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INSECT-MICROBIOME INTERACTIONS: IMPLICATIONS FOR PEST MANAGEMENT AND ECOSYSTEM HEALTH

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ABSTRACT

The most varied group of animals, insects, have intricate connections with a wide variety of microbes that comprise their microbiome. Insect physiology, metabolism, development, reproduction and immunity are all impacted by these interactions, which have a profound effect on insect biology. The complex relationship between insects and microbiomes is, along with the important consequences for managing pests and the general well-being of ecosystems. The bacteria, fungi, viruses and protists that make up the insect microbiome frequently offer their hosts important advantages. These can include producing vital vitamins, detoxifying toxic substances, assisting in the absorption of nutrients from difficult diets and providing defense against parasitoids and infections. New opportunities for creative pest control techniques arise from an understanding of these complex symbiotic and antagonistic connections. Insect microbiomes have a broad impact on ecosystem health in addition to pest management. As food providers, pollinators and decomposers, insects have a variety of ecological functions that greatly influence plant production, nutrient cycling and biodiversity in general. Many of these processes are mediated by the microbial communities found in insects. Therefore, disturbances to insect microbiomes, which may be brought on by contaminants in the environment or climate change, may have a domino effect on the resilience and stability of ecosystems. In order to create sustainable pest control strategies and to better understand and protect the health of our planet's different ecosystems, further study into these complex interconnections is desperately needed, as this study emphasizes.

INTRODUCTION

Insects, the most diverse class of organisms on Earth, exhibit an astonishing array of adaptations that have allowed them to colonize nearly every terrestrial and freshwater habitat. This evolutionary success is increasingly being attributed not solely to the insects themselves, but to the intimate and often indispensable partnerships they form with diverse microbial communities their microbiomes. These microbial associates, including bacteria, fungi, viruses and archaea, reside in various insect tissues, most notably the gut, influencing a wide spectrum of host physiological processes, behavior and ecological interactions (**Engel and Moran, 2013; Gurung et al., 2019**). Insects represent one of the most diverse and ecologically influential groups in the animal kingdom, occupying a broad range of ecological niches and playing crucial roles in pollination, decomposition and food web dynamics. A key factor contributing to their evolutionary success is the intimate association with microbial communitiescollectively known as the insect microbiomethat inhabit their guts, reproductive organs and external surfaces (**Douglas, 2015; Engel & Moran, 2013**). These microbial partners are not merely incidental; they perform essential functions related to host nutrition, immune defense, detoxification, reproduction and behavior (**Crotti et al., 2012; Hansen & Moran, 2014**).The growing understanding of insect-microbiome interactions has revealed novel opportunities for sustainable pest management. Conventional pest control strategies, particularly chemical pesticides, face increasing challenges due to the development of insecticide resistance, collateral damage to non-target species and negative environmental impacts (**Desneux et al., 2007**).

In contrast, microbiome-based interventions offer targeted,

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ecologically friendly alternatives. Strategies such as symbiont-mediated interference, paratransgenesis and microbiome manipulation have demonstrated potential for disrupting pest fitness or reducing vector competence in disease-transmitting insects (**Beard et al., 2002; Wang et al., 2021; Weiss & Aksoy, 2011**). For example, engineered symbionts have been used to block pathogen transmission in mosquitoes, representing a promising tool in the fight against vector-borne diseases like malaria and dengue (**Dennison et al., 2014**).The recognition of the profound impact of the insect microbiome has revolutionized our understanding of insect biology, moving beyond a host-centric view to a more holistic perspective that integrates the microbial dimension. This paradigm shift holds immense promise for addressing global challenges, particularly in agriculture and environmental conservation. As traditional chemical pesticides face increasing scrutiny due to concerns about environmental pollution, non-target effects and the evolution of pest resistance, harnessing the power of insect-microbiome interactions offers a sustainable and specific alternative for pest management. Simultaneously, comprehending these interactions is crucial for appreciating the vital roles insects play in maintaining ecosystem health, from nutrient cycling to pollination.Beyond applications in pest control, insect-microbiome relationships are deeply connected to ecosystem health. These microbial symbionts can influence host population dynamics, interspecies interactions and nutrient cycling. However, environmental stressors such as pesticide exposure, habitat loss and climate change may disrupt these microbial associations, leading to unintended consequences for insect fitness and ecological stability (**Thompson et al., 2020; Zhu et al., 2021**). Therefore, a comprehensive understanding of insect-microbiome ecology is essential not only for improving pest management strategies but also for preserving biodiversity and ecosystem resilience in the face of global change. This review synthesizes current research on insect-microbiome interactions, with a focus on their biological functions, applications in pest management and broader implications for ecosystem health.

The multifaceted roles of the insect microbiome

The insect microbiome is far from a mere passenger; it is an active and often essential partner in the host's life. Its functions are diverse and deeply integrated into insect physiology and ecology:

Nutrient acquisition and metabolism: Many insects rely on their symbionts to supplement nutrient-poor diets or to digest complex, recalcitrant compounds. For instance, gut bacteria in termites and wood-feeding beetles enable the breakdown of lignocellulose, a challenging plant component (**Li et al., 2021b**). Similarly, endosymbionts in aphids provide essential amino acids and vitamins often lacking in their sap-based diet (**Mondal et al., 2023**). This nutritional upgrading can significantly impact insect growth rates, development and reproductive fitness.

Detoxification of plant toxins and pesticides: Insects constantly encounter an array of secondary metabolites in their diets, many of which are toxic. The microbiome plays a crucial role in detoxifying these compounds, enabling insects to exploit a broader range of food sources. More critically, certain

Table 1. Roles of gut microbiota in insect biology

Aspect	Microbiota functions	Examples	References
Development	Digestion of complex polysaccharides,synthesis of essential nutrients	*Buchnera* in aphids produces amino acids,cellulolytic microbes in termites	**Douglas (1998); Bignell (2000)**
Immunity	Immune priming,competitive exclusion of pathogens-Detoxification	*Lactobacillus plantarum* primes immunity in flies,*Regiella* defends aphids from fungi	**Lee et al. (2013); Scarborough et al. (2005); Kikuchi et al. (2012)**
Behavior	Modulation of olfaction & taste mating signals,social interactions	Microbiota influence food preference in *Drosophila,*microbes affect bee learning	**Wong et al. (2017); Raymann & Moran (2018); Liu et al. (2017)**

Table 2. Microbial Contributions to Insect Nutrient Metabolism

Microbial pathway	Microbial function	Metabolic outcome	Insect examples	Key microbes	References
Fermentation	Breaks down dietary polysaccharides (e.g., cellulose) into short-chain fatty acids	Provides energy via SCFAs (acetate, propionate)	Termites, beetles, *Drosophila*	*Treponema*, *Acetobacter*, *Lactobacillus*	Brune (2014); Wong et al. (2017)
Vitamin synthesis	Produces B-complex vitamins, biotin, folate	Supports development and metabolism	Tsetse flies, ants, weevils	*Wigglesworthia*, *Blochmannia*	Aksoy et al. (1995); Douglas (1998)

Amino acid synthesis	Synthesizes essential amino acids lacking in insect diet	Enables growth and reproduction	Aphids, carpenter ants	*Buchneraaphidicola, Blochmannia*	Douglas (1998); Russell et al. (2009)
Nitrogen recycling	Converts uric acid and waste products into usable nitrogen compounds	Enhances nitrogen retention	Cockroaches, termites, ants	*Blattabacterium, Bacteroidetes*	Sabree et al. (2009); Brune (2014)
Nitrogen fixation	Fixes atmospheric nitrogen via gut symbionts	Supplements nitrogen in low-protein diets	Wood-feeding beetles, termites	Diazotrophic bacteria (e.g., *Klebsiella*)	Brune &Ohkuma (2011)
Detoxification andbio-conversion	Detoxifies plant secondary metabolites & modifies toxic compounds	Expands dietary range and resilience	Leaf beetles, bark beetles	*Pseudomonas, Enterococcus, Serratia*	Adams et al. (2013)

insect gut bacteria have been found to degrade pesticides, conferring insecticide resistance to their hosts (**Kikuchi et al., 2011; Nayak et al., 2018**). This symbiont-mediated detoxification is a significant factor in the evolution and spread of pesticide resistance in pest populations (**Gressel, 2018**). Living organisms, especially plants and animals, are constantly exposed to a diverse array of toxins, including natural plant secondary metabolites (phytotoxins) and synthetic chemicals such as pesticides. To survive, they have evolved complex detoxification strategies at molecular, biochemical, cellular and organismal levels. Understanding these mechanisms is crucial for improving crop resilience, pest management and safeguarding environmental and human health.

Mechanisms: Plants produce secondary metabolites (e.g., alkaloids, glycosides, phenolics, terpenoids) as defense chemicals against herbivores and pathogens. However, these compounds can be toxic to the plants themselves and to those feeding on them. Detoxification generally occurs via enzymatic transformation, sequestration, or metabolic inactivation. A key enzymatic system in plants and plant-feeding organisms is the cytochrome P_{450} monooxygenase family, which oxidizes toxins to make them more water-soluble and easier to eliminate. Insects such as the Colorado potato beetle exhibit upregulation of multiple cytochrome P_{450} in response to both plant allelochemicals and synthetic pesticides, indicating a shared pathway for detoxifying natural and synthetic xenobiotics **(Zhu, 2016)**. Similarly, in mammals, diversity within the cytochrome P_{450} 2B gene family contributes to the ability of herbivores to tolerate plant toxins in their natural diets **(Malenke, 2012)**.Other enzymes involved in detoxification include glutathione S-transferases and UDP-glycosyltransferases. For example, UDP-glycosyltransferases play a crucial role in determining the host plant range for generalist and specialist insect herbivores by conjugating toxic compounds, making them less harmful **(Wang, 2024)**.

Role of microbial symbionts: Microbial symbionts residing in the digestive tracts of herbivorous insects and ruminants significantly enhance the detoxification of plant toxins. For instance, the gut microbiota of certain flea beetle pests enables degradation of toxic isothiocyanates derived from their host plants. When these microbes are suppressed, unmetabolized toxins accumulate, highlighting the critical detoxification role played by microbial partners **(Shukla, 2020)**. Rumen microorganisms similarly allow grazing ruminants to adapt to toxic plant diets by metabolizing otherwise harmful compounds **(Loh, 2020)**.

Pesticide detoxification in plants and animals: Modern agriculture extensively employs synthetic pesticides, necessitating robust detoxification mechanisms in both plants and the pests they target. Plants activate pathways similar to those used against natural toxins. For example, brassinosteroids, a class of plant hormones, stimulate the expression of genes encoding cytochrome P_{450s}, oxidoreductases and other detoxifying enzymes, thereby enhancing the breakdown of a wide range of pesticides **(Zhou, 2015)**.Insects develop resistance to pesticides primarily through overexpression of detoxification enzymes such as cytochrome P_{450s}, esterases and glutathione S-transferases **(Siddiqui, 2023)**. Resistance can also involve changes in gene expression regulated by specific transcription factors, as observed in the model insect Drosophila melanogaster **(Misra, 2011)**. Such adaptations reduce the efficacy of many chemical treatments, complicating pest control efforts **(Ahmad, 2024)**.

Biochemical and genetic targets: In addition to enzyme-based detoxification, other targets essential for biotransformation include ABC transporters and hydrolases involved in de-esterification. Studies on the olive fruit fly, a major agricultural pest, reveal a broad complement of detoxification gene families, including P_{450s}, GSTs and carboxylesterases, crucial for metabolizing both phytotoxins and insecticides **(Pavlidi, 2013)**.Gene editing experiments in the fall armyworm and other species have identified specific detoxification gene clusters that enable pests to survive exposure to both plant-derived and synthetic toxins, highlighting the tight evolutionary link between plant defense chemistry and chemical control strategies **(Ahmad, 2024)**.

Environmental and ecological context: Environmental factors such as temperature, diet composition and microbiome diversity play key roles in modulating detoxification capacity. For example, warmer temperatures have been shown to depress the hepatic detoxification capacity of marsupial folivores, reducing their ability to process plant secondary metabolites**(Beale, 2022)**.Animals also possess behavioral adaptations, such as selective foraging, to minimize toxin ingestion, complemented by physiological and microbial mechanisms for internal detoxification**(Launchbaugh, 2001)**.

***Microbial and plant-based bioremediation*:** In environments contaminated with persistent pesticides, the use of microbial degradation (bioremediation) and phytoremediation (plant-based remediation) is an emerging strategy for detoxification. Microbial systems can break down hazardous organochlorines and other pollutants, transforming them into environmentally innocuous products **(Chaudhry, 1991)**. Similarly, plants accumulate or transform environmental contaminants, providing cost-effective and sustainable remediation options **(Arthur, 2005)**.

Case studies and examples: Honey bees deploy metabolic and antioxidant pathways to tolerate dietary toxins such as nicotine, which has implications for pesticide risk assessment in pollinator health **(Rand, 2015)**.Insects exposed to certain phytotoxins, like myrigalone A, induce a phased detoxification program affecting hormone and antioxidant gene networks **(Nakabayashi, 2022)**.Integrated pest resistance management and breeding for increased detoxification capacity can lower dependency on chemical control methods and mitigate environmental impacts. Detoxification of plant toxins and pesticides is a multifaceted process involving coordinated enzyme systems, genetic regulation, symbiotic interactions and behavioral strategies. Evolutionary pressures from both natural and synthetic toxins drive the continual adaptation of detoxification mechanisms in plants, animals and microbes. Leveraging these natural processes can enhance crop and livestock resilience, reduce pesticide residues in food and remediate contaminated environments for sustainable agriculture and health.

Immune system modulation and pathogen protection: The insect microbiome is intimately involved in shaping the host's immune system. Commensal microbes can prime insect immune responses, making them more resistant to pathogen attack (**Gupta et al., 2022**). Conversely, some symbionts can directly produce antimicrobial compounds that inhibit the growth of pathogens, offering direct protection to the host (**Berasategui et al., 2016**).

Reproduction and development: The microbiome can influence various aspects of insect reproduction, including fecundity, fertility and even mate choice (**Napitupulu, 2023**). In some cases, specific microbial strains can alter host reproductive strategies, such as the *Wolbachia* bacterium which can induce cytoplasmic incompatibility, leading to reproductive manipulation in its host insects (**Goodyear et al., 2023**). The microbiome can also regulate developmental processes like molting and metamorphosis by influencing hormone production (**Number Analytics, 2025**).

Behavioral modulation: Microbial metabolites can act as semiochemicals, influencing insect behavior, including aggregation, foraging and mating cues. Disrupting these microbial signals offers a novel approach to altering pest behavior and reducing crop damage (**Preprints.org, 2025**).

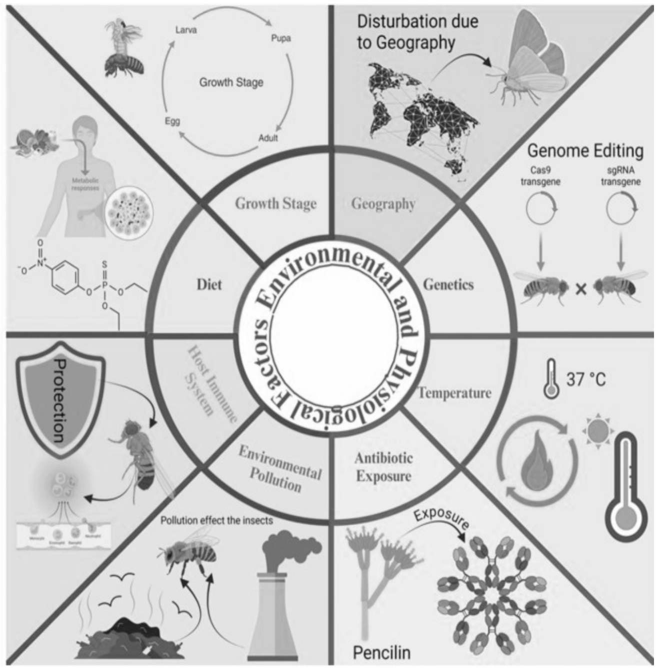

Figure 1:The intricate physiological and environmental aspects affecting insects are depicted in the larger, real image. The embryonic stage, the transition from egg to adult and additional metabolic processes regulated by diet are its main concerns. While genetic sources, such as gene editing using Cas9 and sgRNA, include adaptation and evolution, insect growth is also impacted by location and perturbation **(Haider et al., 2025).**

Implications for pest management

The deep understanding of insect-microbiome interactions has opened exciting new avenues for sustainable pest management, moving beyond broad-spectrum chemical interventions. The evolution of pesticide resistance is a pressing concern, particularly due to over-reliance on chemical controls. Resistance in pests such as the diamondback moth (*Plutellaxylostella*) and various aphid species has rendered many conventional pesticides ineffective, necessitating diversified management approaches (**Whalon et al., 2008**). This drives research into alternative control methods, including RNA interference (RNAi), microbial biopesticides and pheromone-based mating disruption (**Isman, 2006; Christiaens et al., 2020**).

Microbial biopesticides: While entomopathogenic microorganisms like *Bacillus thuringiensis* (Bt) have been used as biopesticides for decades, advances in microbiome research are enhancing their efficacy. By understanding the host microbiome, it may be possible to engineer or select microbial biopesticides that are more targeted and potent against specific pests, minimizing harm to non-target organisms (**Harnessing the Microbiome, 2025**).

Table. 3: Microbial Biopesticides.

Microbial biopesticides	Efficacy
Trichoderma spp.	Antagonistic fungal agents used widely for controlling several pests and as plant growth enhancers. It is also used for production of commercially important enzymes-hemicellulases, proteases, 1, 3-glucanase and cellulases
Pseudomonas fluorescens	This bacteria controls root rot and wilts diseases of banana, bean, cotton, groundnut, pigeon pea, soya and tomato. It is also effective against s the rice blast and sheath blight of paddy.
Beauveria bassiana	It is infectious against 200 insect hosts and can also be used in the management of various species of termites, grasshoppers, pyrilla of sugarcane, root grub, coconut *Rhinoceros* beetle brown plant hopper (BPH) in paddy and coffee berry borer
Lecanicillium lecanii	It is used against soft bodies, sucking type pests, present in green house conditions. It is highly effective against thrips, aphids, hoppers, scales, mites and whiteflies.
Nomuraea rileyi	It acts as a natural mortality factor in some major lepidopteran insect pests like *Helicoverpa* sp., Semiloopers, *Spodoptera* sp., cutworms in transitional climates with high humidity.
Hirsutella thompsonii	A pathogenic fungus which causes infection in mites present on crops, fruits and plantation crops. It can be easily mass produced on carbon rich substratum particularly rice and sorghum. It is facultative in their nature.

Symbiont-targeted pest control: Manipulating key insect symbionts to disrupt essential physiological processes offers a highly specific control strategy.

- **Antibiotic treatment:** In laboratory settings, the use of antibiotics to destroy insect gut symbionts has been shown to increase insect mortality and susceptibility to insecticides (**Siddiqui et al., 2022**). While direct field application of antibiotics is not feasible, this demonstrates the principle of targeting symbionts.
- **Paratransgenesis:** This involves genetically modifying symbiotic bacteria to express molecules that interfere with insect development, reproduction, or pathogen transmission. A notable success is the use of *Wolbachia* bacteria to suppress mosquito populations and reduce the transmission of diseases like dengue (**Manipulating insect microbes, 2021**).
- **CRISPR/Cas9 and RNAi:** These advanced genetic tools allow for precise manipulation of insect gut symbionts, altering their functions to the detriment of the insect host (**Siddiqui et al., 2022**). For example, RNAi can be used to silence genes in symbionts that are crucial for host survival or detoxification.

Disruption of microbiome-mediated resistance: Given the role of gut microbiota in pesticide degradation, strategies can be developed to disrupt these microbial pathways, thereby re-sensitizing pests to existing insecticides. This could involve identifying and targeting the specific microbial enzymes responsible for detoxification (**Kikuchi et al., 2012**).

Host-microbiome engineering: This ambitious approach involves genetically modifying the insect host itself to alter its microbiome, introducing traits that render it less harmful, less fertile, or more susceptible to natural enemies. This is an emerging field with significant ethical and practical considerations.

Integrated pest management (IPM) enhancement: Microbiome-based strategies are highly compatible with IPM principles, offering specific, environmentally friendly tools that can be integrated with other control methods. This includes using microbiome-boosted baits, pheromone disruption techniques informed by microbial signaling and targeted microbial management for location-dependent solutions (**Preprints.org, 2025**).

Implications for ecosystem health

Beyond pest management, insect-microbiome interactions have profound implications for the health and functioning of entire ecosystems. Nutrient Cycling of Insects, often aided by their microbiomes, are critical decomposers, breaking down organic matter and facilitating nutrient cycling in terrestrial ecosystems (**MsangoSoko et al., 2020**). For instance, cellulose-degrading bacteria in insect guts contribute significantly to carbon and nitrogen cycles. Pollination services,while the direct role of the insect microbiome in pollination is an active area of research, it can indirectly influence pollinator health and fitness by providing essential nutrients and modulating immune responses (**Number Analytics, 2025**). Healthy pollinator populations are vital for maintaining plant diversity and agricultural productivity. Ecosystem Resilience,the microbiome can mediate insect resilience to environmental stressors, such as heat extremes and pesticide exposure (**Maggu et al., 2025**). Understanding these microbiome-mediated buffering capacities is crucial for predicting and mitigating the impacts of climate change and anthropogenic disturbances on insect populations and the ecosystem services they provide. Biocontrol agents and beneficial insects,just as microbiomes can be manipulated for pest control, they can also be enhanced in beneficial insects (e.g., natural enemies, pollinators) to increase their efficiency and resilience. This could involve boosting their reproductive rates, resistance to pesticides, or overall fitness through targeted microbial interventions (**Manipulating insect microbes, 2021**).

Challenges and future directions

Despite the immense potential, the field of insect-microbiome interactions faces several challenges like Complexity of Microbiomes, Culture-Independent Methods and Functional Validation, Transmission and Persistence of Manipulated Microbiomes, Regulatory Frameworks and Public Acceptance and Ecological Cascading Effects**.** Insect microbiomes are highly diverse and dynamic, influenced by host genetics, diet, developmental stage and environmental factors. Unraveling the precise functions of individual microbial species and their complex interactions within the community remains a significant challenge. Advanced sequencing technologies (e.g., high-throughput sequencing, multi-omics approaches) are crucial for this endeavor (**Frontiers in Microbiology, 2022; Frontiers in Microbiology, 2019**).Many insect microbes are difficult to culture in the laboratory, making functional studies challenging. Developing robust culture-independent methods and techniques for functional validation (e.g., gnotobiotic insect models, synthetic communities) is essential. For field applications, ensuring the stable transmission and persistence of introduced or manipulated microbial strains within insect populations is critical. Understanding the ecological factors influencing microbial colonization and persistence is vital. The release of genetically modified microbes or insects with altered microbiomes will require careful consideration of regulatory frameworks and public acceptance. Transparent communication and thorough risk assessments are paramount. While targeting specific pests, it is crucial to consider potential non-target effects on beneficial insects or the broader ecosystem. A thorough understanding of ecological ramifications is necessary before widespread deployment of microbiome-based interventions. Future research will likely focus on developing more sophisticated tools for precise microbiome manipulation and identifying novel microbial strains with potent biocontrol potential. Understanding the interplay between insect host genetics and microbiome composition, integrating microbiome data with ecological models to predict outcomes of interventions and translating laboratory findings into practical, field-deployable solutions for sustainable agriculture and environmental conservation will also be future research.

CONCLUSION

The study of insect-microbiome interactions is transforming our understanding of insect biology and opening unprecedented opportunities for addressing critical challenges in pest management and ecosystem health. By harnessing the power of these intricate symbioses, we can move towards more specific, environmentally sound and sustainable strategies for controlling insect pests, while simultaneously enhancing the resilience and functionality of natural ecosystems. As research continues to unveil the hidden complexities and immense potential of the insect microbiome, it promises a future where ecological balance and agricultural productivity can be achieved in greater harmony.

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Conflict of interest

Author has no conflict of interest

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