrysopidae) play a vital role in reducing mealybug numbers through predation [2].

The effectiveness of biological control, however, depends on several factors, including environmental conditions, the availability of suitable host plants, and the synchronization of predator-prey or host-parasitoid life cycles [10]. Laboratory studies have demonstrated that factors such as temperature and humidity can significantly influence the efficacy of biological agents. For example, parasitoids like *Aenasius bambawalei* perform optimally at specific temperature and humidity ranges, highlighting the importance of considering environmental conditions when implementing biological control programs [11].

Given the advantages and limitations of both biological and chemical control methods, integrated pest management (IPM) strategies have gained traction. IPM emphasizes the use of multiple tactics, combining biological control with selective use of chemicals, cultural practices, and monitoring tools to achieve sustainable pest management [6]. IPM aims to reduce reliance on chemical pesticides, enhance the effectiveness of biological control agents, and promote ecological balance [7]. By integrating different methods, IPM offers a more holistic and sustainable approach to managing mealybug populations.

In this review, we aim to explore and compare the efficacy of biological control agents and chemical insecticides in managing mealybug infestations. Through this comparative analysis, we seek to identify the strengths and weaknesses of each approach and highlight the potential of integrated pest management as a more sustainable and effective strategy for long-term control.

2. MANAGEMENT OF PMB IN THE INDIAN SUBCONTINENT

In 2008, the Indian subcontinent became acquainted with *Paracoccus marginatus*, commonly known as the papaya mealybug, when it was first detected in Coimbatore, Tamil Nadu. Like a silent invader, it quickly spread to neighboring states over the next few years reaching Kerala, Andhra Pradesh, Karnataka, West Bengal, Assam, and Gujarat by 2012 [12]. Its presence was also recorded as far as Rajasthan, signaling its rapid expansion across the region. However, India was not the only target; by 2008, it had found its way to Sri Lanka, and soon after, to Bangladesh, the Maldives, Pakistan, and Nepal. Despite its small size and the wingless nature of the female *P. marginatus*, the species thrived by taking advantage of natural elements. Air currents, rain, irrigation, birds, and even unsuspecting farm equipment helped transport the immature insects over short distances. Alongside this, the movement of fruits, vegetables, and other plant materials accelerated the bug's journey, leaving no corner untouched. Some species of ants, particularly those attracted to the honeydew secreted by the mealybug, further assisted in its movement, creating an ecosystem of mutual benefit. Faced with such a swift and destructive spread, managing this pest became a crucial task. Farmers and agricultural experts employed a combination of tactics: regular scouting for infestations, pruning and burning affected plant parts, and removing alternate host plants. Isolating infested fields and sanitizing farm equipment before moving them to clean areas also became a key part of the strategy. Systemic insecticides and organophosphates were used, though the mealybug's waxy coating often necessitated repeated applications for effectiveness. Biological solutions also stepped into the arena. Entomopathogenic fungi like *Verticillium lecanii*, *Beauveria bassiana*, and *Metarhizium anisopliae* showed promise in laboratory settings, causing significant mortality in the pests. In addition, neem-based biopesticides were put to use, though their effectiveness was limited by the mealybug's unique biology. The real breakthrough came with classical biological control an approach that relied on introducing natural predators. Predatory species like *Spalgis epius* and several beetles from the Coccinellidae family proved valuable in keeping the mealybug population in check. Spiders, lacewings, and hoverflies joined the battle, all helping to regulate the pest population.

Meanwhile, on the other side of the world, in Mexico, natural parasitoids had already demonstrated their ability to control *P. marginatus* populations. The U.S. Department of Agriculture (USDA) took note and, in 1999, initiated a biological control program. Key parasitoids, *Acerophagus papayae*, *Pseudleptomastix mexicana*, and *Anagyrus loecki* were reared and released in various regions, including Florida, the Caribbean Islands, and tropical countries in South America. Their success prompted further releases in Indonesia, Thailand, Cambodia, and Malaysia, where they effectively managed the pest.

The Indian subcontinent, too, embraced this classical biological control strategy. Parasitoids specific to *P. marginatus* were introduced, and these tiny wasps began to target the immature mealybugs, inserting their eggs into the soft bodies of their hosts. As the wasp larvae grew, they would consume the mealybugs from the inside, eventually killing them and helping to curb the population in a sustainable way.

This multifaceted approach combining chemical control, biological agents, and vigilant farming practices has been essential in managing the spread of *P. marginatus* across India and beyond. The fight against this invasive pest continues, but with the help of nature's own defenders, farmers now have a powerful ally in their efforts to protect their crops.

The papaya mealybug (*Paracoccus marginatus*), a pest native to Central America and the Caribbean, was first detected in Palau in March 2003, where it caused severe damage to crops such as papaya, plumeria, and hibiscus. To control its spread, 24,586 parasitoids *Anagyrus loecki*, *Pseudleptomastix mexicana*, and *Acerophagus papayae* (Hymenoptera: Encyrtidae) were imported from Puerto Rico and released in Palau from August 2003 to June 2004. While *Anagyrus loecki* and *A. papayae* proved to be promising biological control agents, no field recovery of *P. mexicana* was observed despite multiple releases. Within six months, these exotic parasitoids successfully reduced papaya mealybug populations to undetectable levels. This successful implementation of classical biological control has significantly lowered the risk of the mealybug spreading to other islands in the Republic of Palau and neighboring Micronesian regions [9].

The papaya mealybug (*Paracoccus marginatus*) became a significant pest in India in 2009 due to the extensive damage it caused to economically important crops. With a wide host range spanning over 60 plant species, it primarily infests the veins, midribs of older leaves, young leaves, and fruits, causing them to turn yellow and eventually dry out. Heavy infestations lead to the production of honeydew, which promotes the growth of black sooty mold, further reducing fruit quality and market value. Female mealybugs are light greenish-yellow, while adult males are deep red with a single pair of wings. The pest completes its life cycle in 19-30 days, with 11 to 13 generations occurring each year. Currently, it is managed through an integrated pest-management approach that combines chemical, biological, and cultural control methods [21].

3. BIOLOGICAL CONTROL AGENTS OF MEALYBUG

Biological control is a critical strategy in mealybug management, utilizing natural enemies such as parasitoids and predators to reduce pest populations. For instance, the papaya mealybug (*Paracoccus marginatus*) caused significant damage in Central America, the Caribbean, and later Palau. In Palau, a classical biological control program was implemented by importing three parasitoid species *Anagyrus loecki*, *Pseudleptomastix mexicana*, and *Acerophagus papayae* from Puerto Rico. Over 24,586 parasitoids were released, and within six months, *A. loecki* and *A. papayae* successfully reduced the papaya mealybug population to undetectable levels. This reduced the risk of spread to other Pacific islands [9].

In the Indian cotton belt, *Phenacoccus solenopsis* outbreaks were managed through the identification of 17 parasitoids and predators, notably *Aenasius bambawalei*, which was found to be the most effective [2]. Additionally, the functional response of predators such as *Scymnus coccivora* showed that its different life stages were highly efficient in controlling *P. solenopsis* populations, with the highest predation rate seen in fourth instar grubs [11].

Studies on predation of *Cheilomenes sexmaculata*, a potential predator of mealybugs, revealed that it was more effective against second instar mealybugs [22].

Table 1. The new host plants and families for *Paracoccus marginatus*

Family	Host Plant	References
Acanthaceae	*Fistulosa sp.*, *Pachystachys lutea* Nees	Miller & Miller, [13]
Aizoaceae	*Trianthema portulacastrum L.*	Matile-Ferrero & Etienne, [14]
Amaranthaceae	*Achyranthus aspera L.*	Tanwar et al., [15]
Annonaceae	*Annona muricata L.*, *Annona squamosa L.*	Martinez et al., [16]
Apocynaceae	*Plumeria spp.*, *Plumeria acutifolia L.*	Chen et al., [17]
Aracaceae	*Roystonea regia* (Kunth)	Martinez et al., [16]
Compositae	*Ambrosia cumanensis Kunth*, *Parthenium hysterophorus L.*, *Tridax procumbens L.*, *Bidens pilosa L.*	Ben-Dov, [18]; Tanwar et al., [15]
Capridaceae	*Cleome viscose L.*	Miller & Miller, [13]
Caricaceae	*Carica papaya L.*	Williams & Granara de Willink, [19]
Commelinaceae	*Commelina benghalensis L.*	Tanwar et al., [15]
Convolvulaceae	*Convolvulus arvensis L.*, *Ipomoea carnea Jacq.*	Williams & Granara de Willink, [19]
Euphorbiaceae	*Acalypha spp.*, *Euphorbia hirta L.*, *Jatropha curcus L.*, *Phyllanthus niruri L.*, *Manihot esculenta*, *Ricinus communis*	Martinez et al., 2005; Williams & Granara de Willink, [16]
Fabaceae	*Acacia sp.*, *Bauhinia sp.*, *Cajanus cajan (L.)*, *Erythrina abyssinica Lam.*, *Glyricidia sepium (Jacq.)*, *Mimosa pigra L.*, *Tetramnus labialis (L.)*	Miller & Miller, [13]; Matile-Ferrero & Etienne, [14]
Lamiaceae	*Leucas aspera (Willd)*, *Ocimum sanctum L.*	Tanwar et al., [15]
Lauraceae	*Persea americana Mill.*	Miller & Miller, [13]
Malpighiaceae	*Malpighia glabra L.*	Matile-Ferrero & Etienne, [14]
Malvaceae	*Abutilon indicum L.*, *Ceiba pentendra (L.)*, *Gossypium hirsutum L.*, *Hibiscus mutabilis L.*, *Hibiscus rosa-sinensis L.*, *Malvasicus arboreus (Torr & Gray)*, *Sida sp.*	Tanwar et al., [15]; Matile-Ferrero & Etienne, [14]
Moraceae	*Morus alba L.*	Williams & Granara de Willink, [19]
Myrtaceae	*Psidium guajava*	Tanwar et al., [15]
Poaceae	*Uniola paniculata L.*, *Zea mays L.*	Miller & Miller, [13]
Polygonaceae	*Coccoloba sp.*	Matile-Ferrero & Etienne, [14]
Rosaceae	*Raphiolepis umbellate Thunb.*, *Rosa sp.*	Matile-Ferrero & Etienne, [14]
Rubiaceae	*Canthium inerme (L.)*, *Hamelia sp.*, *Mussaenda sp.*	Tanwar et al., [15]; Miller & Miller, [13]
Rutaceae	*Citrus paradise Macfad.*	Matile-Ferrero & Etienne, [14]
Solanaceae	*Cestrum nocturnum L.*, *Lycopersicon esculentum Mill.*, *Solanum torvum Sw.*, *Solanum melongena L.*	Tanwar et al., [15]; Miller & Miller, [13]
Sterculiaceae	*Guazuma sp.*	Matile et al., [20]
Verbenaceae	*Clerodendrum paniculatum L.*, *Tectona grandis L.*	Miller & Miller, [13]

Source: [17]

Laboratory trials have also investigated environmental factors affecting parasitoid efficiency. For example, *A. bambawalei* was most effective at 25±2°C and 65±5% relative humidity, demonstrating the importance of optimizing conditions for biological control agents [10]. Additionally, studies on the chemical ecology of *Acerophagus papayae* revealed that certain volatile organic compounds (VOCs) from papaya and tapioca influenced mealybug feeding and the effectiveness of parasitoids [8].

The papaya mealybug, *Paracoccus marginatus*, has emerged as a major agricultural pest, particularly affecting papaya crops. This pest is known for causing extensive damage by feeding on plant sap, leading to stunted growth, yellowing of leaves, and even plant death. Due to the severity of the infestation, researchers have explored various biological control methods as alternatives to chemical pesticides, which often have adverse environmental effects.

One of the most promising control strategies involves the use of entomopathogenic fungi. Amutha and Banu [23] investigated the efficacy of these fungi in controlling *P. marginatus* and found that they were highly effective. Similarly, Ayyasamy and Regupathy [24] confirmed the fungi's efficacy in both laboratory and field conditions, suggesting that such biological agents could be a viable method for managing the mealybug in real-world agricultural settings. Biological control, in general, has been a focus of integrated pest management (IPM) strategies. Fazlullah et al. [25] reviewed successful biological control efforts in India, where natural enemies such as parasitoids were deployed to regulate *P. marginatus* populations. Muniappan et al. [26] and Myrick and Meyerdirk [27] documented similar efforts in tropical regions, including the Republic of Maldives, where biological control agents were introduced and significantly reduced the pest population without the need for chemical intervention. The spread of *P. marginatus* has been well-documented across different regions of India, further highlighting the pest's adaptability and threat to agriculture. Krishnakumar and Rajan [28] first reported its occurrence in Kerala, while Lalitha et al. [29] documented its presence in West Bengal. Other notable reports include the spread in Gujarat [30], Andhra Pradesh [31], and Assam [32], indicating the pest's widespread distribution throughout the country.

In terms of controlling these expanding populations, studies have shown that natural enemies, especially parasitoids, play a critical role. Mani et al. [33] conducted extensive research on the natural enemies of *P. marginatus* and found several parasitoid species that effectively suppress the pest. Similarly, Shylesha et al. [34] and Sakthivel et al. [35] demonstrated the successful use of classical biological control by introducing parasitoids to curtail *P. marginatus* populations in field conditions. These natural enemies help maintain the ecological balance and reduce reliance on chemical pesticides. Overall, biological control remains a sustainable and environmentally friendly method for managing *Paracoccus marginatus*. As this pest continues to spread across various regions, integrating entomopathogenic fungi and parasitoids into pest management practices is critical for minimizing the economic and environmental damage caused by this invasive species.

4. CHEMICAL CONTROL OF MEALYBUG

While biological control is vital, chemical control remains a key component in managing mealybug outbreaks. Laboratory studies by Biswas et al. [36] on the efficacy of various chemical insecticides, including Sevin 85 SP and Dimethoate 40 EC, showed significant mortality of papaya mealybug (*P. marginatus*). In contrast, botanical oils such as Neem oil and Karanja oil offered moderate to low levels of control. Other insecticides, such as Deltamethrin 2.5 EC, showed moderate effectiveness, while polythene bands and ladybird beetles provided little control.

Innovative chemical solutions, such as using *Citrus sinensis* waste, were explored [37]. Methanol extracts of the fruit peels showed a promising 88% mortality rate against mealybugs, highlighting the potential of plant-derived insecticides. Similarly, studies on combinations like spinetoram and sulfoxaflor proved highly effective against pink hibiscus mealybug (*Maconellicoccus hirsutus*) when applied through foliar sprays [38].

Another comprehensive study by Ganjisaffar et al. [39] tested seven insecticides on various life stages of *M. hirsutus* and found that treatments such as sulfoxaflor and acetamiprid had significant effects on egg hatch rates and nymph survival. Notably, spirotetramat and buprofezin had lower immediate mortality but showed increased effectiveness over time. Moreover, the effective management of *Maconellicoccus hirsutus* (Hemiptera: Pseudococcidae) on ornamental plants requires a comprehensive understanding of its biology and behavior, which informs integrated pest management strategies that combine biological controls with targeted chemical applications [40].

Furthermore, integrated pest management (IPM) modules, as implemented by Punjab Agricultural University, have reduced the incidence of mealybug infestations by promoting natural enemies and reducing chemical sprays [6]. In a similar study, insect growth regulators like Buprofezin were found to effectively reduce mealybug populations without harming beneficial species, providing a sustainable alternative to harsher chemicals [7].

5. CONCLUSION

The management of mealybugs, particularly in economically significant crops, requires a well-rounded approach that considers both the immediate and long-term impacts of pest control methods. Chemical control, while effective in rapidly reducing mealybug populations, poses serious risks such as pesticide resistance, environmental contamination, and the destruction of beneficial organisms. On the other hand, biological control, utilizing natural enemies like parasitoids and predators, offers an eco-friendly and sustainable alternative. However, the effectiveness of biological agents can be influenced by environmental conditions, and they may take longer to achieve significant population reductions compared to chemical methods.

A comparison of these two approaches suggests that neither alone can provide an entirely effective or sustainable solution. Instead, Integrated Pest Management (IPM), which combines the selective use of chemical insecticides with biological control agents, represents the most viable long-term strategy. IPM not only reduces the ecological risks associated with chemical use but also enhances the effectiveness of biological control. Implementing IPM strategies can help achieve sustainable mealybug management by reducing pesticide reliance, preserving biodiversity, and promoting ecological balance.

To achieve the best results in managing mealybug infestations, future efforts should focus on further refining IPM programs, optimizing the combination of biological and chemical controls, and tailoring strategies to local environmental conditions. This approach ensures effective pest suppression while minimizing harm to the environment and non-target organisms.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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