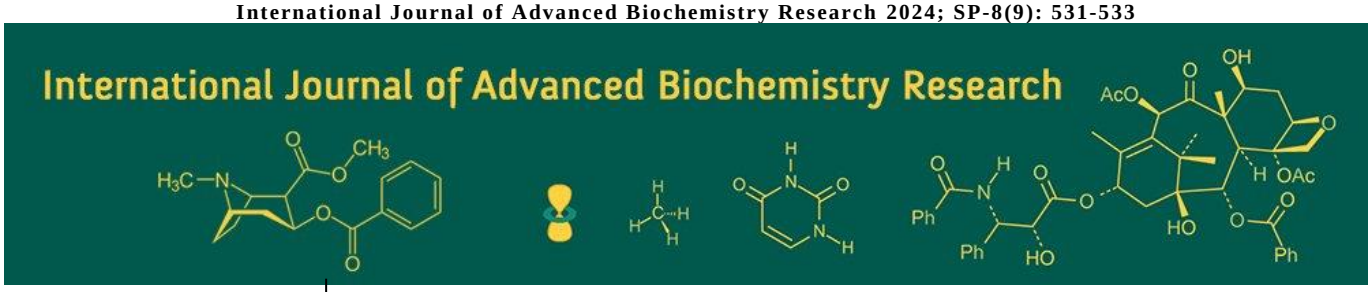

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Ecology and management of mealybugs in agriculture: A comprehensive overview

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Abstract
Mealybugs (Hemiptera: Pseudococcidae) are a significant pest group affecting a wide range of crops globally. Their invasive nature, high reproductive capacity, and ability to inflict damage through sap-sucking, honeydew excretion, and pathogen transmission make them formidable adversaries in agricultural systems. This review provides a comprehensive overview of the host range and diversity of mealybug species, emphasizing their ecological and economic impacts on agriculture. It highlights the major invasive species in India, including *Phenacoccus solenopsis*, *Paracoccus marginatus*, *Phenacoccus madeirensis*, *Pseudococcus jackbeardsleyi*, and *Phenacoccus manihoti*. The study further explores the various integrated pest management (IPM) strategies employed to manage these pests, combining cultural, biological, and chemical control methods. A thorough understanding of the biology, host specificity, and ecological adaptations of mealybugs is crucial for developing effective and sustainable management practices to mitigate their impact on agriculture. This review aims to synthesize current knowledge, identify gaps, and provide insights into future research directions for managing mealybug infestations in diverse agro-ecosystems.

Keywords: Ecology, management, mealybugs, *Phenacoccus solenopsis*, *Paracoccus marginatus*

Introduction
Mealybugs (Hemiptera: Pseudococcidae) are a diverse group of sap-sucking insects that pose a significant threat to global agriculture. They infest a wide range of host plants, including economically important crops, ornamentals, and fruit trees, causing substantial yield losses and economic damage. Their ability to thrive in various environmental conditions and their polyphagous nature make them particularly challenging to manage (Pimentel *et al*., 2001) [1].
The introduction and spread of invasive mealybug species are exacerbated by the globalization of trade, which facilitates the movement of pests across borders. In recent decades, India has witnessed the invasion of several exotic mealybug species, including the cotton mealybug (*Phenacoccus solenopsis* Tinsley), papaya mealybug (*Paracoccus marginatus* Williams and Granara de Willink), Madeira mealybug (*Phenacoccus madeirensis* Green), Jack Beardsley mealybug (*Pseudococcus jackbeardsleyi* Gimpel & Miller), and cassava mealybug (*Phenacoccus manihoti* Matile-Ferrero) (Rathee and Dalal, 2018; Joshi and Rameshkumar, 2017) [2, 3]. These pests are particularly problematic due to their rapid reproductive rates, ability to hide in crevices, and resistance to several conventional pesticides.
The impact of mealybug infestations is not limited to direct feeding damage. They also excrete honeydew, which promotes the growth of sooty mold, further reducing the photosynthetic ability of plants and leading to significant qualitative and quantitative losses in crop yields. Additionally, mealybugs can transmit plant pathogens, compounding their detrimental effects on agriculture (Joshi, 2017) [4].
Effective management of mealybugs requires an integrated approach that combines cultural, biological, and chemical control methods. The development of Integrated Pest Management (IPM) strategies tailored to specific mealybug species and their host plants is essential for sustainable agricultural production. Surveys and studies to understand the host range and

infestation levels of mealybugs are crucial in developing these IPM strategies (Sahu *et al*., 2019) [5].

Several studies have been conducted worldwide to better understand the biology, host range, natural enemies, and management strategies for different mealybug species. For instance, surveys in Chhattisgarh, India, have documented the presence of multiple mealybug species on diverse host plants across various families (Sahu *et al*., 2019). Similarly, research on the biology and control of invasive mealybugs, such as the striped mealybug (*Ferrisia virgata*) on cotton, highlights the pest's potential to cause significant damage to economically important crops (Oliveira *et al*., 2014) [6].

This review aims to synthesize the current knowledge on the host plants and diversity of mealybug species, focusing on their biology, ecological impacts, and management strategies. Understanding the host range and diversity of mealybugs is critical for developing effective management practices and mitigating the economic losses caused by these pervasive pests.

Host Range and Infestation Levels

A comprehensive survey by Sahu *et al*. (2019) [5] in the Chhattisgarh plain region revealed 132 plant species as potential hosts for mealybugs, with 72 species from 28 families confirmed as hosts. These hosts included a diverse range of plants such as pulses, oilseeds, vegetables, fruits, fiber crops, sugarcane, ornamentals, medicinals, forest trees, and weeds. The highest number of host plants belonged to the families Malvaceae and Asteraceae, followed by Fabaceae, Apocynaceae, Solanaceae, Rosaceae, Amaranthaceae, and Lamiaceae. Infestation levels varied among these plants, with 36 species showing low infestation, 12 with medium infestation, and 24 with high infestation. Among the mealybug species identified, *Phenacoccus solenopsis* was the most dominant, infesting 14 different host plants with a maximum infestation level of 46.66%.

Life Cycle and Reproduction

Studies on the life cycle and reproductive behavior of different mealybug species highlight significant differences. Awadallah *et al*. (1979) [7] investigated the life cycle of *Ferrisia virgata* on sprouting potato tubers, noting that the mealybugs reproduced through parthenogenesis under certain conditions, producing only females. They found significant differences in developmental durations across various generations and thermal conditions. Mortality rates were higher during nymphal stages in the autumn/winter generations compared to spring/summer. Oliveira *et al*. (2014) [6] studied the population growth of *F. virgata* on four cotton cultivars in Brazil and found the pest to be highly polyphagous with significant potential as a cotton pest.

Control Strategies and Biological Control

The management of mealybugs has primarily focused on biological control strategies. Chong *et al*. (2015) [8] emphasized the importance of biological control in managing *Maconellicoccus hirsutus* in urban landscapes, while Susikaran *et al*. (2018) [9] explored the predatory efficiency of *Cryptolaemus montrouzieri* and *Chrysoperla zastrowi sillemi* against *M. hirsutus* on different host plants. Fand *et al*. (2012) [10] investigated the use of plant products and insect pathogenic bacteria like *Photorhabdus luminescens* for controlling *P. solenopsis* in cotton, highlighting the need for caution when integrating biopesticides with other biological control agents due to potential bioecological hazards. An in-depth investigation and comprehensive studies of Indigenous Technical Knowledge (ITK) for the management of sucking pests are crucial. Such efforts can provide valuable insights and potentially lead to the effective management of specific pests like the mealybug, thereby enhancing sustainable pest control practices in agricultural systems (Borkakati *et al*., 2023) [11]. Several important crops, such as *Bhut Jolokia* (Hot Chilli), are vulnerable to attacks by various sucking pests, among which the mealybug stands out as a significant pest. Given the damage it causes, the use of biopesticides that are specifically suitable for managing sucking pests can be an effective approach for controlling mealybug infestations. Implementing biopesticide-based management strategies may help reduce pest populations while minimizing environmental impacts and promoting sustainable agriculture (Saikia *et al*., 2019) [12]. The exploration and identification of natural enemies of mealybugs are highly beneficial for the biological control of this pest. By understanding and utilizing these natural predators or parasitoids, it becomes possible to develop environmentally friendly, sustainable strategies to manage mealybug populations, thereby reducing the need for chemical pesticides and promoting ecological balance in agricultural ecosystems (Borkakati *et al*., 2018) [13].

Invasive Species and Their Impact

Several invasive mealybug species have emerged as major threats to agriculture in India. Lepakshi *et al*. (2018) [14] reported the spread of *Phenacoccus madeirensis* to cotton-growing areas in South Karnataka and Maharashtra. They noted that male mealybugs had a slightly longer nymphal period than females. Similarly, the rhizome mealybug (*Formicococcus polysperes*) has been reported to cause significant damage to ginger crops in Meghalaya, India, with infestation rates as high as 55.48% by November (Momin *et al*., 2018) [15].

The papaya mealybug (*Paracoccus marginatus*) has spread to several regions globally, including India, since its description in 1992. It is highly polyphagous, attacking over 70 plant species, and causes severe economic losses. Biological control measures, especially the introduction of parasitoids like *Acerophagus papayae*, have been highly effective in managing populations of *P. marginatus* (Mani *et al*., 2012; Sharma and Muniappan, 2021) [16, 17].

Conclusion

The host range and diversity of mealybugs represent a significant challenge to global agriculture, particularly in tropical and subtropical regions like India. Comprehensive surveys and studies, such as those conducted by different researchers, provide valuable insights into the biology, host range, and management strategies for these pests. Effective management of invasive mealybug species will require a combination of biological control, careful use of biopesticides, and well-planned IPM strategies to minimize economic losses and protect crop yields.

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