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FEATURING

- From Giant Scales to Minute Pit Scales: The Enduring Legacy of Harold Morrison and Louise M. Russell
- A Conversation with a Woman Who Shaped Plantation Entomology in India: Dr. Chandrika Mohan
- TÊTE-À-TÊTE with Dr. T. V. K. Singh
- El Niño and Indian Insect Biodiversity: Understanding Climate Variability and its Ecological Consequences

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Cover page image: Mating Pair of Grey pansy, *Junonia atlites* (Lepidoptera) submitted by Mr. Rahul Babanrao Bhende from Wardha district Maharashtra, India.

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EDITORIAL

AI and NextGen Entomologists: Use it to Learn, not to replace Learning

Artificial intelligence (AI) is increasingly being incorporated into scientific education and research, and entomology is no exception. AI opens new possibilities for students and researchers, ranging from automated insect identification and image-based pest recognition, to literature discovery, molecular analysis, data interpretation and scientific writing. The critical question for the next generation of entomologists is not whether to use AI but how to use it responsibly. Entomology is an observational and evidence-based science. Correct identification of an insect requires knowledge of morphology, biology, ecology, behavior, distribution and increasingly, molecular characters. Artificial intelligence can help with these processes but should not replace the development of these foundational skills. An AI-generated identification is a hypothesis and only said to be accurate when it is tested using appropriate taxonomic keys, authoritative literature, reference specimens, expert knowledge or molecular evidence. In recent times we observe executive "help-seeking behaviour" of students that is looking for an immediate answer or fix to a problem rather than trying to understand the concept. This is not restricted to students only it extends to young faculty too.

Next generation entomologists should therefore view AI as a learning assistant rather than an answer generating machine. Instead of asking AI simply to provide the answer to an entomology question, students should use ai to explain difficult concepts, generate self-assessment questions, clarify terminologies or organize information for further reading. There are many examples in the field of entomology where young entomologists can use AI, like to understand difference between complete vs incomplete metamorphosis, principles of IPM, mode of action for insecticide etc. Later they must consult original and authoritative literature to confirm the authenticity.

Responsible use becomes particularly important in scientific writing. AI can help improve grammar, structure and clarity, but young entomologists should not submit AI-generated text as their own intellectual work. Scientific arguments, interpretations, observations and conclusions must originate from the researcher and be supported by evidences or references. AI will also suggest references but, references suggested by AI should always be checked against the original publication because AI systems can produce inaccurate, incomplete or even nonexistent citations. Similarly, students should never fabricate observations, experimental results, specimen records, statistical values or references with the help of AI.
AI also brings significant opportunities for entomology. Image recognition tools can assist with preliminary pest identification, machine-learning approaches can support automated insect monitoring; computer vision can quantify damage and AI can help analyse large datasets generated from biodiversity surveys, trapping projects and molecular studies. However, young entomologists should understand the limitations of datasets, model bias, false positives, false negatives and the importance of expert validation.

The goal of education is not merely to obtain correct answers, it is to develop the ability to observe, question, analyse, verify and think independently. If young entomologists use AI to avoid reading taxonomic literature, examining specimens, learning identification characters or understanding experimental

methods, they may become dependent on a tool without developing scientific competence. In contrary, when AI is used thoughtfully, it can make learning more interactive, accelerate routine tasks and allow young entomologists to spend more time on observation, experimentation and scientific reasoning.

It will be important that the future entomologist will likely work alongside AI, but not compete with it. The essential skill will therefore be neither rejecting AI nor accepting it unquestioningly, but learning to question, verify and responsibly use its outputs. Let AI help us identify faster, analyse better, summarize better and learn more but never let it replace the curiosity, observation and critical thinking that define an entomologist.

V.V. Ramamurthy and P.R. Shashank

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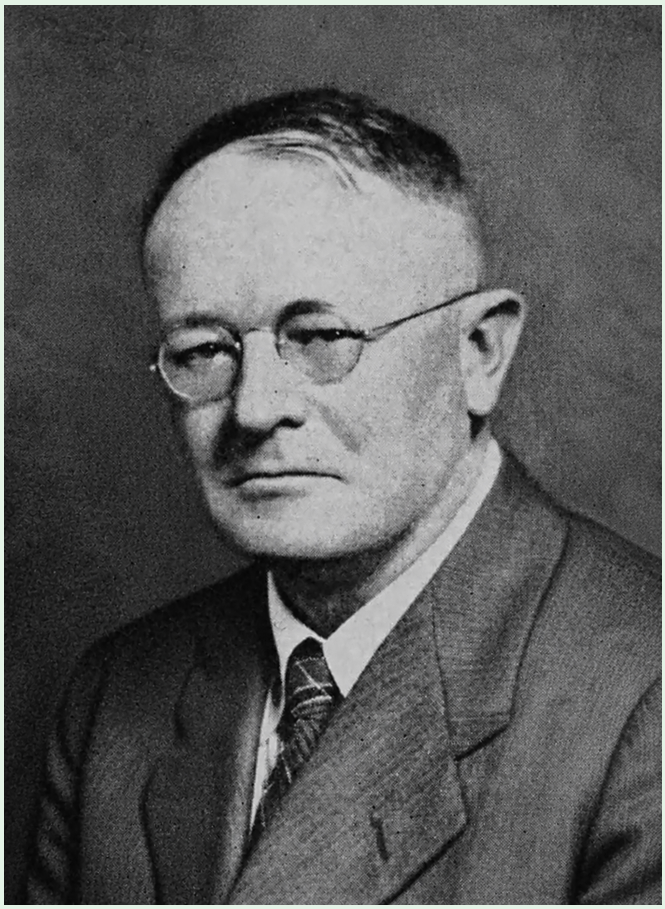
FEATURED ARTICLE

From Giant Scales to Minute Pit Scales: The Enduring Legacy of Harold Morrison and Louise M. Russell

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Harold Morrison (1890–1963)



Louise May Russell (1905–2009)

Classical taxonomy is often described as a science of details, and nowhere is this more evident than in the study of scale insects (Hemiptera: Coccomorpha). Long before molecular techniques, digital imaging and online databases transformed biological research, taxonomists relied almost entirely on painstaking slide preparation, careful microscopic observation and an intimate understanding of morphology. Every specimen demanded hours of preparation, every character required careful interpretation, and every published description reflected years of accumulated experience. Among the pioneers who elevated this discipline to the high standards

were Harold Morrison and Louise May Russell. Although they specialized in different groups of scale insects, Morrison in the comparatively large and morphologically complex giant scale insects (Margarodidae and Monophlebidae) and Russell in the minute pit scale insects (Asterolecaniidae), their scientific philosophy was remarkably similar. Their combined legacy continues to inspire generations of taxonomists.

Harold Morrison was born on 24 May 1890 in McCordsville, Indiana. His fascination with natural history was nurtured during his school years by an inspiring science teacher, Miss Rousseau McClelan, who encouraged his growing interest in Entomology. After studies at Stanford University and Cornell University under the celebrated Professor John Henry Comstock, he completed postgraduate work at Harvard University, earning the Doctor of Science degree in 1927.

Morrison's professional career began as the State Entomologist of Indiana, where he published his first studies on scale insects, including the comprehensive The Coccidae or Scale Insects of Indiana. In 1916, he joined the United States Department of Agriculture as a Plant Quarantine Inspector and later served as an Entomological Explorer in the West Indies, collecting scale insects and other arthropods. In 1920, he was appointed the USDA's scale insect specialist, a position he held until his retirement in 1960. He also directed the Bureau's taxonomic investigations during a formative period in its history.

To appreciate Morrison's achievements, one must remember the conditions under which he worked. Preparing permanent microscope slides was itself an art requiring patience and precision. Literature was scattered among journals published across the world, communication with fellow specialists was slow, and every identification demanded painstaking comparison with original descriptions and type material. Yet Morrison transformed the study of scale insects through meticulous observation and uncompromising scientific standards. He refined techniques for preparing permanent microscope slides and improved mounting methods that became standard practice for scale insects and other minute arthropods. His monumental work, A Classification of the Higher Groups and Genera of the Coccid Family Margarodidae, was the first classification of a coccid family based on all available developmental stages and remains a landmark in Systematic Entomology.

Morrison's influence extended well beyond his publications. Scientists from around the world sought his advice because they knew every enquiry would receive a thoughtful and carefully reasoned reply. The high esteem in which he was held is reflected in the numerous patronyms bestowed in his honour, with about 15 species bearing his name. He believed that taxonomy advanced through the free exchange of knowledge, and he gave unstintingly of his time to colleagues. His work was strengthened by the invaluable assistance of his wife, Emily Reed Morrison, an accomplished scholar, Cornell graduate, and his former assistant. She played a major role in bibliographic research and produced meticulous illustrations of the large, structurally complex scale insects that Morrison studied—a demanding task because of their elaborate appendages and densely setose bodies. Together they demonstrated that classical taxonomy often flourishes through dedicated scientific partnership.

One of Morrison's most enduring contributions was not a publication, but the encouragement he offered to a young scientific assistant. In 1927, Louise May Russell, a recent

Cornell graduate, joined the USDA as a Senior Scientific Aid to prepare microscope slides of scale insects. Morrison quickly recognized her exceptional aptitude for systematic work and encouraged her to apply for a professional position. She was appointed Junior Entomologist in 1929, beginning a remarkable scientific career that would eventually place her among the foremost authorities on Sternorrhyncha.

Born on 6 May 1905 on a farm in Crown Point, New York, Russell belonged to a generation in which relatively few women pursued postgraduate education in science. After obtaining Bachelor's and Master's degrees from Cornell University, she devoted almost her entire professional life to the USDA. Her ability and dedication were rewarded with successive promotions until she became a Senior Research Entomologist and later headed a research unit.

Although Morrison became synonymous with the study of margarodids and monophlebids, Russell established herself as the world's leading authority on pit scales. Her classic 1941 monograph on Asterolecaniidae remains one of the finest examples of systematic revision in the Coccoidea. She described 84 new species, and remarkably, none has subsequently been synonymized—a rare distinction that speaks eloquently of the accuracy of her observations and the quality of her scholarship. During a scientific career spanning nearly eight decades she published 106 scientific papers, including 31 on aphids, 28 on whiteflies, nine on scale insects, seven on psyllids, two on cicadas, and one on cercopids. Even more extraordinary, her final scientific paper appeared when she was 101 years old.

Russell's contribution extended far beyond research publications. She identified nearly 50,000 lots representing more than 2,00,000 specimens, providing an indispensable service to quarantine, pest management, and systematic research. She also enriched the National Collection through fieldwork and by securing important reference collections for future generations. Following mandatory retirement in 1975, she continued to work voluntarily for more than twenty-five years, travelling regularly to the laboratory well into her nineties because she simply loved studying insects mounted on microscope slides. Scientists throughout the world admired not only her scholarship but also her generosity in helping others. She spent considerable time helping others and was honoured by scientists worldwide for this effort with numerous patronyms—three genera and 23 species. Although she never earned a doctoral degree, she served on several graduate student committees and was affectionately known to many simply as "Dr Russell"—a mark of the immense respect she commanded among her peers.

The careers of Morrison and Russell beautifully illustrate that the size of the organism never determines excellence in taxonomy under study. Morrison devoted himself to the comparatively large and structurally elaborate margarodids, whereas Russell unravelled the taxonomy of the minute pit scales. Yet both relied on the same principles: painstaking slide preparation, meticulous microscopic examination, careful illustration, exhaustive study of the literature, and an unwavering commitment to scientific accuracy. Their classic monographs remain indispensable references decades after publication because they were built upon rigorous observation rather than convenience. They also shared another quality that distinguished the finest naturalists of their generation—a willingness to help colleagues freely and generously, recognizing that taxonomy

progresses through collaboration and the sharing of knowledge.

For many coccidologists of my generation, the works of Morrison and Russell were not merely references on a library shelf but constant companions at the microscope. Their monographs, identification keys, illustrations and meticulous descriptions guided countless identifications, resolved difficult taxonomic problems and quietly shaped the way we approached systematic research. In remembering them, we honour not only two extraordinary scientists but also a tradition of careful observation, intellectual honesty and selfless service that continues to inspire every taxonomist devoted to the fascinating world of scale insects.

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TÊTE-À-TÊTE

From Insect Ecology to Sustainable Agriculture: A Visionary Journey in Entomology, Innovation, and Farmer-Centric Science.

- An Inspiring Conversation with Prof. T.V.K. Singh

Prof. Thakur Vinod Kumar Singh (T.V.K. Singh) is an eminent agricultural entomologist with over four decades of distinguished contributions to teaching, research, extension, academic administration, and institutional development. He obtained his **B.Sc. (Agriculture)** with distinction from the College of Agriculture, Rajendranagar (1976), **M.Sc. (Entomology)** from Andhra Pradesh Agricultural University with a State Fellowship (1978) and **Ph.D. in Entomology** from the Indian Agricultural Research Institute (IARI), New Delhi, under the ICAR Senior Research Fellowship (1989). He also underwent specialized training in **Insecticide Resistance** at the **University of Florida, USA**, as a FAO Fellow.

During his illustrious career, Prof. Singh served in several key academic and administrative positions, including **Senior Professor, Vice Principal, Principal, Associate Director of Research, Dean of Agriculture, Director of Extension, and Comptroller** in ANGRAU and PJTSAU. He has significantly contributed to agricultural education and research through curriculum development, national monitoring committees, QRT committee member, ICAR review missions, and university governance.

His research has primarily focused on **insect ecology, population dynamics, insecticide resistance, integrated pest management (IPM), resistance monitoring, ecological modelling, and molecular characterization of resistance in major agricultural insect pests**. He established the **Insecticide Resistance Monitoring Laboratory** at PJTSAU and pioneered the **F_1 screening technique** for estimating resistance to Bt cotton in India along with his students. His work on resistance allele frequency, fitness costs, and resistance management strategies in *Helicoverpa armigera* and *Spodoptera litura* has received national recognition.



Dr. T.V.K. Singh

(Former Dean of Agriculture & Former Emeritus Scientist, PJTAU, Rajendranagar, Hyderabad-500030, India)

Prof. Singh has published **over 170 research papers**, authored **13 books**, contributed **4 book chapters**, edited **2 books**, and delivered more than **40 keynote and lead lectures** at national and international conferences. He has successfully guided **15 M.Sc. and 5 Ph.D. students** as Major Advisor and served as Minor Advisor to more than **30 postgraduate scholars**.

He is a **Fellow of the Royal Entomological Society (London),**



Prof. TVK Singh addressing during inaugural session of Entomology 2022: Innovations & entrepreneurship

Linnean Society of London, Entomological Society of India, Plant Protection Association of India, and Indian Society of Oilseeds Research. His contributions to agricultural education have been recognized with the **University Meritorious Teacher Award (1996)** and the **State Meritorious Teacher Award (2007)**.

Following his retirement, Prof. Singh served as the **first ICAR Emeritus Scientist at PJTSAU**, **Consultant at ICRISAT**, **Adjunct Professor**, **Visiting Professor**, and **Chief Content Reviewer for the Plantix mobile application (PEAT GmbH, Germany)**. He has trained more than **4,000 farmers** under joint program of Society for Elimination of Rural Poverty (SERP), government of A.P and ICRISAT, Farmer Producer Organizations (FPOs) and agricultural officials across India and abroad on crop production, integrated pest management, and sustainable agriculture.

At present, Prof. T.V.K. Singh is serving as **Chief Editor of the Indian Journal of Plant Protection** and **Editor of the Indian Journal of Ecology**, and is a member of the editorial boards of several reputed national and international scientific journals. His lifelong contributions have established him as one of India's leading authorities in agricultural entomology, insect ecology, and insecticide resistance management.

MR (Dr. M. Rajashekhar): Sir, Tell something about your early life?

TVK (Dr. TVK Singh): Born in a teachers' family and from childhood, learning and education atmosphere existed. Studied in Hindi medium. Ours was the first batch of SSC, and Intermediate. As a Science student, only one goal was to become Doctor. Wrote MBBS entrance test which was conducted by Government for the first time, could not get through entrance. I feel lucky that I could

not get through M B B S entrance. Destiny brought me to this Profession. Truly speaking I did not know that agriculture is being taught as a subject. One of my mother's colleagues brought the application form, filled it, got admission and joined B.Sc. (Agril.) degree programme. That's how my journey begun.

MR: Sir, Who are your role models?

TVK: In my childhood days, my mother, aunt and maternal grandmother were role models who themselves were teachers, who taught me to be sincere, possess dignity, have patience and be disciplined in life. In our undergraduatation days, Entomology as a subject was taught from second year onwards. First course was taught by **Late Prof. G.P.V. Reddy**, who was a very dedicated teacher. His style of teaching attracted many students, his teaching was unique and it appears that it's coming from his heart. I am lucky that later he became my M.Sc. Guide. In fact I consider him my role model because of his teaching only, I choose Entomology as my professional career. Truly speaking, I try to learn and imbibe few qualities of every one specially teachers. Few faculty members who influenced my professional career and teaching are Dr.K.S.R.K. Murthy, Dr.T.B. Gour, Dr.K.N.Mehrotra and Sri.Sunil Kumr (student of Birch, famous Insect Ecologist). Another role model of mine and to whom, I owe a lot is **Late Dr. K.M. Singh**, my Ph.D. Chairman who was a perfect human / gentlemen. Infact I learnt humility, empathy, integrity, patience from Dr. K M Singh. To me Dr.G.P.V. Reddy and Dr.K.M. Singh are not only teachers but they are real Gurus, whom I adore a lot.

MR: What fascinated you about insects during your formative years?

TVK: For me, born in city and never exposed



Prof. TVK Singh interacting along with Honorable Vice chancellor & university officers with Late Dr. S. Ayyappan (DG-ICAR).



Prof. TVK Singh receiving best teacher award from the hands of Late Dr. Y.S. Rajashekhara Reddy (Chief minister of A.P.)

to village life, insects remained a group of nuance creatures and to name them bed bugs, mosquitoes, houseflies and cockroaches. I had limited exposure to the vast diversity of insects except studying about honeybees and silk worms in Intermediate course. My interest in Entomology and to be an entomologist begun in graduation, wherein I had wonderful teachers of APAU, who kindled interest in the subject.

MR (Dr. M. Rajashekhar): Sir, being a teacher, what should be the qualities of a Good teacher?

TVK: I always treated teaching as the most Noblest Profession. For me each class is similar to that of going to temple, like worshipping God. One should respect and show kindness to students. A teacher must be clear and engage actively in teaching viz., explain things clearly and in simple language, use fun or creative methods to make lessons interesting. A teacher must be a good communicator with fairness towards one and all students. He should have lot of passion and energy. One must enjoy teaching and shows enthusiasm. Teacher must be supportive and helpful. He must remain student throughout life learning new things and passing it on to students.

MR: As an eminent entomologist specializing in Ecology, Toxicology, Transgenics, and IPM, how do you perceive the transformation of Entomology over the last few decades?

TVK: In my view, entomology especially agricultural entomology has undergone a massive transformation. It has evolved from basic chemical pest control during the Green Revolution into a sophisticated, sustainable science. Today, our

discipline integrates pest forecasting, Host Plant Resistance (HPR), and Artificial Intelligence (AI) to ensure global food security and sustainability.

Immediately after independence, our primary focus was to prevent famines and overcome severe food shortages. We relied heavily on aggressive crop protection to achieve food self-sufficiency. During the Green Revolution era, High-Yielding Varieties (HYVs) were introduced, but they were highly susceptible to pests. To protect them, we relied heavily on organochlorines and organophosphates (OPs), which eventually triggered severe ecological imbalances like pest resistance, resurgence, and other environmental hazards.

This paved the way for the Era of IPM, which combined cultural practices HPR, and biocontrol. The period from 1990 to 2010 can be defined as the Era of Biodiversity and Biotechnology, highlighted by the introduction of Bt cotton in India. Post-2010, we entered the Era of Digital Entomology. New frontiers have emerged, such as digital and AI-based forecasting, invasive pest management, nanotechnology, and insect DNA barcoding. I am heartened to see many young entomologists driving research in these areas. Today, the impact of climate change on insect pests and the role of agroecology have gained immense significance. We are now deeply focused on conserving agriculturally vital insects, particularly pollinators and predators.

MR: In your opinion, why is Entomology considered one of the most dynamic and strategically important disciplines in ensuring global food and nutritional security?

TVK: Entomology is undeniably dynamic and strategically vital because insects represent over half of all living organisms. They are highly diverse and exceptionally adaptable to changing environments. When discussing global food security, insects play dual, critical roles as both vital pollinators and destructive agricultural pests. As pollinators, they are essential for human survival, with around 75% of our crops depending on them for fruit and seed set. Modern research is also exploring insects as viable alternative protein sources.

Furthermore, many insect species act as vectors for deadly diseases such as malaria, dengue, and kala-azar. By understanding their biology, we can track outbreaks and devise precise control strategies. Because insects are highly sensitive to environmental changes, they also serve as excellent bioindicators for ecosystem health, pollution, and climate shifts. Finally, we see the rise of a circular bioeconomy pioneered by innovations like the Black Soldier Fly, which efficiently converts organic waste into high-quality animal feed and protein.

MR: Sir, modern agriculture is facing increasingly complex pest scenarios. What are the biggest challenges currently confronting the field of crop protection?

TVK: In my opinion, the complex pest scenarios and invasive pest outbreaks confronting modern agriculture especially in the Indian context are largely man-made, driven by systemic greed. The primary culprits are widespread monocropping, an over-dependence on synthetic pesticides, and the overarching effects of climate change. Compounding this issue is the status of Indian soils, which are severely depleted of essential nutrients, indirectly impacting plant health, defense mechanisms, and overall crop productivity.

MR: Climate change is dramatically influencing insect behaviour and pest outbreaks worldwide. From your

scientific perspective, how do changing climatic conditions alter pest ecology and management strategies?

TVK: To understand how climate change accelerates pest outbreaks, we must look at the key drivers: shorter insect life cycles, polyphagous feeding habits, expanding geographical ranges, congenial microclimates, and the continuous availability of host plants. Paradoxically, climate shifts can also alter insect metabolism, leading to extended feeding windows.

Consider the recent devastating outbreaks of the invasive Fall Armyworm (*Spodoptera frugiperda*). FAW became a global agricultural menace due to its extraordinary migratory range, rapid breeding cycle, and ability to feed on over 353 different plant species. Its short life cycle, high reproductive capacity, voracious feeding habits, and cryptic (hidden) behaviour made it exceptionally destructive. Its rapid spread was further aggravated by a lack of native natural predators in newly invaded regions and its rapidly developing resistance to common insecticides.

Similarly, the outbreak of the invasive Chilli Black Thrips (*Thrips parvispinus*) is directly linked to warmer temperatures and high humidity, coupled with the indiscriminate overuse of insecticides and extended crop seasons. This resilient species has aggressively displaced native thrips populations infesting chilli crops across India.

Climate change is centered around global warming, elevated temperatures, rising atmospheric CO_2 levels, frequent droughts, and erratic rainfall patterns. Elevated temperatures directly accelerate the reproduction, development, behavior, and geographical distribution of pests. Furthermore, our generation is witnessing a significant rise in atmospheric CO_2. Higher CO_2 alters plant physiology and weakens natural plant defense mechanisms against herbivores. While elevated CO_2 allows plants to grow faster, it dilutes their nutritional value by altering carbon-to-nitrogen ratios. Consequently, insect pests exhibit compensatory feeding, consuming significantly more foliage to meet their nutritional needs.

These climate shifts disrupt traditional pest management. We must adapt our strategies by modernizing our monitoring networks, moving away from fixed calendar-based spray schedules, increasing the use of biopesticides, adopting targeted chemical applications, and enforcing crop diversification.

MR: Sir, how important is ecological understanding in designing resilient and environmentally sustainable pest management systems for the future?

TVK: Ecology is the fundamental pillar of sustainable plant protection; its primary principle is to shift pest management away from chemical dependency toward preventive, nature-based solutions. Sustainable pest management is deeply aligned with IPM, serving as an ecologically sound, environmentally friendly, and economically viable approach focused on minimizing pesticide usage through a combination of holistic practices.

This approach is vital because it preserves biodiversity, protects soil health, minimizes chemical residues, and safeguards human and environmental well-being. To leverage ecology as a driver for sustainable management, we must deeply analyze predator-prey dynamics, insect life cycles, phenology, and how climate variations alter plant-pest relationships. The future of pest protection relies on Ecological Engineering, pheromone traps, biopesticides, climate-resilient crop varieties, and biotechnology, supported by precision tools

like drones, IoT sensors, and AI for early pest and disease identification.

MR: With increasing concerns over pesticide resistance, residue issues, and environmental safety, what should be the future direction of Integrated Pest Management (IPM) research and implementation?

TVK: Pesticide Resistance (PR) stands as one of the most critical challenges in modern agriculture, driven primarily by the chronic misuse and overuse of chemical inputs. In India, numerous agricultural and public health pests have already developed widespread resistance. In agriculture, major pests like the Cotton Bollworm (*Helicoverpa armigera*), Pink Bollworm (*Pectinophora gossypiella*), Tobacco Caterpillar (*Spodoptera litura*), and Whitefly (*Bemisia tabaci*) show high resistance levels. In public health, vectors like *Anopheles* and *Aedes* mosquitoes, houseflies, and bedbugs present similar challenges.

To effectively delay and manage pesticide resistance, future IPM research and implementation must reduce reliance on single chemical classes. We must prioritize the rotation of insecticides with distinct, diverse modes of action, implement habitat manipulation, expand the use of biopesticides, and strictly enforce applications based on verified Economic Threshold Levels (ETLs).

MR: As a specialist in toxicology and transgenics, how do you evaluate the role of biotechnology and genetically engineered crops in future insect pest management programs?

TVK: In its early years, ecology was viewed largely as an academic or colonial pursuit, but it has since evolved into a robust, multidisciplinary applied science. Following Independence, India faced severe food shortages; consequently, the focus of ecological research shifted toward applied agricultural entomology to minimize harvest losses, as our nation could simply not afford to lose food to pests.

Here, I must honour the memory of the late **Dr. S. Pradhan**, universally revered as the *Father of Modern Applied Entomology in India*. He pioneered the development of the biometer and biograph, revolutionized desert locust management, and proposed the definitive 'Biotic Theory' of locust cycles. Dr. Pradhan was a true visionary who conceptualized the "Plant Protection Umbrella" and realized very early that agriculture could not solely rely on chemical inputs. He was instrumental in shifting our country's crop protection strategy toward Integrated Pest Management (IPM).

While the Green Revolution achieved food security, its intensive agricultural practices and monocropping systems inadvertently triggered outbreaks of secondary pests. By the 1990s, our research shifted decisively toward ecological IPM, as it became clear that exclusive reliance on chemicals was neither ecologically viable nor economically sustainable.

Lately, our ecological research has shifted toward monitoring and mitigating invasive alien pests. We have transitioned from basic population dynamics, life-table studies, and the documentation of biotic factors to cutting-edge genomic studies designed to resolve cryptic species complexes. Furthermore, comprehensive studies on the multi-trophic effects of global warming and climate change are now in full vogue across state agricultural universities and national institutes.

In population dynamics, we continue to rely on life tables and the calculation of the intrinsic rate of increase for key economic pests, while

measuring how shifting abiotic factors influence pest generations. Mathematical modeling and forecasting are also being utilized but not to a significant extent. Today, considerable research is also being channelled into chemical ecology, focusing on plant secondary metabolites, semiochemicals, sex pheromones, and herbivore-induced plant volatiles (HIPVs) to manipulate pest behavior naturally.

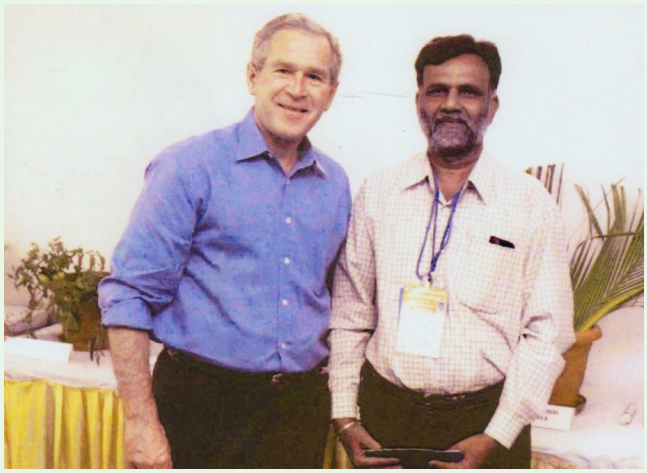
MR: Sir, how can young scientists integrate modern tools such as AI, precision agriculture, genomics, remote sensing, and digital pest surveillance into contemporary entomological research?

TVK: I am immensely gratified to see that many of our younger entomologists are seamlessly merging traditional field work with cutting-edge technology. They are utilizing machine learning algorithms and Artificial Intelligence (AI) for automated insect identification and automated tracking of adult flight patterns.

Young researchers are also actively employing CRISPR-Cas9 gene-editing tools to engineer pest susceptibility or drive population suppression. The field is expanding rapidly with the integration of automated IoT field sensors, smart pheromone traps, high-resolution hyperspectral imaging, and drone-based precision pesticide delivery systems.

MR: What future thrust areas in Entomology do you believe deserve priority attention to address emerging agricultural and ecological challenges?

TVK: Future entomological programs must be oriented toward integrating new, cutting-edge technologies with core basic and applied sciences. Drawing from my personal and research experience, I believe the following thrust areas deserve



Prof. TVK Singh with George W. Bush (President of U.S.A) during his visit to ANGRAU in 2006.

immediate, prioritized funding and attention. Developing macro-level predictive models for pest outbreaks using real-time GIS and satellite data; Studying the detailed biochemical and physiological effects of elevated CO_2 and ambient temperatures on insect biology, host defenses, and compensatory feeding; Investigating how changing climatic parameters alter insect vector-pathogen relationships and transmission efficiencies.

Rigorously monitoring insect biodiversity to protect native pollinators, soil-dwelling decomposers, and natural predatory complexes; Accelerating whole-genome sequencing of major economic pests and beneficial insects, alongside the molecular characterization of insecticide resistance mechanisms; Establishing a synchronized, nationwide digital network for monitoring insecticide resistance levels in real time and Developing eco-friendly nano-formulations and micro-encapsulated biopesticides to ensure targeted delivery with minimal environmental residue.

MR: In your opinion, how can agricultural universities make Entomology education more innovative, interdisciplinary, and globally competitive for present-day students?

TVK: Globally, agricultural entomology is undergoing a paradigm shift, transitioning from conventional pest control to a dynamic matrix of ecology, genomics, and digital technology. To keep pace, our agricultural universities must immediately modernize their course curricula. Currently, a significant portion of our academic syllabi remains outdated, focused almost exclusively on basic taxonomy, chemical insecticides, and standard pest management routines. While the subject is advancing rapidly elsewhere, I am pained to observe that the number of entomology courses has actually been reduced in several of our domestic universities.

To bridge this global gap, we must integrate advanced, forward-looking subjects into the core curriculum, such as Insect Genomics, Bioinformatics, Invasion Biology, Computational Entomology, and the application of AI and Machine Learning in Pest Forecasting.

We must foster interdisciplinary education and research. Universities should establish specialized Centres of Excellence in niche domains where foundational infrastructure and expert faculty are already available. Our academic research must shift toward solving real-world agricultural problems to build robust industry linkages, backed by strengthened, field-based experiential learning.

MR: Sir, many students perceive Entomology as a difficult subject. How can educators inspire young minds to develop a genuine passion and curiosity toward insect science and crop protection?

TVK: Entomology is frequently perceived as a difficult or dry subject in agricultural universities primarily because students assume they are simply expected to memorize an overwhelming number of scientific names and taxonomic keys. In reality, this is a misconception; it is one of the most vibrant, interactive, and lively disciplines in agriculture.

Educators can make the subject incredibly engaging by moving away from rote learning and shifting toward hands-on, practical experiences. Engaging students in active laboratory rearing of insects allows them to observe live, fascinating transformations across an insect's life cycle firsthand. Encouraging students to conduct active field collections, bringing specimens back to the laboratory, sort them taxonomically, and systematically spread their wings and body parts builds strong morphological clarity.

Excursions: Organizing academic visits to butterfly parks and natural reserves sparks natural curiosity. Leveraging interactive mobile identification applications and encouraging macro-insect photography blends modern student hobbies with scientific observation.

Ultimately, the responsibility rests on the teacher's ability to innovate inside the classroom and ignite that initial spark of curiosity.

MR: Sir, how important is direct farmer interaction and field exposure in shaping a socially responsible and practically oriented entomologist?

TVK: For any agricultural graduate, direct farmer interaction and experiential field exposure are absolutely critical to evolving into a competent, practical professional. An entomologist must be inherently passionate and inquisitive, possessing a natural drive to step out of the laboratory and visit actual farms.

Time and again, whenever we interact with the farming community, their most urgent field queries relate directly to plant protection, pest outbreaks, and yield losses. While theoretical knowledge provides the necessary foundation, it is

practical field exposure that cements the subject deep into a scientist's perspective.

Above all, it is our core social responsibility to guide farmers, helping them protect their crops, secure their livelihoods, and drive national food security and economic growth. By visiting rural fields and engaging in unstructured interactions with farmers, we also learn invaluable lessons from indigenous technical knowledge (ITK) and time-tested rural traditions that no textbook can replicate.

MR: Sir, what opportunities do you foresee for entomologists and plant protection graduates in private-sector crop protection industries, agri-biotech companies, and agri-tech startups?

TVK: The landscape has changed dramatically over the last twenty years, opening up a universe of diverse, lucrative opportunities for young entomologists who possess genuine passion and operational zeal. In earlier days, postgraduate options in entomology were highly restricted; a graduate had to choose between the ICAR system, state agricultural universities, or conventional corporate pesticide marketing.

Today, the private sector has expanded far beyond the traditional agrochemical industry into global biotechnology firms and cutting-edge agri-tech startups. Within the modern corporate agrochemical sector, a graduate can thrive as a Specialized Toxicologist, Field Biologist, or Product Development Manager. Conversely, in the fast-growing agri-biotech domain, positions are open for Molecular Entomologists and Transgenic Trait Specialists.

Exciting new niches are also emerging in digital and precision agriculture. Plant protection graduates are actively being recruited as high-value Agricultural Consultants, Remote Sensing Market Strategists, and Drone-IPM Operations Specialists. For any young professional willing to innovate and push boundaries, the sky is truly the limit.

MR: How can stronger collaboration between academia, research institutions, industries, and extension systems accelerate innovation in plant protection sciences?

TVK: The traditional system where academia researches in a vacuum, industry sells independently, and extension networks struggle to pass on outdated line-department recommendations is no longer viable.

An optimized collaborative framework should operate across four key pillars:

Academia & Research Institutions: Universities and ICAR bodies must focus their post-graduate research on industry-vetted challenges. Instead of publishing isolated papers on baseline biology, academic laboratories should partner with private R&D centers to co-develop molecular diagnostic tools, map insect resistance genes, and validate eco-friendly biological molecules.

Private Industry & Agri-Tech Startups: The corporate sector must invest heavily in academia through targeted research grants, sponsored chairs, and dedicated student incubation hubs. While major agrochemical and biotech firms can fund large-scale toxicology trials and commercialize nano-formulations, agile agri-tech startups can build the digital infrastructure such as training machine learning models on university insect-museum data to build real-time, automated field-diagnostic smartphone apps.

The Extension System: The transfer of technology must move from a slow, linear process to a real-time, digital pipeline. Krishi Vigyan Kendras



Prof. TVK Singh showing microscopic insects to Late Dr. Y.S. Rajashekhara Reddy

(KVKs) and Farmer Producer Organizations (FPOs) should act as live testing grounds where joint university-industry pilots are evaluated. When an invasive pest like *Thrips parvispinus* emerges, the extension network must instantly feed field data back to University and ICAR labs and industry product developers, enabling the rapid deployment of targeted, data-driven IPM responses.

Institutionalizing Joint Consortiums: We need to establish formal, permanent institutional platforms such as a National Plant Protection Consortium driven by bodies like the PPAI, Entomological Society of India, Ecological Society of India, Association for Advancement of Pest Management in Horticultural Ecosystems and many more. This consortium would bring scientists, corporate product heads, and policy makers together quarterly to align research agendas with actual market and field requirements.

By creating this continuous loop of data, funding, and field feedback, we can ensure that Indian plant protection sciences remain globally competitive, ecologically sustainable, and deeply impactful for the farmers we serve.

MR: Could you share your insights on *Helicoverpa armigera*, an insect pest you have dedicatedly researched for over 20 years?

TVK: The insect *Helicoverpa armigera* fascinates me immensely. When we were students, it was never taught as a major pest; indeed, you will look in vain for any significant mention of its pest status in older entomological textbooks. Today, *Helicoverpa armigera* commonly known as the Cotton Bollworm, Gram Pod Borer, or

Old-World Bollworm is recognized globally as a highly polyphagous, migratory moth and one of the most economically destructive agricultural pests, inflicting billions of dollars in crop damage annually.

The larvae are voracious feeders that attack over 180 plant species, targeting high-value crops such as cotton, tomato, maize, pigeon pea, chickpea, and soybean. Only the larval stage causes damage by boring directly into buds, flowers, and fruiting structures (bolls and pods). In cotton, their feeding leaves distinctive, clean-cut circular boreholes on fruiting bodies, triggers the yellowing and flaring of bracts, and leads to the premature shedding of squares and young bolls. The adults are exceptionally strong fliers, capable of migrating tens of kilometres in a single night, which allows massive populations to expand rapidly across vast geographical areas.

My personal journey with *H. armigera* began in the late 1990s while I was posted at Palem in erstwhile Mahabubnagar district of Telangana. I observed with grave concern that despite farmers in the Gadwal area spraying their cotton fields 15 to 20 times a season, the pest remained completely uncontrolled. This was followed by a devastating outbreak in the red gram (pigeon pea) crop during 1998 across the Vikarabad and Tandur belt of Ranga Reddy district. Driven by these crises, I initiated extensive toxicological research on *Helicoverpa*. Our preliminary bioassays on the resistance ratios of commonly used chemical molecules revealed staggering resistance levels, frequently exceeding 100- to 200-fold compared to susceptible baselines.

H. armigera stands out as an important agricultural pest due to its polyphagous nature, unique metabolic adaptations, high expression of detoxifying esterases, and reduced cuticular permeability via specific glycoproteins. The selection pressure applied by indiscriminate spraying has been exceptionally high. Throughout the late 1980s and 1990s, recurring outbreaks frequently resulted in regional agricultural calamities, wiping out substantial percentages of total yields. Due to the pest's high reproductive rate, continuous pesticide exposure, and short life cycle, it evolved widespread resistance. Populations of *Helicoverpa* exhibited massive often 50- to >100-fold—resistance to synthetic pyrethroids in India.

In the central and southern states of India, *H. armigera* developed extreme resistance to synthetic pyrethroids, alongside long-term, stable cross-resistance to conventional organophosphates and carbamates like quinalphos and methomyl. Worryingly, modern populations are also displaying reduced susceptibility to newer chemistries like spinosad and indoxacarb.

I also served as the District Coordinator for Mahabubnagar and the State Coordinator for Andhra Pradesh for the Technology Mission on Cotton (TMC) - Mini Mission II (MM-II). This major Government of India initiative was aimed at enhancing cotton production, productivity, and quality. Coordinated primarily by the ICAR-Central Institute for Cotton Research (CICR), this project served as a vital vehicle to transfer advanced plant protection technologies directly from laboratories to farmers' fields.

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WOMEN IN ENTOMOLOGY

A Conversation with a Woman Who Shaped Plantation Entomology in India: Dr. Chandrika Mohan



Dr. Chandrika Mohan is a distinguished entomologist and Principal Scientist at the ICAR–Central Plantation Crops Research Institute (CPCRI), Regional Station, Kayamkulam, Kerala. She started her career at ICAR- Indian Lac Research Institute, rebranded as ICAR-National Institute of Secondary Agriculture, Ranchi Jharkhand. With decades of experience in agricultural entomology, she has made significant contributions to the understanding and management of insect pests affecting India's major plantation crops, particularly coconut. She has received Father Gabriel Memorial Gold medal for 1st Rank in M.Sc. from Calicut University and secured 2nd Rank in MPhil in Zoology with entomology specialization.

Her research focuses on pest ecology, diagnosis, and sustainable pest management strategies, with a strong emphasis on biological control and eco-friendly approaches. Working at the interface of laboratory science, field research, and farmer-centric extension, Dr. Mohan has played a vital role in translating entomological research into practical solutions for coconut growers. Her work has helped address emerging pest problems and changing pest dynamics in plantation ecosystems, especially under the influence of climate variability.

Dr. Mohan has been actively involved in the identification and management of major and emerging insect pests, contributing to improved surveillance, advisory services, and integrated pest management (IPM) strategies. She has authored and co-authored several research papers, technical bulletins, and book chapters, and has contributed to national training manuals on palm and plantation crop health management. Her scientific outputs reflect a balance between rigorous research and applied relevance.

Beyond research, Dr. Mohan is deeply committed to extension and capacity building. Functioned as focal point expert from India in International Workshops organized by SAARC and FAO on coconut pest management. She has been closely associated with farmer outreach programmes, including Farmer Field Schools, field diagnostics, training programmes, and national initiatives such as Mera Gaon Mera Gaurav. Through



these efforts, she has strengthened the linkage between scientists and farming communities, ensuring that entomological innovations reach the field in a meaningful way.

In recognition of her contributions to plantation crop entomology, Dr. Chandrika Mohan received the Dr. K.K. Nirula Memorial Prize (2021) for her outstanding work in the biological suppression of coconut pests and delivered the inaugural Dr. K.K. Nirula Memorial Lecture at a national seminar. She is also a regular invitee at scientific conferences, webinars, and training programmes, where she shares her expertise with researchers, students, and extension professionals. She was associated with projects funded by NATP, ICAR-AP Cess fund, ICAR-out reach network projects, DBT, CFC/DFID/APCC/FAO, CDB and Kerala State Department of Agriculture on various IPM aspects of coconut.

As a woman scientist in a field-intensive discipline, Dr. Mohan's career stands as an inspiring example of perseverance, scientific excellence, and leadership. Her journey highlights the crucial role women play in strengthening applied entomology and sustainable agriculture in India. Through her research, mentorship, and extension work, she continues to contribute to resilient plantation crop systems and to the advancement of entomology as a discipline.

Bhagyasree S N (BSN): What inspired you to choose entomology as a career, and how did your journey lead you to ICAR-CPCRI?

Dr. Chandrika Mohan (CM): I was born and raised in the remote village of Anakkara in the Palakkad district, Kerala, where I completed my primary education in a government school (Malayalam medium). With a strong interest in biology, I pursued a B.Sc. in Zoology at Pattambi Government College.

For a girl from a small village, the common career choices were becoming a Bank Employee or a School Teacher. However, I felt neither of these paths aligned with my aspirations. Wanting to study further, I enrolled in the M.Sc. Zoology program at Government College Madappally, specializing in Entomology—an experience that ignited my deep interest in the subject.

After completing my M.Sc., I secured admission for an M.Phil. at Calicut University. It was during this time that I learned about the ARS exam from my seniors. Later, I joined the Ph.D. program at Calicut University, which helped me to realize that my passion lay in research. Encouraged by my seniors, I decided to attempt the ARS exam and was fortunate to secure the first rank in the subject (Entomology). This achievement was overwhelming, but the joy soon turned into anxiety when I received my posting order to the Indian Lac Research Institute in Ranchi (then Bihar)—a place far beyond what my family had ever imagined for me. I was unsure if I could continue pursuing my dream. However, my father, my greatest role model, supported me wholeheartedly and personally accompanied me to Ranchi, where I joined the institute in 1986.

My training at NAARM was an eye-opener, introducing me to research management. It took nearly a year to adjust to the new environment and

the crop, Lac, I was working on at Ranchi. In 1989, I moved to ICAR–CPCRI and joined the headquarters in Kasaragod to work on Crop Protection in coconut.

BSN: Is there any defining moment, mentor, or field experience that shaped your interest in Plantation crop entomology which is considered challenging field?

CM: At ICAR–CPCRI Kasargod, I was entrusted with a project on white grub management - one of the major challenges faced by farmers in the region and a priority area for the institute. Through this work, I developed a systematic sampling technique, studied the pest's bioecology, and formulated an effective chemical management strategy for its control.

In 1994, I was transferred to the Regional Station at Kayamkulam, where I increasingly recognized the importance of sustainable management approaches for perennial crops. The station had a strong legacy in crop protection research and was home to highly accomplished scientists specializing in entomology, plant pathology, and nematology.

My Ph.D. guide and mentor, the late Dr. B. Sathiamma, a devoted expert in biological control, played a pivotal role in nurturing my interest in the field and shaping my commitment to environmentally responsible pest management.

BSN: Which insect species or ecological interaction has fascinated you the most during your research, and why?

CM: The coconut black headed caterpillar, Opisina arenosella Walker has always fascinated me, particularly for its remarkable ability to survive in challenging field conditions atop coconut palms, enduring strong coastal winds and fluctuating temperatures. The insect exists within a complex natural ecosystem, surrounded by a diverse array of parasitoids—each highly specific to different larval instars and pupal stage —as well as numerous predators found in the field.

BSN: Plantation crop entomology involves extensive fieldwork. What are some unique challenges and rewards of working in such ecosystems?

CM: Coconut, predominantly cultivated as a homestead crop in Kerala, grows in close association with people. Consequently, the loss of even a single palm is felt profoundly—both by farmers whose livelihoods depend on it and by the scientists committed to safeguarding the crop. Implementing pesticide spraying for pest management is largely impractical due to environmental and health concerns, as well as the shortage of skilled labor. Additionally, data collection in coconut fields heavily depended on trained climbers, making the process even more challenging. In coconut research, to correlate any pest management study to yield it takes a minimum of three years to generate data. However, perennial nature of the crop gives more freedom to work on sustainable nature-friendly management options.

BSN: As a woman scientist in entomology, what challenges did you face early in your career, and how did you overcome them?

CM: Although I had registered for a full-time Ph.D. at Calicut University in 1985 with a CSIR fellowship, I was unable to continue due to my posting at the Lac Research Institute in Ranchi. Later, when I chose to return to my Ph.D., balancing a demanding career with the responsibilities of raising two young daughters, especially with my husband working in another city, was undoubtedly challenging. I adapted by shifting to a part-time Ph.D, a decision that allowed me to progress academically without compromising my career

and family.

BSN: How important has mentorship been in your career, and how do you support young researchers especially women today?

CM: My research guide, the late Dr. B. Sathiamma, has been one of the greatest inspirations in my scientific journey. Her sincerity, dedication, and remarkable work ethic left a lasting impression on everyone who worked with her. She exemplified punctuality in submitting reports and constantly reminded her juniors about the judicious use of government resources no matter how small the expenditure. She often emphasized that our work ultimately serves the farmers, and that we must demonstrate technologies ourselves in the field. Only then, she taught us, can we gather genuine feedback, refine our interventions, and make them more farmer friendly and impactful.

I was also fortunate to have exceptional colleagues at ICAR–CPCRI Kayamkulam. My seniors, Dr. C. P. R. Nair, Mr. P. Rajan, and my junior Dr. A. Joseph Rajkumar, whose support and teamwork greatly enriched my professional experience. We always worked as a cohesive unit, and this spirit of collaboration is something I wholeheartedly recommend to all young researchers. Strong teamwork not only strengthens research outcomes but also shapes us into better scientists and individuals.

BSN: What strategies helped you balance scientific work, field responsibilities, and personal life?

CM: Extended working hours were quite common at the ICAR-CPCRI Regional station, Kayamkulam, during that period, often involving intensive fieldwork and week long official tours. Through all of this, I was blessed with two wonderful daughters who were remarkably understanding and supportive of my work commitments and frequent travel. My mother would often visit and help care for them in my absence, and our neighbour, Mrs. Alamelu Srinivasan (Wife of Dr. Srinivasan ICAR-CPCRI), extended her unconditional support during those years at CPCRI Quarters. Their presence and encouragement made it possible for me to continue pursuing my professional responsibilities with confidence and peace of mind.

BSN: What skills beyond academic knowledge are essential for success in applied entomology today?

CM: Along with strong academic skills in insect species identification, patience is essential. Equally important is the ability to listen to and understand problems faced by farmers, combined with the readiness to engage in extensive fieldwork.

BSN: How do you see the role of entomologists evolving in ensuring food security, ecological resilience, and sustainable agriculture?

CM: We must always think about holistic plant health management especially in plantation crops rather than in pest management. Nowadays ecosystem management is given much importance with higher awareness on “One Health”. Biological control has become a strategic pillar of sustainable agriculture playing a crucial role in pest management while safeguarding food security and environmental health.

BSN: If you could change one thing about how entomology is taught or practiced in India, what would it be?

CM: We need to provide students with more hands-on practical exposure, developed through strong collaborations with institutes working on field crops, so that their interest in the subject can be meaningfully nurtured.

BSN: Looking back, what gives you the greatest sense of fulfilment as an entomologist and scientist?

CM: Seeing farmers adopt the technologies I developed and witnessing their positive impact directly in the field has been deeply rewarding.

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GENERAL ARTICLE

Host Plant Associations in Butterflies: Ecological Importance and Conservation Significance

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Abstract

Butterflies are among the most conspicuous and widely appreciated insects, yet their survival depends on more than the presence of nectar-bearing flowers. The larval stages of butterflies require suitable host plants for feeding, growth and successful development. Host plant availability strongly influences oviposition and larval survival. Ultimately, it shapes the local distribution, population persistence, and overall diversity of butterflies. Many butterfly species are closely associated with one or a few plant taxa, while others use a wider range of hosts. These relationships shape not only the ecology of individual species but also broader patterns of community structure and habitat occupancy. In India, where both butterfly and plant diversity are high, host plant associations provide an important foundation for understanding butterfly biology and for developing effective conservation strategies. This article discusses the ecological role of larval host plants in butterflies, influence on diversity and distribution and their significance in habitat management and conservation.

Keywords: Butterflies, host plants, larval ecology, oviposition, diversity, conservation.

Introduction

Butterflies hold a special place in entomology because they are ecologically important, visually attractive and relatively easy to observe in the field. They are often used in ecological studies because their distribution and abundance reflect the quality and composition of surrounding vegetation. However, butterfly ecology cannot be understood fully by focusing only on adults. The butterfly life cycle includes egg, larva, pupa and adult stages and the successful completion of this cycle depends on the availability of appropriate resources at each stage (Dennis *et al*., 2004; Tiple *et al*., 2011).

Among these resources, larval host plants are of central importance. Female butterflies do not lay eggs randomly on vegetation. Instead, they select plant species that can support larval feeding and development. This choice is crucial because newly hatched larvae are often highly dependent on the plant selected by the female and have limited ability to move in search of better food. Thus, host plant choice directly affects survival, growth and reproductive success (Dennis *et al*., 2004).

Host plant relationships also influence broader ecological patterns. They affect local distribution, seasonal occurrence, habitat suitability and population stability. A site may contain abundant nectar plants and still fail to support breeding populations if larval host plants are absent. For this reason, host plant associations are fundamental not only to butterfly biology but also to conservation and habitat restoration (Tiple

et al., 2011; Nitin *et al*., 2018).

Host Plants and Butterfly Life History

Host plants are the plants on which butterflies lay eggs and on which caterpillars feed after hatching. In many species, host use is highly specific. Some butterflies utilize only one plant species or a narrow range of closely related plants, whereas others can feed on a broader set of hosts. This variation in host specificity is one of the defining features of butterfly natural history (Dennis *et al*., 2004). The process begins with oviposition. Female butterflies identify suitable plants using a combination of plant form, surface texture, colour, microhabitat and especially chemical cues. Plant secondary compounds often play a major role in host recognition. A plant that appears suitable to a human observer may be chemically unacceptable to a butterfly, whereas a less conspicuous native plant may be the preferred host. Such selectivity is adaptive because larval development depends heavily on plant suitability (Dennis *et al*., 2004).



Figure 1: Adult butterfly visiting a flowering plant for nectar feeding in its natural habitat. (Photo: Diksha Chopra at Shimla, H.P.)

Host plants also determine larval performance. Nutritional value, water content, leaf toughness and defensive chemistry can influence feeding rate, growth, development time



Figure 2: Butterfly larva feeding on foliage, highlighting the importance of larval host plants in butterfly development. (Photo: Neeraj at HP)

and survival. Poor-quality host plants may delay development and increase larval exposure to predators and parasitoids. In contrast, suitable host plants support rapid growth and successful pupation. Therefore, host plant availability is not simply about food presence; it is about access to the correct food under the correct ecological conditions (Tiple *et al*., 2011).

Host Specificity, Diversity and Butterfly Assemblages

Host plant associations shape butterfly diversity at several levels. At the species level, host specificity often determines habitat occupancy and geographic distribution. Specialist species are usually more vulnerable to habitat disturbance because they depend on a narrow set of plant resources. Generalist species may persist more easily in modified landscapes because they can use a wider range of plants. This difference partly explains why some butterfly species decline rapidly with habitat change while others remain common (Dennis *et al*., 2004).

At the community level, host plant diversity contributes to butterfly richness. Comparative studies have shown a strong positive relationship between the diversity of host plants and the richness of butterfly species. Ferrer-Paris *et al*. (2013) demonstrated that butterfly species richness is strongly correlated with host plant diversity across higher taxonomic levels. This finding suggests that plant diversity provides the ecological foundation for butterfly diversity, since a wider variety of host plants can support a broader butterfly assemblage.

Host use also has evolutionary significance. Butterfly diversification has long been linked to plant associations and more recent network-based analysis suggest that both host shifts and the retention of ancestral host use capacity have contributed to butterfly diversification. Braga et al. (2018) showed that host-associated diversification is driven not only by shifts to new plants but also by variation in host use and butterfly plant network structure.

Evidence from Indian Studies

Indian studies illustrate the importance of host plant associations particularly well. In a detailed study from Nagpur city, Tiple *et al*. (2011) documented larval host plants for 120 butterfly species and recorded 126 host plants. Their work showed that butterflies in a tropical urban landscape depend on a wide range of plant forms, including trees, herbs, shrubs, climbers and parasitic plants. The study also demonstrated that host specificity, egg batch size and the number of host plants used were associated with butterfly population patterns in the city.

A broader perspective comes from the Western Ghats, one of the world's major biodiversity hotspots. Nitin *et al*. (2018) compiled an updated checklist showing that about 834 plant species or species groups belonging to 88 families are used by 320 butterfly species in the Western Ghats. This checklist reveals the extraordinary scale and complexity of butterfly plant relationships in India and highlights the dependence of both endemic and widespread species on specific larval food plants. These studies show that host plant research is not merely descriptive. It provides essential insight into breeding biology, resource use, landscape ecology and conservation priorities. In the Indian context, where butterfly diversity varies across forests, grasslands, scrub, wetlands, agricultural mosaics and urban habitats, host plant documentation remains a highly valuable form of natural history research (Tiple *et al*., 2011; Nitin *et al*., 2018).

Field Observations on Host Plant Associations from Northwest India

Field observations from Northwest India further highlight the importance of larval host plants in determining butterfly occurrence and habitat use. During surveys, several lycaenid butterflies were recorded in association with their larval host plants and characteristic habitats. *Pratapa icetas* was recorded from Kareri Village, Himachal Pradesh, where its known larval host plant *Scurrula ferruginea* was present in the habitat. *Horaga onyx* was recorded from Himachal Pradesh and Uttarakhand, where its documented larval host plant *Coriaria nepalensis* occurs. The Common Silverline, *Cigaritis vulcanus*, was documented from different localities with reported host plants including *Ziziphus* spp. and *Plectronia parviflora*. Field observations also revealed habitat preferences linked with vegetation structure. *Loxura atymnus* showed a preference for shaded habitats near bamboo vegetation in the Doon Valley, whereas *Satyrium sassanides* was observed in high-elevation montane habitats of Lahaul Spiti. These observations emphasize that conservation

Table 1: Larval host plant associations of Indian butterflies.
Source: Nitin et al. (2018), and documented host plant records from literature.

Butterfly species	Common name	Butterfly family	Major larval host plant species (representative)	Host plant family
Arhopala amantes	Large Oakblue	Lycaenidae	*Terminalia paniculata*, *Hopea ponga*, *Shorea robusta*, *Syzygium cumini*	Combretaceae, Dipterocarpaceae, Myrtaceae
Danaus chrysippus	Plain Tiger	Nymphalidae	*Calotropis gigantea*, *Calotropis procera*	Apocynaceae
Delias eucharis	Indian Jezebel	Pieridae	*Dendrophthoe falcata*, *Scurrula parasitica*	Loranthaceae
Horaga onyx	Common Onyx	Lycaenidae	*Mangifera indica*	Anacardiaceae
Junonia lemonias	Lemon Pansy	Nymphalidae	*Barleria cristata*, *Hygrophila auriculata*	Acanthaceae
Pieris canidia	Cabbage White	Pieridae	*Brassica oleracea*, *Rorippa indica*	Brassicaceae
Rapala manea	Slate Flash	Lycaenidae	*Mangifera indica*, *Acacia pennata*, *Saraca asoca*	Anacardiaceae, Fabaceae
Surendra quercetorum	Common Acacia Blue	Lycaenidae	*Acacia pennata*, *Albizia odoratissima*	Fabaceae

of butterfly diversity requires protection of both adult habitats and larval host plant resources.

Sorrel Sapphire, *Heliophorus sena*, has been recorded using *Rumex hastatus* as its larval host plant. Among the oakblues, the Sahyadri Rosy Oakblue, *Arhopala alea*, uses *Terminalia paniculata*, *Hopea* spp. and *Syzygium salicifolium*, whereas the Large Oakblue, *Arhopala amantes*, uses several tree species belonging to the families Combretaceae, Dipterocarpaceae, Fabaceae, Lythraceae and Myrtaceae. Common and widespread butterflies also show recognisable host associations: the Lime Swallowtail, *Papilio demoleus*, commonly uses citrus and other Rutaceae, while the Plain Tiger, *Danaus chrysippus*, breeds mainly on milkweeds such as *Calotropis* spp (Robinson et al., 2010, Kalesh and Prakash, 2015).

Conservation Significance

The conservation of butterflies is often approached by emphasizing nectar-rich flowering plants for adults. Although nectar plants are important, this approach is incomplete if it neglects larval host plants. A habitat may attract adult butterflies for feeding but still fail to support breeding populations if females cannot find appropriate host plants for oviposition. Effective conservation therefore requires a life-cycle approach in which both adult and larval resources are maintained (Tiple *et al*., 2011; Nitin *et al*., 2018). This issue is particularly important in modified landscapes. Urbanization, roadside clearing, replacement of native vegetation with ornamental plants and habitat simplification may reduce host plant availability even when green cover remains.



Figure 3: Butterfly larva associated with foliage, representing the dependence of immature stages on suitable plant resources. (Photo: Diksha Chopra at Shimla, H.P.)

Such habitats may appear suitable visually but may function poorly for butterfly reproduction. In many cases, the loss of larval host plants is one of the most important hidden causes of butterfly decline (Dennis *et al*., 2004). Conservation planning should therefore prioritize native vegetation and locally relevant host plants. Restoration efforts in gardens, campuses, parks and reserve edges can be improved by including plant species known to support local butterfly larvae. This is especially important for specialist butterflies, which may depend on a limited set of host taxa. Because host plant diversity is linked to butterfly richness, protecting plant diversity is also a practical strategy for conserving butterfly communities more broadly (Ferrer-Paris *et al*., 2013).

Natural History Value and Future Scope

Host plant associations remain one of the most rewarding areas of butterfly natural history. Careful observation of egg laying behaviour, larval feeding, resting sites, shelter-building and pupation can reveal valuable ecological information. Even simple field observations can contribute significantly when accompanied by accurate plant identification and photographic documentation. There is also considerable scope for future work in India. Many regional host plant associations remain poorly documented and there is need for more field-based studies across seasons, elevations and habitat types. Changes in land use and climate may alter both plant availability and butterfly behaviour, making long-term observations increasingly important. Continued collaboration among professional researchers, amateur naturalists, students and citizen scientists could greatly improve available knowledge on butterfly host use in India (Nitin *et al*., 2018).

Conclusion

Host plant associations are central to the ecology and conservation of butterflies. They influence oviposition, larval survival, development, habitat use and long-term population persistence. Evidence from both global comparative studies and Indian field research shows that butterfly diversity is closely tied to host plant diversity. For this reason, butterfly conservation should not focus solely on adult nectar resources. Equal attention must be given to the plants that sustain immature stages. A stronger host plant perspective will improve butterfly research, strengthen natural history documentation and lead to more effective conservation planning.

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GENERAL ARTICLE

The Silent Sculptor inside the Tobacco Stem - *Scrobipalpa aptatella* (Walker, 1864)

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Introduction

When farmers walk through a newly planted tobacco field in the early morning, the crop often appears healthy from a distance. The leaves sway gently in the breeze, the stems stand upright, and the field looks calm and green. But inside a few innocent-looking plants, a secret drama is unfolding. Deep within the stem lives a tiny hidden artist — the tobacco stem borer, *Scrobipalpa aptatella* (Walker, 1864). Unlike caterpillars that openly chew leaves or beetles that attack from outside, this insect prefers darkness. It lives silently inside the stem, tunneling, feeding, growing, and transforming without being seen.

The invisible thief

Like a silent thief inside a house, the stem borer eats the plant from within while the farmer notices nothing at first. The story usually begins when a tiny moth lays eggs on tender tobacco plants. Soon, the young larva hatches and searches for a safe entrance. Instead of feeding openly, it bores directly into the stem. Once inside, the insect becomes a hidden tenant. As days pass, the larva feeds internally on soft tissues. The plant reacts to this invasion by producing abnormal growth around the injured area. Slowly, the basal portion of the stem swells and becomes enlarged like a knot or gall (Fig. 1a). To the farmer, this bulged region looks strange — almost as if the stem has developed a tumor. But inside that swollen chamber, the larva is comfortably feeding and preparing for its next stage of life (Jagadish, 1979). The gall is not just a symptom; it is the insect's secret house, which looks like a mysterious swelling at the base.

The stem first becomes food, shelter, nursery, and finally a coffin (not exactly as the adult emerges out from this secret house freely). The plant becomes its prison for two important stages i.e., larva and pupa.

An insect that fears fresh air

Most living creatures crave for air i.e. oxygen for survival. Humans need fresh air every moment. Animals struggle without oxygen. Even underground insects create breathing tunnels. But the tobacco stem borer is different. This insect survives only as long as it remains hidden inside the stem. If the swollen gall is carefully pierced or split open, exposing the larva to direct air and sunlight, the larva quickly dies (Fig. 1b). What an irony of nature! The same air that gives life to humans becomes deadly to this concealed insect. The very stem that protects the insect also becomes its trap



Figure 1. Various life stages and characteristic symptoms of damage caused by *Scrobipalpa aptatella* in tobacco (a) Gall at the basal portion of the stem (b) Larva inside the split open stem (c) Pupation site inside the stem (d) Multiple galls/ swellings on stem

when exposed to air. Farmers in some regions traditionally pin or puncture the swollen stem portion after noticing fresh galls. Once exposed, the delicate larva cannot tolerate the sudden environmental change. Nature itself becomes the pesticide. This simple observation teaches an important lesson: sometimes understanding an insect's weakness is more powerful than spraying chemicals. The stem borer survives in darkness, hidden from the world. But the moment sunlight and fresh air enter its chamber, its life ends.

The secret transformation inside the stem

As the larva matures, it prepares for one of nature's greatest miracles — metamorphosis. Inside the same stem tunnel, the caterpillar changes into a pupa. During this stage, it remains inactive, silently transforming into an adult moth. The pupation region often becomes more swollen and corky (Fig.1c). If the stem is cut open carefully, one can observe the brown pupa resting inside like a passenger in a sleeping chamber. Then comes the final act. One day, the adult moth emerges by cutting a neat circular hole through the stem wall. The hole looks as though someone drilled it using a tiny machine (Rao and Rao, 1956; Sarala *et al.,* 2022). The moth escapes into the outside world, leaving behind an empty tunnel and a damaged plant. The adult moth cuts an almost perfect round hole as an escape door while emerging.

Does one insect attack only one plant?

A common question among farmers is: Does a single stem borer remain in one plant throughout its life? The answer is mostly yes during the larval stage. Once the larva enters a tobacco stem, it generally stays inside that single plant because the stem provides food, shelter, and protection. It completes feeding and pupation within the same stem (Fig. 1d). However, the adult moth emerges out from the gall is capable of laying eggs on many plants during the season. A single female moth can lay eggs on several tobacco plants. Thus, while one larva usually damages one plant, the next generation can spread widely across the field. However, if the multiple larvae emerges can able to bore the same plant where eggs laid, and we found up to 3 larvae (galls) in a single plant. That is why early detection is extremely important. One unnoticed gall today may become the source

of many infestations tomorrow. You can explain that one swelling alone can reveal feeding, growth, pupation, and adult emergence.

Why the damage is serious?

The stem is the backbone of the tobacco plant. When the insect tunnels inside; uptake gets disrupted, plant vigor declines, growth becomes stunted, leaves remain smaller, this may also cause horizontal growth or breakage near the basal portion of the plant (Sreenivas, 2022). In some cases, the damage can further expose the plant to secondary infection, particularly by *Fusarium* species, resulting in wilt disease. The gall formation also weakens the stem structurally. In severe infestations, yield and leaf quality may reduce significantly. Since the pest hides internally, farmers often notice damage only after the swelling appears.

Nature's tiny engineer

Though harmful, the tobacco stem borer is also an example of nature's astonishing engineering. Imagine this tiny insect: entering a narrow stem, building tunnels, creating a protected chamber, transforming inside, and finally carving a perfect circular exit hole. All this happens silently inside a single plant stem. To a scientist, it is fascinating; To a farmer, it is alarming; and to nature, it is simply

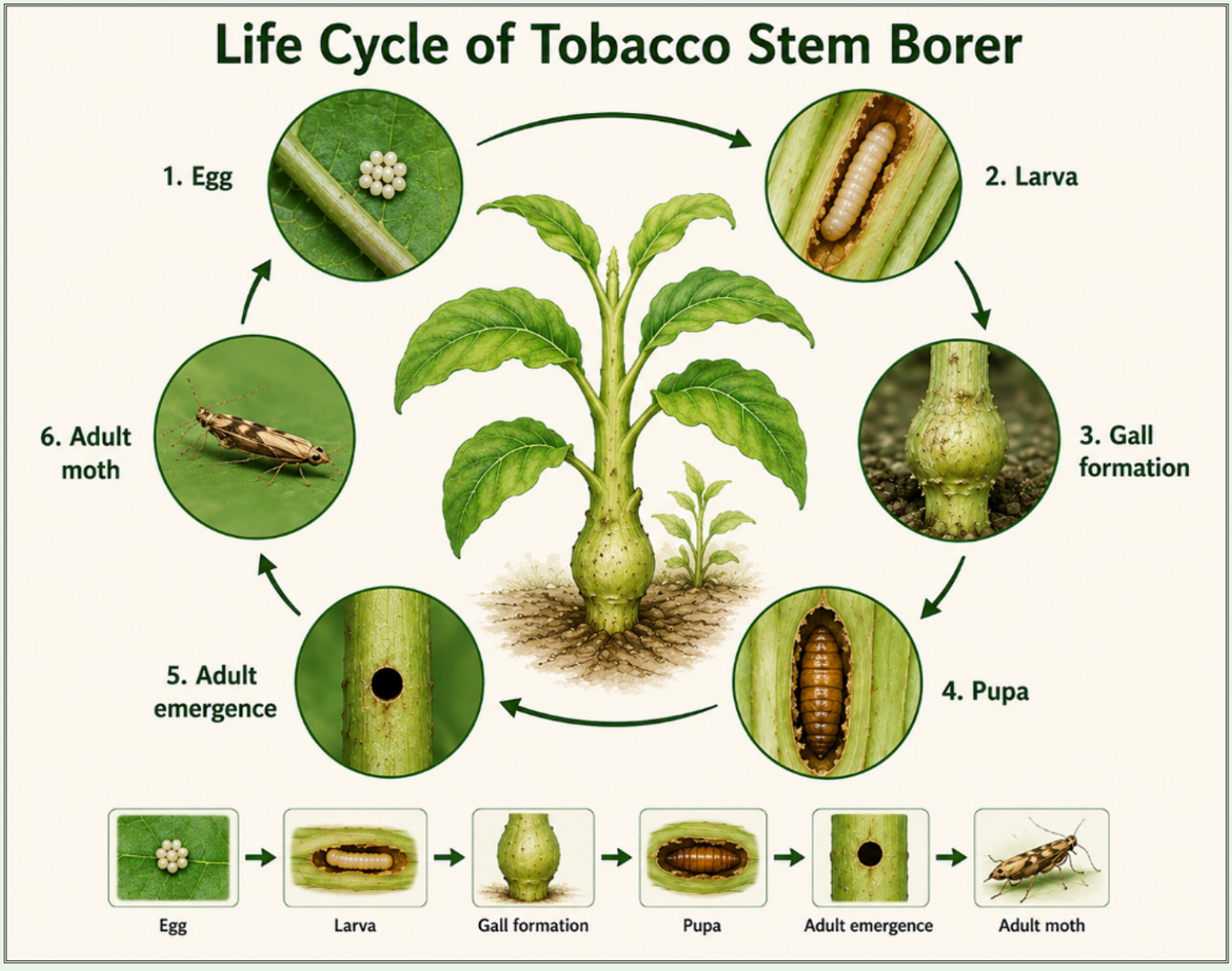


Figure 2. Life cycle of Tobacco stem borer
(Designed using ChatGPT, by giving the biology instructions from the available literature)

survival.

A short life: A lasting impact

Interestingly, the life of the tobacco stem borer is also closely tied to its hidden lifestyle. The adult moth lives only for a short period, but during that time the female lays eggs on several tobacco plants across the field, helping the pest spread from one generation to another. Unlike some insects that reproduce only once in a dramatic final act, the moth may continue laying eggs over a few days before dying naturally. After mating and egg laying, the quiet cycle begins again — eggs hatch, larvae bore into fresh stems, new galls develop, and another hidden generation grows silently inside the plant.

Waiting silently between seasons – off-season survival

Even after the tobacco crop is harvested and the field appears empty, the story of the stem borer does not completely end. The insect quietly survives the off-season by hiding inside leftover stem pieces, stubbles, dried plant residues, and sometimes in alternate host plants growing nearby (Jagadish, 1979). Larvae or pupae concealed within these dry stems remain protected from harsh weather and enemies. When the next tobacco season begins, the adult moths emerge from these hidden shelters and start laying eggs on young plants once again. Thus, an unnoticed infested stem left in the field can become the starting point for a fresh infestation in the following season. This is why sanitation is extremely important in tobacco cultivation (Rao and Rao, 1956). Removal and destruction of old stalks, deep ploughing after harvest, and cleaning field borders help break the hidden bridge that carries the insect from one season to the next. In many ways, the stem borer spends the off-season like a patient sleeper inside dry stems, waiting quietly for the return of a new tobacco crop.

Nature also sends hunters

Although the tobacco stem borer hides safely inside the stem, it is not completely beyond nature's reach. Tiny parasitoid wasps, such as *Trichogramma* spp. (Rao and Sreedhar, 2013) and *Chelonus heliopae* (Patel *et al.*, 1958) attack the pest's eggs and early developmental stages, while predatory insects and wandering spiders constantly search tobacco fields for hidden prey. Some natural enemies attack the eggs or young larvae before they enter the stem, while others wait for the vulnerable stages during emergence. Thus, even this secret insect is part of a larger ecological battle taking place silently in the field. Nature always maintains balance — for every hidden pest, there is often a hidden hunter waiting nearby.

Why chemicals often fail

Farmers are often surprised when insecticide sprays do not give satisfactory control against tobacco stem borer. The reason lies in the insect's hidden lifestyle. By the time swelling becomes visible and spraying begins, the larva is already deep inside the stem, protected like a soldier hiding safely inside a bunker. The stem walls shield the insect from direct contact with chemicals, making late-stage control difficult. This is why early detection, field sanitation, and exposing the grub by splitting or pinning the swollen stem are often more effective than repeated spraying alone.

Outsmarting the hidden enemy – Management of tobacco stem borer

The tobacco stem borer teaches farmers an important lesson: a hidden enemy must be detected early. Since the insect spends most of its life safely inside the stem, ordinary spraying often fails once the larva enters the plant. Therefore, careful observation in the field becomes the farmer's greatest weapon.

- Clean cultivation also plays an important role. Removal of old crop residues, volunteer tobacco plants, and nearby weeds helps reduce carryover of the pest from one season to another.
- The moment a swollen gall-like bulge appears near the basal stem region, the plant should be examined closely. Experienced farmers sometimes gently pierce or split the swollen portion using a pin, thorn, or sharp stick.
- Plants showing severe swelling or drying should be removed and destroyed before the adult moth emerges. Otherwise, the moth escapes through its neat circular exit hole and flies away to lay eggs on many more tobacco plants across the field.
- Balanced fertilizer use should be encouraged because excessive nitrogen creates soft succulent growth that may attract more infestation.
- Farmers who regularly walk through their fields, observe stems carefully, and remove early infestations often succeed better than those depending only on chemicals. In many ways, management of tobacco stem borer is not merely spraying against an insect — it is understanding the secret life of a creature that lives hidden inside the stem.
- Under severely infested situations, after pinning the galls, the fields can be sprayed with recommended insecticides (Sreedhar, 2014).

Why scientists find the Tobacco Stem Borer fascinating

To a farmer, the tobacco stem borer is a damaging pest. But to scientists, it is also a remarkable example of hidden insect adaptation and survival. Its entire life revolves around living inside a narrow plant stem — a tiny world where it feeds, grows, transforms, and finally emerges as an adult moth. Studying such an insect helps researchers understand how insects manipulate plant tissues, avoid predators, survive harsh environments, and complete their life cycle within a confined space. One of the most fascinating features is the gall-like swelling formed on the stem. Scientists are interested in how such a small larva can trigger the plant to alter its growth and create a protective chamber around it. The insect also demonstrates extraordinary behavioural adaptation: it survives safely in darkness inside the stem but becomes highly vulnerable when suddenly exposed to open air. The perfectly circular exit hole made by the adult moth is another marvel of natural engineering. Researchers study how the insect senses the correct direction for emergence and cuts through the stem wall at the right time without becoming trapped inside. The pest is also important in ecological and pest management studies because it remains hidden from many conventional insecticide sprays. Understanding its behavior helps scientists design better integrated pest management strategies using early detection, biological control, and cultural practices rather than depending only on chemicals. In many ways, the tobacco stem borer is not merely a crop pest — it is a living example of how insects evolve specialized lifestyles to survive inside plants.

Final reflection

The story of *Scrobipalpa aptatella* (Gelechiidae: Lepidoptera) reminds us that not all enemies attack openly. Some remain hidden, silently feeding from within. Yet this insect also carries a strange weakness: it survives in darkness but dies in open air. Perhaps nature is telling us something profound — every hidden problem

loses strength when exposed to light. And in every tobacco field, beneath the green leaves and quiet breeze, this small unseen drama continues season after season.

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GENERAL ARTICLE

Why Mosquitoes Prefer Some People More Than Others: The Sensory Biology of Differential Host Attraction

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Abstract

Differential attractiveness of humans to mosquitoes is a major factor in individual exposure to diseases spread by vectors. In India alone, this burden includes hundreds of thousands of cases of dengue, malaria, and chikungunya each year. This article summarizes the current understanding of the sensory and chemical basis of mosquito host selection. It starts with the peripheral olfactory system, which allows female mosquitoes to detect signals from potential hosts. Carbon dioxide, sensed by receptors on the maxillary palps, serves as a long-range cue and seems to enhance responses to visual and olfactory signals at closer distances. At landing distance, volatile organic compounds from the skin influence host choice. People who are very attractive to mosquitoes often have higher levels of sebaceous carboxylic acids on their skin, which work with sweat-derived lactic acid and ammonia. ABO blood group, the makeup of the skin microbiome, and genetic factors also affect attractiveness, although the extent varies, and the mechanisms are not fully understood. We also look at species-specific differences in host-seeking behaviour among the mosquito genera most relevant to public health in India: *Aedes*, *Anopheles*, and *Culex*. These differences impact the timing and targeting of vector control efforts. Recent research on modifying the skin microbiome to reduce lactic acid production provides early evidence for microbiome-based alternatives to traditional topical repellents that last longer.

Introduction

Both laboratory and semi-field studies have shown significant differences in how attractive people are to mosquitoes. Some individuals are consistently more attractive to mosquitoes than others, even in the same experimental conditions (Verhulst et al., 2011; Fernandez-Grandon et al., 2015; De Obaldia et al., 2022). This variation matters; since mosquitoes spread some of the most serious infectious diseases, knowing who gets bitten and why can impact disease transmission and control.

The diseases in question vary by vector. *Aedes aegypti* and *Aedes albopictus* carry dengue, chikungunya, Zika, and yellow fever. *Anopheles* species are the only vectors for human malaria. *Culex* species transmit lymphatic filariasis and Japanese encephalitis. These genera not only differ in the pathogens they carry but also in when and how they look for hosts. This distinction will be discussed later in this article, where species-specific attraction is examined along with its importance for vector control in India, where all three genera are common.

This article describes the sensory biology behind how mosquitoes seek and are attracted to



Figure 1. A female mosquito probing human skin during blood-feeding. Only females take blood meals, which supply the protein required for egg development; males feed exclusively on nectar and other sugar sources.

hosts. It covers the peripheral olfactory system, the detection of carbon dioxide and body Odour, as well as blood type, skin microbiome, and genetic influences. After that, it addresses species-specific behaviour, the disease burden in India, and current and upcoming protection strategies.

Mosquito Olfaction: The Sensory Basis of Host Detection

Host-seeking in mosquitoes relies on their sense of smell. The biological mechanisms involved show why the cues described later in this article are detected. The main olfactory organs are the antennae, each made up of thirteen segments covered in hair-like structures called sensilla. Three types of sensilla stand out: sensilla trichodea, which are the most common, sensilla basiconica, known as "grooved pegs," and the less common pitted sensilla coeloconica. These structures contain most of the olfactory sensory neurons, typically two or three in each sensillum. The maxillary palp is another important organ, especially for detecting carbon dioxide.

Two main gene families give this system its ability to be sensitive and specific. Odourant receptors (ORs) pair with a co-receptor, Orco, to create ion channels that respond to certain classes of smelling compounds. Ionotropic receptors (IRs) create a separate system that includes co-receptors IR8a, IR25a, and IR76b. The pathways relying on IR8a are crucial for detecting carboxylic acids and amines, which are prominent in human sweat. Disruption of this pathway significantly reduces attraction to human Odour. Carbon dioxide detection occurs separately through a receptor complex located on the maxillary palps, not on the antennae (McMeniman et al. 2014). Odourant-binding proteins transport these mostly water-insoluble molecules through the fluid in the sensilla to the receptor membrane. Signals from the receptors converge in the antennal lobe of the brain. Neurons that express the same type of receptor project to the same glomerulus, creating a spatial map of odour identity. Downstream circuits then translate this information into flight and landing behaviour.

Only female mosquitoes seek a blood host because blood provides the protein necessary for developing eggs. Their antennae also have a different structure compared to the bushier, more plumose antennae of males. The male antennae are designed to pick up the wingbeat frequency of females during mating swarms rather than cues from hosts. This highlights that the sensory biology discussed here is specific to host-seeking females, not mosquitoes in general.

Carbon Dioxide: The Long-Distance Host Cue

Within this sensory system, carbon dioxide (CO_2) is the main signal mosquitoes use to find a potential host from afar. Female mosquitoes detect CO_2 through the maxillary-palp receptor complex mentioned earlier. They can track a rising CO_2 plume from a considerable distance. Estimates usually place the effective range at several tens of meters under favourable wind conditions.

Table 1. How CO_2 modulates mosquito sensory responses

Effect	Description
Enhanced visual tracking	CO_2 improves the precision with which mosquitoes track moving visual targets
Sharper low-contrast tracking	CO_2 exposure improves tracking of dim or low-contrast objects in flight
Context-dependent odour response	CO_2 strengthens both attractions to host odours and avoidance of repellents, depending on the odour's behavioural value

Humans exhale air that contains roughly 4% CO_2, while the ambient background is about 0.04%. This difference helps mosquitoes follow a trail. Besides attracting them from afar, CO_2 seems to make mosquitoes more responsive to other signals. Experiments in a virtual-reality flight arena revealed that *Aedes albopictus* reacted more accurately to moving visual targets. They adjusted their response to odours, showing increased attraction to host odours and stronger repulsion from unpleasant ones when CO_2 was present (Kato-Namba et al. 2025). Additional research on *Aedes aegypti* has shown that CO_2 detection, through the Gr3 receptor subunit, works together with heat and skin odours to guide their attraction to live hosts. This combination of signals, rather than any single signal alone, helps them effectively seek out hosts (McMeniman et al. 2014).

People who exhale more CO_2, such as pregnant women who exhale about 21% more, larger individuals, and those doing physical activities, tend to attract more mosquitoes. This may explain the common increase in bites during and after exercise or later in pregnancy (Lindsay et al., 2000).

Body Odour Chemistry: Volatile Compounds and Host Discrimination

While CO_2 attracts mosquitoes from a distance, body odour decides if a mosquito lands and seeks a blood meal. Human skin releases hundreds of volatile organic compounds (VOCs). The chemical profile that results is what the IR8a-dependent pathway recognizes.

Carboxylic Acids and Skin Emissions

A 2022 study from the Vosshall laboratory at Rockefeller University, led by Maria Elena De Obaldia, found that carboxylic acids play a major role in how attractive humans are to mosquitoes. Sixty-four volunteers wore nylon sleeves on their forearms for six hours. When tested against *Aedes aegypti*, the main carrier of dengue, Zika, and yellow fever, the scent of the most attractive volunteer was about 100 times more appealing than that of the least attractive (De Obaldia et al. 2022). Chemical analysis indicated that highly attractive individuals produced significantly higher levels of sebaceous carboxylic acids. These fatty-acid compounds come from the skin's sebaceous glands. This difference remained consistent when the same individuals were retested over several years.

Lactic Acid and Ammonia

Lactic acid, released in sweat during exercise, has long been known to attract mosquitoes. A systematic review of the dengue vector *Aedes* spp. found it works with other skin-derived compounds to increase attraction (Mubarak et al. 2021). Ammonia, also found in sweat, seems to require this combination. Early behavioural studies on *Aedes aegypti* showed that ammonia alone had little effect, but when combined with lactic acid, it significantly boosted attractiveness (Geier et al. 1999). This combined effect helps explain why exercise, which raises sweating and lactic-acid

levels, usually makes a person more appealing to mosquitoes.

Blood Type and Mosquito Preference

A popular belief suggests that mosquitoes prefer certain blood types, and the evidence backs this up to some extent. A 2004 study of *Aedes albopictus* landing behaviour found that mosquitoes landed on people with Type O blood almost twice as often as those with Type A, with Type B in between (Shirai et al. 2004). Another laboratory study of *Aedes aegypti* allowed mosquitoes access to all four blood types through membrane feeders, also showing a clear preference for Type O (Prasadini et al. 2019).

Table 2. Reported mosquito landing preference by ABO blood type

Blood type	Relative attraction	Notes
Type O	Highest	Nearly twice as attractive as Type A in landing assays
Type B	Moderate	Intermediate attraction level
Type AB	Moderate	Broadly similar to Type B
Type A	Lowest	Significantly less attractive than Type O

However, these findings should be approached with caution. Texas A&M University entomologist Sonja Swiger noted that comparative trials like these always show a statistical "winner," but this doesn't guarantee blood type is a reliable predictor of any individual's risk (Vargo 2026). Secretor status might matter as much as blood type. About 85% of people secrete a chemical marker of their blood type through the skin, and mosquitoes tend to prefer these "secretors" over "non-secretors," regardless of blood group (Shirai et al. 2004).

The Skin Microbiome Connection

Skin bacteria add another important layer to host attractiveness. A 2011 study on the African malaria vector *Anopheles gambiae* found that the makeup of skin bacteria, not just their presence, influenced appeal. Skin with high numbers of a few bacterial species was more attractive to this mosquito than skin with a diverse mix of bacteria (Verhulst et al. 2011). This pattern may explain why feet and ankles, rich in odour-producing bacteria, are particularly appealing. Some of these bacteria are related to those that create the smell of Limburger cheese, which has sometimes been used in mosquito traps.

Engineered Microbiomes: Toward "Living Repellents"

Since much of this attraction depends on bacteria-produced L- (+)-lactic acid, researchers have started to re-engineer the skin microbiome. In 2024, a team at the University of California, San Diego, led by Omar Akbari, deleted the lactic-acid-producing gene in two common skin bacteria, *Staphylococcus epidermidis* and *Corynebacterium amycolatum*. Mice with the engineered *S. epidermidis* attracted up to 64% fewer mosquitoes than those with the unmodified strain. This reduced attraction lasted for up to eleven days, much longer than the four-to-eight-hour effectiveness of topical DEET (Liu et al. 2024). If similar engineered strains can colonize and thrive on human skin, which remains unresolved, this approach could provide a long-lasting, self-replicating alternative to traditional repellents.

Species-Specific Host-Seeking and Relevance to Vector-Borne Disease Control in India

Much of the biology discussed mainly involves *Aedes aegypti* and *Anopheles gambiae*. However, the mosquito genera responsible for human disease vary greatly in their host-seeking behaviour, and these differences are crucial for applying attraction research to control strategies. *Aedes* species are aggressive daytime feeders, most active in the early morning and late afternoon, and often take multiple blood meals in one reproductive cycle. In contrast, *Anopheles* species primarily feed at night or during twilight, typically seeking hosts that are asleep after dark. *Culex* species are generally active in the early evening and night. A protection strategy focused on one genus, like bed nets for nocturnal *Anopheles*, is ineffective against daytime-biting *Aedes* and vice versa.

Table 3. Major mosquito vectors of human disease in India

Genus / species	Disease(s) transmitted	Peak biting activity
Aedes aegypti, Ae. albopictus	Dengue, chikungunya, Zika	Daytime (early morning, late afternoon)
Anopheles culicifacies, An. stephensi	Malaria	Night / crepuscular
Culex quinquefasciatus	Lymphatic filariasis	Dusk / night
Culex tritaeniorhynchus and allied spp.	Japanese encephalitis	Dusk / night

This distinction is particularly relevant in India, which faces a significant share of the global burden of mosquito-borne disease. *Aedes aegypti* is the main vector of dengue in India, with *Aedes albopictus* as a secondary vector. Malaria is mainly spread by *Anopheles culicifacies* in rural areas and by the increasingly urban-adapted *Anopheles stephensi*. *Culex quinquefasciatus* is the key vector for lymphatic filariasis, while *Culex tritaeniorhynchus* and similar species transmit Japanese encephalitis (Naik et al. 2023). According to the National Centre for Vector Borne Diseases Control, India reported over 233,000 dengue cases and around 255,500 malaria cases in 2024, along with more than 17,800 confirmed chikungunya cases. The country accounts for nearly 40% of the global burden of lymphatic filariasis (NCVBDC 2025).

Given this variety, the attraction biology discussed here is practically important: understanding why certain individuals attract *Aedes* more strongly could help in more targeted use of repellents or spatial control measures in urban areas facing dengue outbreaks. The daytime feeding behaviour of *Aedes* limits the effectiveness of bed nets, which work well against nocturnal *Anopheles* and *Culex*.

Other Factors Influencing Attraction

Several other factors affect mosquito attraction. Pregnancy can double a person's appeal, mainly due to increased CO_2 output (about 21% higher) and raised body temperature (Lindsay et al., 2000). Drinking beer has also been shown to increase attraction to *Anopheles gambiae*, through a mechanism that does not seem to involve changes in exhaled CO_2 or body temperature (Lefèvre et al. 2010). Exercise boosts both lactic-acid production and body heat, which further enhances attraction. Additionally, mosquitoes are drawn to red, orange, and black, which overlap with human skin tones, while blue, green, and white are less noticeable.

Genetics plays a role too. A genome-wide association study of self-reported mosquito bite size, itchiness, and attractiveness, using 23andMe survey data, identified fifteen independent genetic markers linked to these traits. Most of these are related to immune function rather than olfactory biology directly (Jones et al. 2017). This suggests

Table 4. Additional factors affecting mosquito attraction

Factor	Effect on mosquito attraction
Pregnancy	Attracts roughly twice as many mosquitoes, linked to increased CO_2 output (~21%) and body temperature (~0.7°C)
Beer consumption	Increases attraction to *An. gambiae*; mechanism unclear but not attributable to CO_2 or temperature changes
Exercise	Increases lactic-acid output and body heat, raising detectability
Clothing colour	Red, orange, and black attract more strongly; lighter colours (blue, green, white) are less readily detected

that part of an individual's apparent attractiveness may come from their immune and inflammatory response to bites, rather than the odour they emit. This distinction is important when family members report different experiences with mosquito bites.

Protection Strategies

Understanding why mosquitoes prefer certain people is only part of the picture. The sections above also point toward practical, evidence-based ways to reduce individual risk.

Chemical Repellents

DEET (N, N-diethyl-meta-toluamide) remains the most studied repellent. In controlled human trials, a 23.8% DEET formulation provided a mean complete protection time of about five hours (Fradin & Day 2002). Picaridin, a synthetic compound modeled on piperine (a compound found in pepper plants), offers somewhat longer protection at similar concentrations. It lasts up to around 8 to 12 hours at 20%. It also has less odour

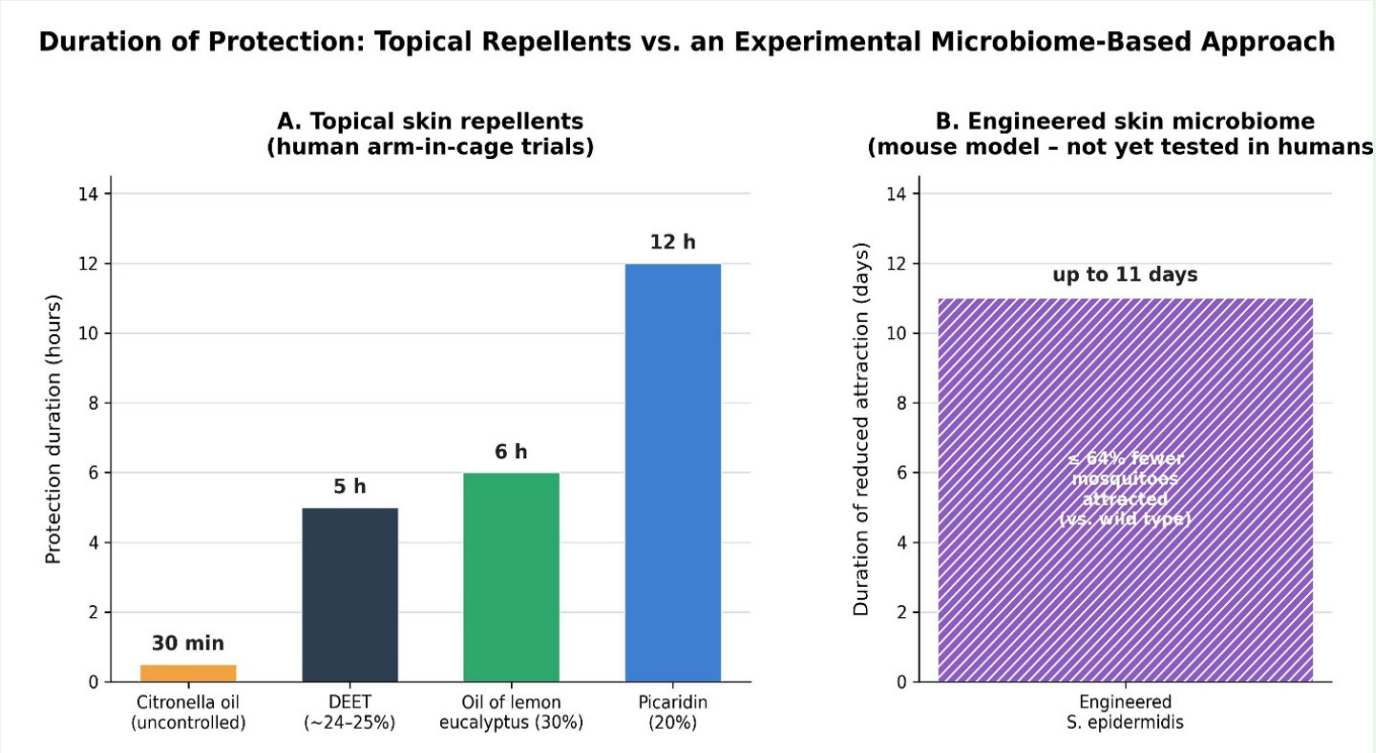


Figure 2. (A) Approximate protection duration of common topical repellents, from controlled human arm-in-cage trials, by active-ingredient concentration (Fradin & Day 2002; CDC 2025). (B) Duration of reduced mosquito attraction conferred by an engineered, lactic-acid-deficient skin bacterium in a mouse model (Liu et al. 2024). Panel B reflects a partial reduction in attraction rather than complete repellency, measured in mice rather than humans, and is shown separately because it is not directly comparable to the human topical-repellent data in Panel A.

and does not break down certain plastics like DEET does (CDC 2025). Oil of lemon eucalyptus provides a plant-based alternative that is effective for about six hours at a concentration of 30 to 40% (CDC 2025).

Behavioural Modifications

Regular bathing reduces the buildup of skin compounds discussed throughout this article. Light-coloured clothing is less detectable than dark clothing, consistent with the visual cues discussed earlier. *Aedes* species bite mostly during the day, while *Anopheles* and *Culex* bite mainly from dusk onward. Therefore, the timing of protective measures should match the locally dominant mosquito species instead of being applied uniformly around dawn and dusk.

Conclusion

Over two decades of chemical, genetic, and microbiome research have clarified why some people attract more mosquitoes than others. Carbon dioxide draws mosquitoes in from a distance, while skin compounds particularly carboxylic acids and lactic acid determine whether they land and bite. Blood type and skin microbiome composition also influence attractiveness, but none of these factors operate alone. The importance of each one can vary across studies and mosquito species.

These mechanisms are not just of academic interest. The mosquito genera responsible for dengue, malaria, and filariasis differ in when and how they seek hosts. Translating attraction biology into practical protection whether through standard repellents, better-timed behavioural precautions, or new microbiome-based approaches requires focus on which mosquito species and diseases are most relevant locally. In a country like India, where *Aedes*, *Anopheles*, and *Culex* all circulate widely, understanding this species-specific detail is key to reducing the burden of mosquito-borne diseases.

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GENERAL ARTICLE

Genomic Insights into Insecticide Resistance in the Fall Armyworm and Implications for Pest Management

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Abstract

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) is a highly invasive and destructive agricultural pest that threatens global food security because of its broad host range, high reproductive capacity, and remarkable adaptability. Since its introduction into Africa and Asia, it has spread rapidly and now infests more than 350 plant species, including maize, cotton, rice, sorghum, and wheat. Although insecticides remain the primary means of control, their effectiveness has declined owing to the rapid evolution of insecticide resistance. Resistance mainly develops through two mechanisms: target-site resistance, where genetic mutations reduce insecticide binding, and metabolic resistance, in which detoxification enzymes such as cytochrome P450 monooxygenases, carboxylesterases, glutathione S-transferases, and ATP-binding cassette transporters detoxify or eliminate insecticides before they reach their target sites. Recent advances in whole-genome sequencing, comparative genomics, transcriptomics, RNA sequencing, single-nucleotide polymorphism (SNP) discovery, and molecular diagnostics have improved the identification of resistance-associated genes and markers and enabled population-level molecular surveillance. Integrating genomic knowledge with insecticide rotation and integrated pest management is essential for delaying resistance evolution and ensuring long-term suppression of fall armyworm populations.

Keywords: Insecticide resistance, genomics, target-site resistance, metabolic resistance, integrated pest management.

Introduction

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), has become one of the most serious invasive insect pests affecting agricultural production worldwide. Originally distributed in the Americas, it has expanded rapidly into Africa, Asia, and Oceania, where it now causes extensive damage to maize and numerous other economically important crops. Its remarkable invasive success is attributed to its long-distance migratory ability, high reproductive capacity, broad host range exceeding 350 plant species, and adaptability to diverse agroecological conditions (Montezano et al., 2018). Since its first occurrence in Karnataka, India, in 2018, the pest has spread throughout nearly all major maize-growing regions, creating significant challenges for crop production and food security. The rapid establishment of fall armyworm populations, together with the increasing occurrence of insecticide resistance, has intensified concerns regarding its sustainable management (Mamahit and Kolondam, 2023).

Evidence of insecticide resistance in *S. frugiperda* was first documented in the United

States during the late 1970s, when field populations from Georgia and Alabama exhibited reduced susceptibility to synthetic pyrethroids. Subsequent studies reported resistance to additional insecticides, including carbaryl, methyl parathion, and trichlorfon (Young and McMillan, 1979). Since then, the pest has developed resistance to multiple insecticide groups, making chemical management increasingly difficult. By 2017, resistance had been recorded against 29 active ingredients representing six different modes of action across the Americas (Van den Berg and du Plessis, 2022). According to the Arthropod Pesticide Resistance Database (APRD, 2025), resistance has now been documented to 47 insecticidal active ingredients belonging to several chemical classes, with approximately 280 confirmed resistance cases reported globally.

Although insecticides remain indispensable for the management of fall armyworm, their field performance has gradually declined in many regions. Frequent and repeated application of the same insecticides imposes strong selection pressure on pest populations, enabling resistant individuals to survive treatments and pass resistance-associated traits to their offspring. As these resistant insects become more prevalent over successive generations, the effectiveness of insecticides decreases, resulting in repeated control failures and making the long-term management of fall armyworm increasingly challenging. Recent advances in genomics have expanded the study of insecticide resistance beyond conventional physiological and biochemical assays. In *S. frugiperda*, whole-genome sequencing has been used to detect resistance-associated variants in genes such as *ace-1*, the voltage-gated sodium channel (VGSC), ryanodine receptor (RyR), and ABCC2, demonstrating the value of genomic approaches for linking genetic variation with resistance phenotypes (Guan et al., 2021). Furthermore, these genomic approaches provide candidate molecular markers that can be incorporated into rapid diagnostics, allowing resistance alleles to be tracked via targeted molecular surveillance before they become widespread in field populations (Mavridis et al., 2025).

How Does Insecticide Resistance Develop?

Insecticide resistance is an evolutionary process driven by natural selection within insect populations. Naturally occurring genetic variation means that a small proportion of individuals may carry genes that reduce their susceptibility to a particular insecticide. Following repeated exposure to the same insecticide, susceptible insects are eliminated, whereas resistant individuals survive and continue to reproduce. Their offspring inherit the resistance traits, gradually increasing the frequency of resistant genes in subsequent generations. As this process continues, resistant individuals become dominant within the population, leading to a progressive decline in the effectiveness of the insecticide (Fig. 1). Consequently, pest management becomes less reliable, and satisfactory control may no longer be achieved even when insecticides are applied at the recommended field rates (Panini et al., 2016).

Mechanism of resistance

Resistance is an adaptive phenomenon that results from physiological and biochemical modifications in insects, enabling them to survive insecticide exposure. These adaptations involve changes in both toxicokinetic and toxicodynamic processes. Toxicokinetic mechanisms influence the absorption, activation, metabolism, transport, and elimination of insecticides, thereby reducing the amount of toxic compound that reaches its target site and contributing to metabolic

resistance. In contrast, toxicodynamic mechanisms alter the interaction between the insecticide and its target through structural modifications, gene amplification, or target-site mutations, thereby contributing to target-site resistance and decreasing the insecticide's effectiveness (Kennedy & Tierney, 2012; Fig. 2).

How Does the Fall Armyworm Outsmart Insecticides?

FAW survives insecticide exposure mainly through **two remarkable defence strategies** (Fig. 3)

- **Changing the insecticide target (Target-site resistance)**
- **Detoxifying insecticides before they can act (Metabolic resistance)**

Together, these mechanisms greatly reduce the effectiveness of chemical control and complicate resistance management.

Changing the Lock: Target-Site Insensitivity

Target-site resistance results from alterations in insecticide target proteins caused by genetic mutations or changes in target-gene expression, thereby decreasing the sensitivity of insects to these chemicals. A useful analogy is to imagine the insecticide as a key and the target protein as a lock. When mutations change the shape or properties of the lock, the key can no longer interact with it effectively, allowing the insect to survive. In *S. frugiperda*, resistance-associated variants have been documented in several target genes, although the strength of experimental evidence differs among targets.

Several important target proteins have been identified in *S. frugiperda*.

Acetylcholinesterase (AChE)

AChE is a serine hydrolase enzyme that terminates nerve impulse transmission by hydrolysing acetylcholine at cholinergic synapses. It contains a conserved **Ser–His–Glu catalytic triad** located within a deep active-site gorge, along with an anionic binding site that facilitates acetylcholine binding. AChE is the primary target of **organophosphate and carbamate insecticides**, which inhibit the enzyme and disrupt

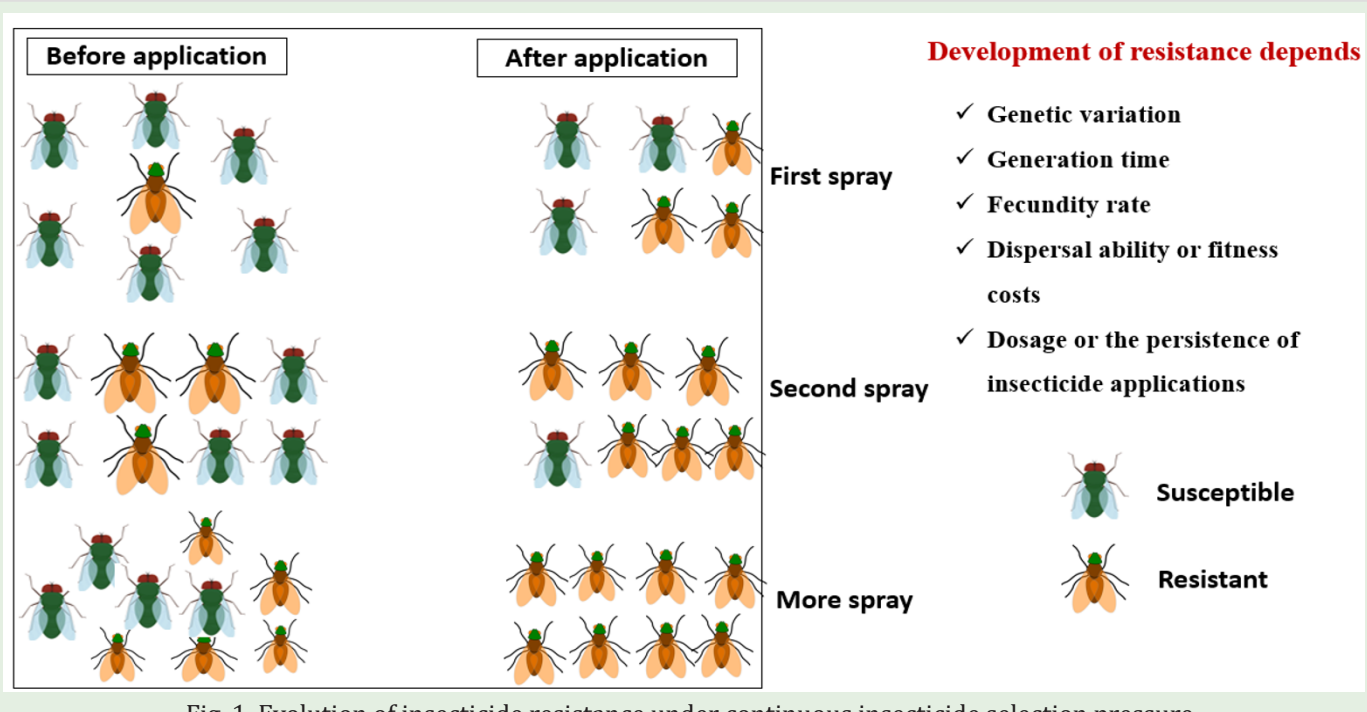


Fig. 1. Evolution of insecticide resistance under continuous insecticide selection pressure

normal nerve function. However, mutations in the **Ace-1** gene reduce the binding affinity of these insecticides, allowing normal nerve transmission to continue and thereby conferring resistance (Davir et al., 2010). In case *S. frugiperda* mutation of *the ace-1* gene revealed three amino acid substitutions in the acetylcholinesterase (AChE) gene (A201S, G227A, and F290V) were associated with organophosphate resistance (Carvalho et al., 2013).

Voltage-gated sodium channel (VGSC)

VGSC consists of six transmembrane segments (S1–S6), where S1–S4 function as voltage sensors and S5–S6 form the sodium-conducting pore. Pyrethroids bind to a hydrophobic pocket between the S4–S5 linker and S5–S6 helices, disrupting normal channel function and causing prolonged nerve excitation. **Knockdown resistance (kdr)** mutations in the **VGSC** gene reduce pyrethroid binding, resulting in insecticide resistance (Field et al., 2017). There are six target VGSC gene mutations (M918T, I936V, F1020S, T929I, L932F, and L1014F) identified in lambda-cyhalothrin resistant population (Wang et al., 2023a). Point mutations in VGSC (T929I, L932F, and L1014F) are associated with resistance to pyrethroid insecticide insecticides and Bt proteins in *S. frugiperda* (Guan et al., 2021).

Glutamate-gated chloride channel (GluCl)

A Cys-loop ligand-gated ion channel that acts as the molecular target of avermectins such as abamectin and emamectin benzoate. Binding of glutamate opens the chloride channel, whereas avermectins bind between adjacent transmembrane domains (M1 and M3), causing prolonged chloride influx, neuronal hyperpolarization, paralysis, and insect death (Ozoe et al., 2013). Alterations in GluCl can reduce insecticide sensitivity and contribute to resistance. Wang et al. (2023b) reported that the higher expression of SfGluCl gene in the head and nerve cord was significantly higher than that in other tissues. They found that the expression level of SfGluCl was significantly higher in eggs than in other developmental stages. Knockdown of the GluCl gene reduced FAW mortality by EB, suggesting its key role in EB effectiveness. Cai et al.

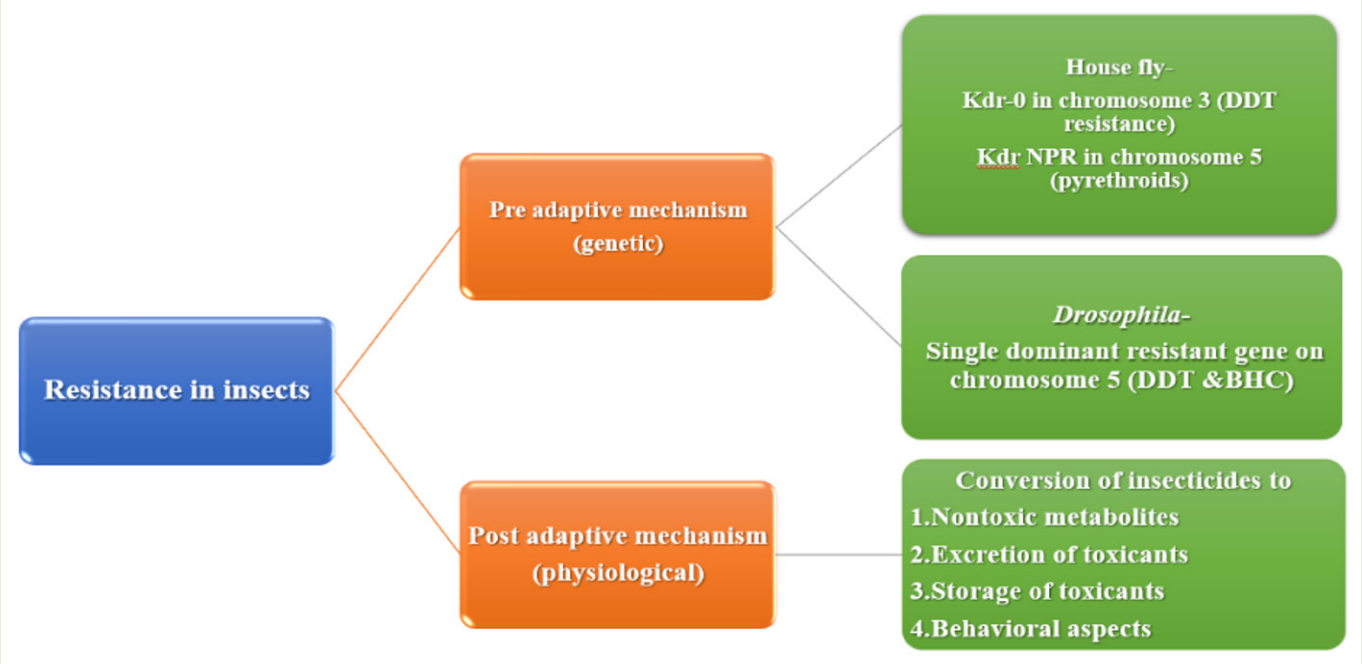


Fig.2. Overview of insecticide resistance mechanisms in insects

(2024) reported that, four target-site mutations—A309V, G314D, A309T, and G326E—were identified in the GluCl channel of the fall armyworm (FAW).

Ryanodine receptor (RyR)

RyR is a calcium-release channel located in the sarcoplasmic reticulum and is the primary target of diamide insecticides, including chlorantraniliprole and flubendiamide. Binding of diamides to the receptor disrupts calcium homeostasis, leading to continuous muscle contraction, paralysis, and ultimately insect death. Mutations such as **G4946E, I4790M, and I4734M** reduce diamide sensitivity and have been reported in resistant lepidopteran pests, including *S. frugiperda* (Zuo et al., 2020). The molecular studies, including PCR amplification and sequencing of a FAW RyR fragment, revealed the presence of an I4790M mutation in the C-terminal region, previously associated with target-site mutations in diamide-resistant lepidopteran pests (Boaventura et al., 2020)

Chitin synthase A (CHSA)

CHSA gene encodes the enzyme responsible for chitin biosynthesis, making it the target of benzoylurea insecticides such as lufenuron. The enzyme contains a catalytic domain and multiple transmembrane helices that facilitate chitin polymer synthesis and transport. Mutations in the **CHSA** gene, particularly **I1043L**, are associated with resistance to benzoylurea insecticides in several insect species. In *S. frugiperda*, however, no resistance-conferring mutation has been identified in **SfCHSA**. Nevertheless, the increased expression of **SfCHSA** after lufenuron exposure indicates that changes in gene regulation may contribute to reduced susceptibility (Lv et al., 2022).

Insect's Chemical Defence Factory: Detoxification mechanism

Metabolic resistance is characterized by increased detoxification of insecticides rather than alterations in their target proteins, limiting the amount of insecticide available to produce toxicity. This defence system functions much like a **chemical processing factory** and involves three major enzyme families.

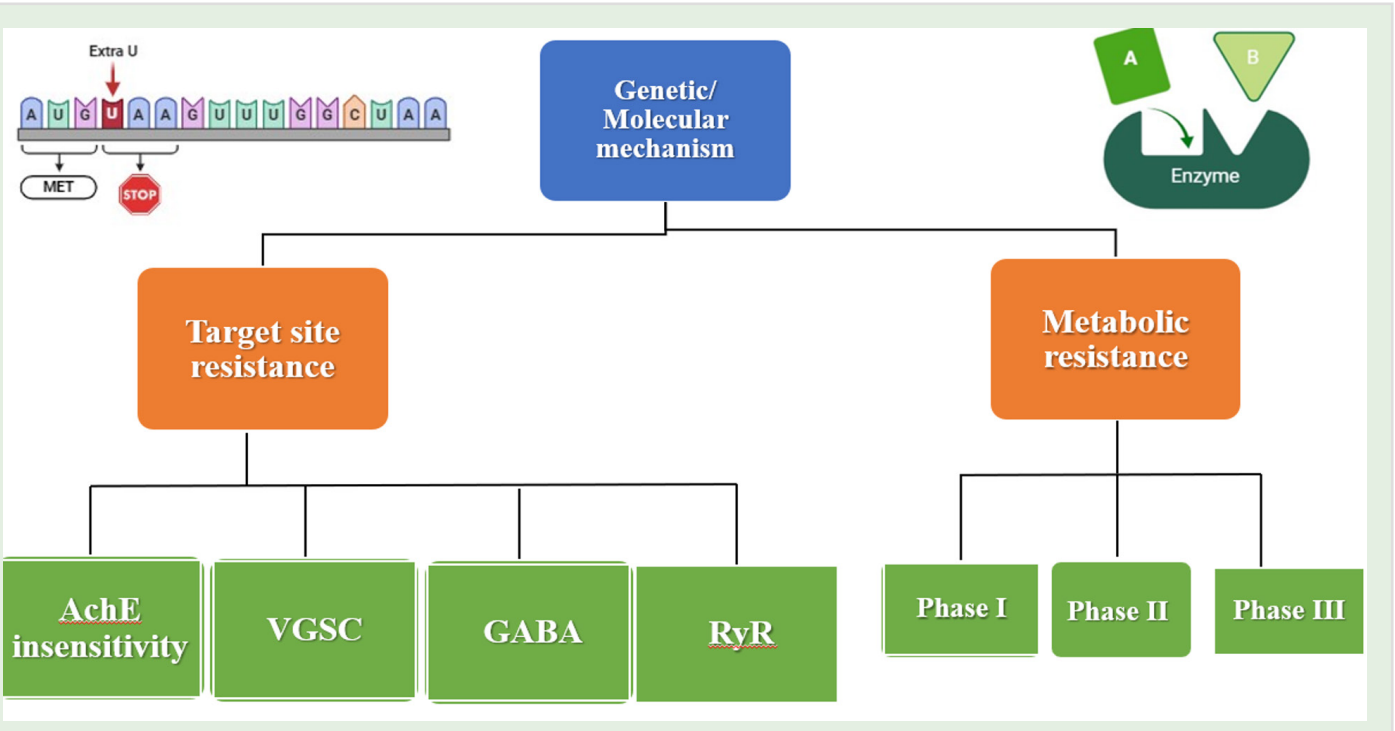


Fig. 3. Molecular basis of insecticide resistance in insects

Phase I: Cytochrome P450 Monooxygenases (CYPs): The First Line of Defence

Cytochrome P450 genes (CYP) represent one of the largest gene families, found in nearly all living organisms. CYPs catalyze a wide range of reactions, including hydroxylation, epoxidation, and oxidation. In insects, CYPs play a role in endogenous metabolism, such as ecdysteroid biosynthesis and hydrocarbon production, and are also involved in detoxifying xenobiotics. Cytochrome P450 enzymes chemically modify insecticides through oxidation, reducing their toxicity. The FAW genome contains an exceptionally large P450 gene family comprising **425 CYP genes**, including **283 species-specific genes**, reflecting its remarkable detoxification potential (Gui et al., 2022).

Carboxyl/Cholinesterases (CCEs): Breaking Down Insecticides

Insect carboxylesterases, also known as carboxyl/cholinesterases (CCEs), are involved in a variety of physiological processes in living things, including the detoxification of different xenobiotics and the metabolism of endogenous substances like hormones, pheromones, and neurotransmitters. They are essential for protection against a variety of allelochemicals found in plants and insecticides (Oakeshott et al., 2005). Carboxylesterases hydrolyse organophosphates, carbamates and pyrethroids before they reach their targets. Nearly **96 CCE genes** have been identified in *S. frugiperda*, and overexpression of members of the **CCE001** family has been strongly associated with metabolic resistance (Gouin et al., 2017).

Phase II: Glutathione S-transferases (GSTs): Neutralising Toxic Molecules

GSTs conjugate glutathione to suitable electrophilic compounds or metabolites, increasing their water solubility and facilitating elimination. In insects, the Delta and Epsilon classes are particularly important for xenobiotic detoxification and have been repeatedly implicated in insecticide resistance GSTs convert toxic metabolites into water-soluble compounds that can be safely removed from the insect body (Koirala et al., 2022). Transcriptomic studies have identified **31 GST genes**, many of which are induced after exposure to chlorantraniliprole and emamectin benzoate (Aioub et al., 2023).

Phase III: ABC Transporters: Pumping Out the Poison

ATP-binding cassette (ABC) transporters do not directly detoxify insecticides enzymatically. Instead, they use ATP to transport insecticides, their conjugates, and other metabolites across cellular membranes, thereby reducing intracellular accumulation and facilitating excretion. Mutations in ABCC2 and ABCC3 have also been associated with resistance to *Bacillus thuringiensis* (Bt) Cry toxins, illustrating that ABC proteins can also act as receptors or components of toxin-response pathways in addition to their transport functions (Franz et al., 2022).

Implication

- Reduced Effectiveness of Insecticides: Leading to control failures and increased pest numbers.
- Increased Use of Insecticides: higher doses and more frequent applications.
- Increased Costs and Economic Losses: Higher costs due to the need for additional insecticide applications.
- Environmental and Non-Target Impacts: Environmental contamination, affecting soil, water, and non-target organisms.
- Cross-Resistance and Multi-Resistance:

Resistance to a single insecticide may also reduce susceptibility to other insecticides within the same or even different chemical classes.

- Challenges for Integrated Pest Management: Resistance can reduce the number of effective chemical options available within IPM programmes, making coordination of biological, cultural, mechanical, physical, and chemical tactics more difficult.
- Rapid Spread of Resistant Invasive Populations: The high dispersal capacity of FAW can facilitate the movement of resistance alleles between regions, particularly when resistant individuals are introduced into newly invaded areas.

Integrated Resistant Management

- Rotation of Insecticides: Insecticides should be rotated according to their IRAC mode-of-action (MoA) groups rather than simply alternating products with different trade names. Sequential use of insecticides with the same MoA can impose similar selection pressure and favour resistant genotypes; rotation across effective MoA groups can reduce this pressure when implemented with appropriate label and resistance-management guidance
- Use of Synergists: Synergists that inhibit specific detoxification enzymes can restore susceptibility in some cases and can also help identify metabolic mechanisms, but their practical use depends on regulatory approval and demonstrated field relevance.
- Negative Cross-Resistance: Negative cross-resistance occurs when resistance to one compound is associated with increased susceptibility to another compound. Where this relationship is experimentally demonstrated, it may provide an additional option for designing rotation strategies.
- Integrated Pest Management (IPM): Combining biological, cultural, mechanical, physical, and judicious chemical control methods to achieve sustainable pest management.
- Biotechnological Approaches: Gene-editing technologies such as CRISPR/Cas9 and RNA interference (RNAi) can help validate candidate resistance genes and may contribute to future diagnostic or control approaches.
- Regular Monitoring: Tracking resistance trends in pest populations to detect early signs and implement timely interventions.

Conclusion

The remarkable adaptability of the fall armyworm has enabled it to evolve resistance through two major mechanisms: **target-site resistance**, in which mutations reduce insecticide binding, and **metabolic resistance**, in which detoxification enzymes rapidly degrade insecticides before they reach their targets. Advances in genomics have greatly improved our understanding of these resistance mechanisms and provided valuable tools for monitoring resistant populations. Nevertheless, sustainable management requires these molecular insights to be translated into routine resistance monitoring and practical insecticide-resistance management. Looking ahead, genomic surveillance, molecular diagnostics, and integrated phenotypic monitoring will play an increasingly important role in detecting emerging resistance alleles, tracking their spread, and supporting evidence-based insecticide selection and IPM programmes. Such

a forward-looking approach can help preserve the effectiveness of existing insecticides, delay resistance evolution, and support long-term management of fall armyworm populations.

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GENERAL ARTICLE

Singing Symbionts: The Fascinating Alliance Between Caterpillars and Ants

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Abstract

The different ways of survival among different species vary based on their size and vulnerability. Insects adopt remarkably striking mechanisms such as camouflage, mimicry, or symbiosis. Symbiosis involves complex associations of insects with one another as well as with other groups, and helps in understanding the ecological dynamics of these groups. The "ant love" of caterpillars, also called myrmecophily, is one such intriguing and complex association between butterfly caterpillars, especially Lycaenidae, and different species of ants. These caterpillars maintain associations with ants in different ways, such as through the release of chemical rewards, production of substrate-borne vibrations, and influencing ant behaviour. The different adaptations of caterpillars help shape associations ranging from facultative to obligate, and from largely mutualistic to subtly manipulative interactions. An extreme form of obligate myrmecophily occurs in the Lilac Silverline, *Cigaritis lilacinus,* whose caterpillars are associated with the cocktail ant *Crematogaster hodgsoni.* The larvae are maintained within ant colonies and receive food from the ants in addition to protection. Several specialized organs have developed in these caterpillars, including the dorsal nectary organ (DNO), or Newcomer's gland, tentacle nectary organs (TOs), and stridulatory structures, muscular contractions, or specialized sclerotized surfaces for producing vibroacoustics, aptly describing them as "singing caterpillars." The association between vulnerable caterpillars and the dominance of ants is remarkably widespread, with nearly 41% of ant genera known to engage in associations with other organisms. Such protection of caterpillars from predators and parasitoids, together with the ecological dominance of ants, may have played an important role in shaping the evolution and persistence of lycaenid-ant associations.

Keywords: Myrmecophily, Vibroacoustic, Caterpillar, Ants, Lycaenidae

Introduction

Survival is the central challenge for every species on Earth, but the ways organisms meet it are remarkably diverse. In insects, despite their small size and apparent vulnerability, these strategies can be especially striking. Butterflies, for instance, evade predators through a range of adaptations: blending into their surroundings (camouflage or crypsis), storing toxins and advertising them with warning colours (aposematism), imitating toxic species (mimicry), or even resembling inedible plant parts (masquerade) (Prabhulinga et al., 2022).

Some butterflies take their interactions with other organisms a step further by forming remarkable alliances with ants. Lycaenidae is particularly well known for these associations, with approximately 75% of its ~5,200 species estimated

to be myrmecophilous, while ant associations have also been reported in roughly 20% of the ~1,500 species of Riodinidae (Pierce & Dankowicz, 2022). In these relationships, caterpillars-and, in some species, pupae-interact closely with ants through a range of chemical, tactile and vibrational signals. This association, known as myrmecophily ("ant love"), can range from loose and facultative interactions to highly specialized obligate partnerships. Many myrmecophilous caterpillars possess specialized organs that help them communicate with, attract and reward ants, often through nutrient-rich secretions (DeVries, 1992). In return, ants may provide protection from predators and parasitoids. Thus, what begins as a simple association can become a finely tuned ecological partnership in which vulnerable butterfly larvae effectively turn their vulnerability into an evolutionary advantage (Basu & Kunte, 2020).

At the heart of this relationship are sugary, energy-rich secretions produced by specialized organs in the caterpillars. Interestingly, similar secretions are produced by plant extrafloral nectaries, which ants also exploit (DeVries, 1992). In both cases, ants are effectively "paid" for their services, protecting the caterpillars, as well as such plants and other associated insects. The protective



Fig.1 An ant individual tending a caterpillar of lime blue butterfly (a lycaenid butterfly), Photo: Raghavendra Rajadhyaksha

role of ants in these associations is well documented across many lycaenid butterflies (Leimar & Axén, 1992; Pierce & Dankowicz, 2022).

The family Lycaenidae, often called the gossamer-winged butterflies, accounts for nearly 40% of all butterfly species globally, making it one of the largest and most diverse groups (Khyade et al., 2018). Many species are characterized by delicate, thread-like tails on their hindwings, ranging from short tufts to long, flowing extensions. Compared to other butterfly families, Lycaenidae is considered a tough and complex group, owing to its remarkable variation in form, colouration, and wing patterns. The complexity is clearly visible in the myrmecophilous nature of their caterpillar, which has adapted quite complex modifications to attract ants (Pierce et al., 2002).

Myrmecophilous Butterfly Caterpillar Adaptations

Lycaenid caterpillars associated with ants possess a remarkable suite of myrmecophilous organs that release chemical rewards, produce substrate-borne vibrations, and influence ant behaviour. These adaptations help shape associations ranging from facultative to obligate (Pierce & Dankowicz, 2022; DeVries, 1992), and from largely mutualistic to subtly manipulative interactions. In India, such associations have been reported in the Scarce Shot Silverline (*Cigaritis elima*), Common Shot Silverline (*C. ictis*), Long-banded Silverline (*C. lohita*), Plumbeous Silverline (*C. schistacea*), Common Silverline (*C. vulcanus*) and Sahyadri Common Tinsel (*Catapaecilma major callone*), particularly in association with *Crematogaster* ants. Other examples include Redspot (*Zesius chrysomallus*), Pointed Ciliate Blue (*Anthene lycaenina*), Large Oakblue (*Arhopala amantes*) and Centaur Oakblue (*Arhopala centaurus*), which are associated with *Oecophylla*



Fig.2 Dark grass blue is one of many butterflies that, as a caterpillar, enters into a symbiosis with ants and is called myrmecophily or love for ants, which has evolved in Lycaenidae and Riodinidae butterflies (Photo: Jyoti Antil)

and other ant genera (Sujitha et al., 2023; Kalesh & Prakash, 2005).

An extreme form of obligate myrmecophily occurs in the Lilac Silverline, *Cigaritis lilacinus*, whose caterpillars are associated with the cocktail ant *Crematogaster hodgsoni*. The larvae are maintained within ant colonies and receive food from the ants in addition to protection, illustrating how deeply some lycaenids can integrate into ant societies (Basu & Kunte, 2020).

These relationships are mediated by several specialized organs. Pore cupola organs (PCOs) release cuticular chemicals that facilitate recognition and acceptance by ants, helping to suppress aggressive responses (Casacci et al., 2019).

The dorsal nectary organ (DNO), or Newcomer's gland, located around the seventh abdominal segment in many lycaenids, produces carbohydrate-rich secretions that reward attending ants and encourage continued tending (Pierce & Dankowicz, 2022; Fiedler 1991). Ants may stimulate secretion through antennal contact, creating a dynamic exchange in which increased attendance can trigger additional rewards. In some species, however, caterpillars can manipulate this exchange by producing droplets and subsequently reabsorbing them before ants consume them (Basu & Kunte, 2020).

Caterpillars can further regulate ant attendance through eversible tentacle nectary organs (TOs). These organs can be rapidly extended and retracted and are involved in signalling during interactions with ants, helping regulate the intensity and persistence of attendance (Pierce & Dankowicz, 2022). Together, chemical recognition, nutritional rewards, tactile signalling and vibrational communication create a sophisticated multimodal communication system, allowing caterpillars not merely to coexist with ants but to actively recruit, reward and manipulate their defensive partners" (Casacci et al., 2019).

Apart from chemical secretions and specialized tentacular or nectary organs, many

myrmecophilous lycaenid caterpillars also communicate with attending ants through substrate-borne vibrational signals-making them, in a sense, "singing caterpillars" (Casacci et al., 2019). These vibroacoustic signals may be produced through stridulatory structures, muscular contractions, or specialized sclerotized surfaces and can help recruit and maintain ant attendance (Travassos, & Pierce, 2000).

In the Imperial Hairstreak, *Jalmenus evagoras*, larvae produce grunts, hisses and drumming sounds, while experiments showed that pupal vibrational calls increase ant attraction and help maintain an attendant ant guard. Larvae also produced more sounds when attended by the tyrant ant *Iridomyrmex anceps*, suggesting that vibrations contribute to maintaining the butterfly–ant association. Thus, chemical secretions may provide ants with information about the caterpillar and its rewards, whereas vibrational signals provide an additional, spatially localized cue that helps draw ants towards and maintain their attention on the caterpillar (Casacci et al., 2019; Travassos, & Pierce, 2000). Rather than functioning as an isolated "sound signal," caterpillar stridulation is therefore better understood as part of a multimodal communication system, in which vibrational cues complement chemical signals to recruit, retain and influence attendant ants (Pierce & Dankowicz, 2022; DeVries, 1990).

A specialized larval stridulatory organ has also been described in the Bright Oak-blue, *Arhopala madytus* (Pierce & Dankowicz, 2022), Similarly, in the riodinid Irēnea Metalmark, *Thisbe irenea*, experimentally silenced larvae received fewer attending ants, providing direct evidence that vibrational signalling can influence ant attendance (Pierce & Dankowicz, 2022; DeVries, 1992).

Myrmecophilous Association: Ants as Bodyguards

Interlocking symbioses are a defining feature of many terrestrial ecosystems, with ants often maintaining relationships with multiple organisms on the same plant. Such interactions are remarkably widespread, with nearly 41% of ant genera known to engage in associations with other organisms (Oliver et al., 2008). In myrmecophilous

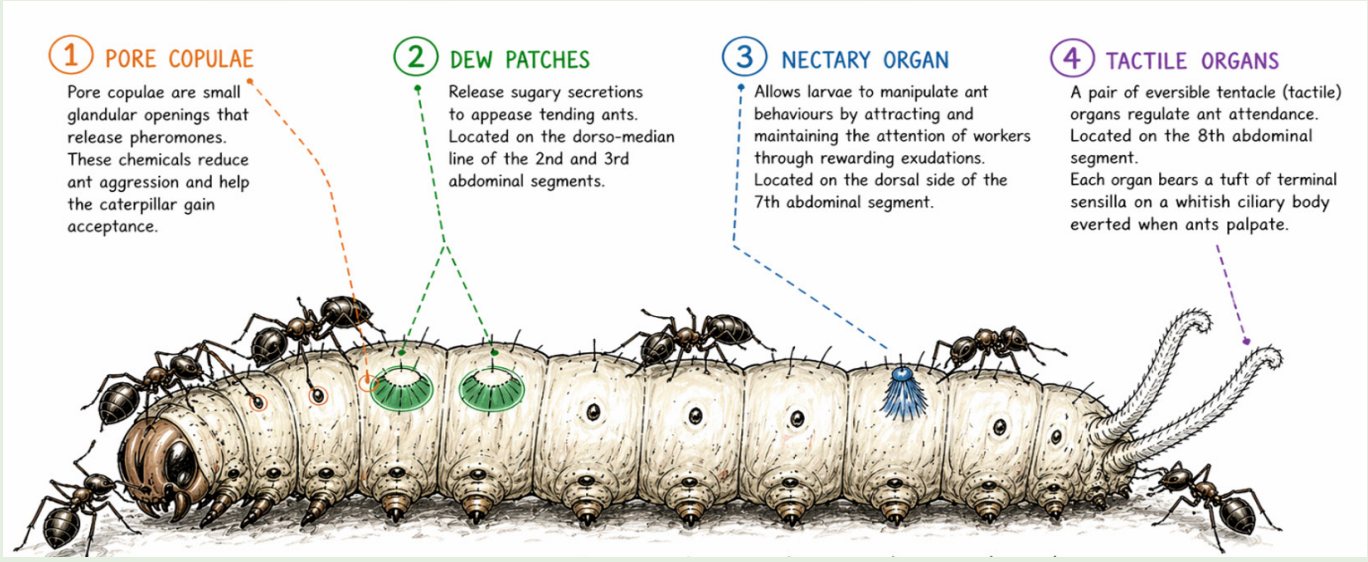


Fig.3 Myrmecophilous Butterfly Caterpillar Adaptations - Specialized morphological and chemical traits that enable caterpillars to interact, integrate, and often exploit ant societies. Each organ plays a distinct role in mediating symbiosis, collectively facilitating communication, appeasement, and mutual benefit with ants. (Photo source: Jyoti Antil)

associations, ants provide protection to butterfly caterpillars from predators and parasitoid, while receiving nutrient-rich secretions in return. The dependence of this relationship is well illustrated by the Reakirt's Blue, *Hemiargus isola*. Its larvae are principally parasitized by the braconid wasp *Cotesia cyaniridis*, which accounted for more than 99% of recorded parasitism, while the tachinid fly *Aplomya theclarum* was also recorded (Weeks, 2003). Experimental exclusion of ants resulted in 78% larval mortality due to parasitism, nearly twice that observed among ant-attended larvae, demonstrating the protective value of ant attendance (Weeks, 2003; Casacci et al., 2019). Moreover, when exposed to simulated attacks, larvae increased their nectar secretion and received greater ant attendance, indicating that caterpillars can actively enhance their rewards when protection is most needed. Thus, the interaction represents more than a simple exchange of food for protection: caterpillars can modulate their rewards to recruit defensive partners, while ants reduce enemy pressure on the caterpillar (Leimar & Axén, 1992). Such protection from predators and parasitoids, together with the ecological dominance of ants, may have played an important role in shaping the evolution and persistence of lycaenid-ant associations (Casacci et al., 2019; DeVries, 1992).

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GENERAL ARTICLE

Insect Epigenetics: Vital Information for Next-Gen Pest Management

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Abstract

Epigenetics is transforming our understanding of insect biology by revealing how gene activity can be regulated without altering the underlying DNA sequence. Through mechanisms such as DNA methylation, histone modifications, and non-coding RNAs, insects rapidly respond to environmental cues, influencing development, behaviour, insecticide resistance, stress adaptation, and interactions with symbionts and pathogens. Unlike permanent genetic mutations, epigenetic modifications are reversible and, in some cases, can be inherited across generations, enabling pest populations to adapt rapidly to changing environments and management practices. Recent discoveries have demonstrated that epigenetic regulation contributes to xenobiotic detoxification, climate resilience, diapause, migration, and host–microbe interactions, highlighting its significance in pest ecology. Advances in RNA interference, CRISPR/dCas9-mediated epigenome editing, epigenetic priming, and small-molecule inhibitors offer exciting opportunities to exploit these mechanisms for sustainable pest control. Although technical and ecological challenges remain, integrating epigenetic knowledge into integrated pest management promises innovative, precise, and environmentally friendly strategies for managing insect pests in the era of climate change and emerging insecticide resistance.

Keywords: DNA methylation; Transgenerational resistance; non-coding RNA; Epi-transcriptomics; Stress memory; dCas9

Introduction

Every insecticide spray, every resistant pest population, every characteristic and miraculous behaviour of insects is being explained nowadays purely through the lens of genetic information: mutations, gene amplifications, inherited alleles. But a quieter layer of biology has been steering these same outcomes all along. It doesn't change a single letter of the genetic code, yet it decides which genes speak, when they speak, and how loudly. In very simple terms, DNA is hardware, and epigenetics is software for a living organism. This is epigenetic, and for anyone working on insect pest management today, it is no longer a curiosity confined to textbooks. It is becoming a working part of the toolkit for next-generation insect pest management.

Epigenetics: Language Beyond DNA

The word epigenetics was coined in the 1940s by embryologist Conrad Waddington, who imagined development as a ball rolling down a landscape of branching valleys, in the sense that genes provide the terrain and the environment nudges the ball's path (Waddington, 1942). Decades of molecular biology later, the definition has sharpened considerably; epigenetics is now understood as the study of mitotically and, in some cases, meiotically heritable changes in gene

function that occur without any change to the underlying DNA sequence.

What makes this field interesting for pest management is the question of inheritance. Not all epigenetic changes are passed on. Some of it is intragenerational: a single cell responds to a stimulus, and that response is faithfully copied every time the cell divides, which is essentially how one genome gives rise to hundreds of different cell types in a developing insect. Some of it is intergenerational: a parent's environment reprograms its germ cells, so the very next generation carries the mark. And a rarer category, transgenerational inheritance, means the change persists even in individuals who were never directly exposed to the triggering stimulus. It is this last category that has excited and worried entomologists the most, because it implies that a single stress event, such as one round of insecticide spraying, could leave a signature that outlives the exposed generation.

Insect Epigenetics and Underlying Mechanisms

Three molecular systems do most of the epigenomic framework; among them, DNA methylation the addition of a methyl group to cytosine bases is the best studied. Interestingly, insects methylate a much smaller fraction of their genome than vertebrates, and the marks are typically enriched within gene bodies rather than at promoters, the reverse of the canonical vertebrate pattern. However, this is a broad trend rather than a fixed rule, and methylation levels and patterns vary substantially across insect orders, ranging from near-total absence in dipterans such as *Drosophila* to appreciable gene-body methylation in Hymenoptera and other lineages that retain a functional Dnmt3 (Field et al., 2004; Provataris et al., 2018). Apart from these methylation marks, the enzymes that write these marks, DNMT1 and DNMT3, are essential for reproduction and development in several insects investigated.

Histone modification is the second major system. DNA in the nucleus is spooled around histone proteins, and chemical tags, acetyl groups being the best known, determine how tightly that spool is packed. Loosely packed chromatin is accessible to transcription machinery; tightly packed chromatin is silent. Enzymes called histone acetyltransferases and deacetylases add and remove these tags respectively, and their balance has been shown to govern the timing of metamorphosis in moths and beetles (Mukherjee *et al.,* 2012).

The third system, non-coding RNA, encompasses several classes of small RNAs that regulate gene expression through mechanistically distinct routes. Small interfering RNAs (siRNAs) and microRNAs (miRNAs) act primarily at the post-transcriptional level: loaded into Argonaute proteins within the RNA-induced silencing complex (RISC), they base-pair with complementary messenger RNA to trigger its cleavage or translational repression, without directly altering chromatin state. PIWI-interacting RNAs (piRNAs), by contrast, function predominantly in the germline, where PIWI-clade Argonautes use them to silence transposable elements; alongside transcript cleavage, piRNA–PIWI complexes can be recruited to nascent transcripts at target loci to deposit repressive histone marks such as H3K9 methylation and promote heterochromatin formation - a chromatin-associated, transcriptional silencing role that siRNAs and miRNAs generally lack. Together, these pathways make non-coding RNA a genuinely two-tiered regulatory layer, both of which are now recognised as central to antiviral defence, silencing of mobile genetic elements in the

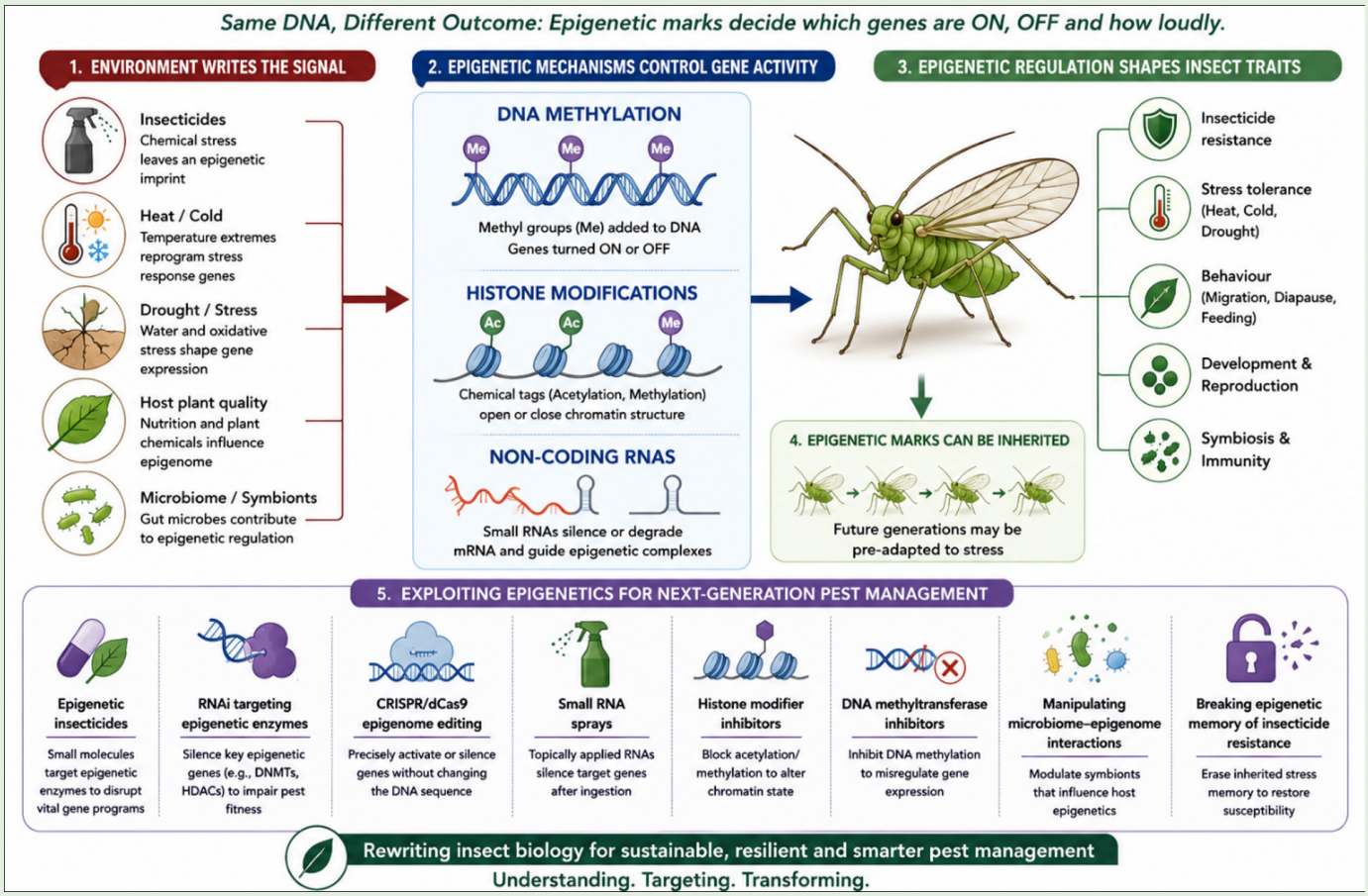


Figure: Epigenetic mechanisms in insects and their potential in pest management.
(Figure generated in FIGURELABS Tool: https://figurelabs.ai)

germline, and xenobiotic degradation (de Vanssay et al., 2013).

Insect Epigenome-Regulated Mechanisms: Refining Present Control Methods

Insect Physiology and Development

Development and reproduction in insects are epigenetically gated at several checkpoints. The transcriptional co-activator CREB-binding protein (CBP) also called as Nejire, which carries histone acetyltransferase activity, sits at the centre of a network with hundreds of interacting partners governing hormone signalling, metamorphosis, and circadian rhythm across insect orders (Hung et al., 2007). Because many downstream physiological outcomes converge on a small set of epigenetic regulators, these nodes are attractive candidates for targeted disruption.

Insect Behaviour

Two of the most dramatic insect behaviours are diapause and long-distance migration; both carry a possible epigenetic signature. In the parasitoid wasp *Nasonia vitripennis*, DNA methylation tracks the photoperiodic timer that guides the insect when to enter and exit dormancy, echoing the well-established role of epigenetic regulation in circadian clocks more broadly (Pegoraro et al., 2016). In the monarch butterfly, the same set of migratory genes is present in every generation, but it is switched on or off depending on the season, producing the reversal in flight direction seen between the outbound autumn migration and the return journey in spring, hypothesised to a possible epigenetics regulation, though not fully evident (Zhu et al., 2009). Much more concrete

evidence in insect behaviour is the migratory locust *Locusta migratoria*; epigenetic regulation has been experimentally linked to behavioural phase change. Knockdown of DNA methyltransferase 3 (Dnmt3) altered locomotor activity associated with the transition between solitarious and gregarious phases and produced substantial changes in brain gene expression, implicating DNA methylation in the regulation of phase-related behaviour (Hou et al., 2020). More recently, chromatin accessibility was shown to regulate promoter usage of the dopamine-synthesis gene *henna* in response to population density, providing a mechanistic link between chromatin remodelling and gregarious behaviour (Li et al., 2025). Because gregarious locusts form migratory swarms, these findings demonstrate how epigenetic regulation can contribute to the behavioural plasticity underlying swarm formation and migration.

Drivers of Insecticide Resistance

Insecticide resistance costs the world tens of billions of dollars annually, and for decades the story was almost entirely genetic with target-site mutations, detoxifying enzyme amplification. The first evidence linking epigenetic modification to insecticide resistance came from the peach-potato aphid, *Myzus persicae*, where loss of resistance in clonal lineages was accompanied by a simultaneous loss of DNA methylation at the amplified esterase gene (Field et al., 1989) demonstrated methylation is tightly associated with the transcriptional state of the gene, although the direct causal role was not established. Since then, the investigations have widened considerably. Recent studies describe how DNA methylation can silence or activate detoxification genes, how histone acetylation dynamically remodels chromatin around stress-responsive loci and, in whiteflies, how an RNA-level modification called m6A methylation on the CYP4C64 detoxification gene transcript enhances its expression and boosts enzymatic breakdown of insecticide, adding an entirely new "epi-transcriptomic" layer to the resistance story (Yang et al., 2021). The sublethal effect on parental generations drives the resistance marks to change in methylation pattern in the resistance conferring CYP genes of intergenerational offspring (Brevik et al., 2021). Evidence for the inheritance of stress-associated epigenetic changes across generations is emerging in insects, but the extent to which such inheritance contributes directly to insecticide resistance remains species and context-dependent. Unless we understand these mechanisms, solely the classic insecticide resistance mechanisms can't manage xenobiotic resistance in insects (Mogilicherla and Roy, 2023).

Microbiome Interactions

Many sap-feeding pests, whiteflies and aphids depend on obligate bacterial symbionts for nutrients supply, and the relationship is regulated epigenetically from both sides. Wolbachia infection, for instance, reshapes genome-wide DNA methylation patterns in the mosquito *Aedes aegypti* (Ye et al., 2013), silencing some genes and de-repressing hundreds of others, in part by suppressing the host's own methyltransferase (Zhang et al., 2013). Because Wolbachia-based approaches are already deployed for vector control, understanding this epigenetic cross-talk is directly relevant to refining those programmes.

Insect Parasite Interaction

Entomopathogens manipulate the host's epigenome rather than its DNA sequence, hijacking histone acetylation and deacetylation to delay development or blunt immune gene expression, buying themselves time to establish infection. Recent studies in this area describe it as a two-way

epigenetic arms race: hosts fine-tune immune gene expression through methylation, histone marks and small RNAs to fight back, while pathogens counter by reprogramming those very same systems (Sharakhov and Sharakhova, 2015).

Climate Adaptation

Heat waves, cold snaps, drought, starvation, and other environmental extremes are becoming increasingly frequent under climate change, challenging insect survival across ecosystems. Traditionally, stress tolerance in insects was attributed to physiological acclimation and natural selection acting on genetic variation. However, recent research has revealed that insects can also develop "epigenetic stress memory", enabling them to rapidly adjust gene expression without altering their DNA sequence. The epigenetic mechanisms modulate genes involved in heat shock proteins (HSPs), antioxidant defence, energy metabolism, osmotic regulation, and immunity. Studies in insects such as *Drosophila melanogaster*, *Tribolium castaneum*, aphids, and mosquitoes suggest that some of these epigenetic signatures can persist beyond the exposed individual and be inherited by subsequent generations, producing offspring that are better equipped to withstand similar environmental stresses. Such transgenerational plasticity allows pest populations to establish rapidly in new environments, survive extreme climatic events, and expand their geographical distribution.

Understanding these adaptive mechanisms opens new opportunities for sustainable pest management. Targeting the epigenetic machinery that governs stress tolerance could reduce the ability of pests to cope with heat, cold, and drought, making them more vulnerable to climatic extremes and increasing the efficacy of insecticides and biological control agents. Integrating epigenetic insights into pest forecasting could also improve predictions of climate-driven pest outbreaks and invasions. As global temperatures continue to rise, deciphering insect epigenetic stress responses will be crucial for developing resilient and climate-smart integrated pest management strategies.

Approaches to Reframe these Epigenetic Mechanisms for Insect Pest Control

Unlike DNA sequence, epigenetic marks are, in principle, reversible, which is exactly what makes them attractive as management targets.

CRISPR-Cas9 has added a second layer of precision. Beyond making outright gene deletions, a catalytically "dead" version of the Cas9 enzyme (dCas9) can be fused to activator or repressor domains and guided to a specific locus, switching a gene on or off without cutting the DNA at all, a programmable epigenome editing (Brocken et al., 2018). This has already been demonstrated in flies, ants and butterflies, and offers a route to testing exactly which epigenetic marks are functionally responsible for a given pest phenotype, rather than merely correlated with it.

Epigenetic priming in plants, an adaptive strategy observed in plants, enhances the activation of induced defence mechanisms, fortifying plants against impending herbivore threats. RNA-directed DNA methylation (RdDM) is another approach to utilise these epigenetic mechanisms, making plants resistant to insects. So far, the proof of concept for these techniques has been performed in a few model plants (Reddy et al., 2025).

Finally, the use of small-molecule drugs that interfere chemically with the enzymes writing or erasing epigenetic marks includes 5-azacitidine and zebularine, which block DNA methylation, while compounds such as trichostatin A inhibit histone deacetylases. In the carpenter ant, one such

drug reversibly altered worker behaviour, and its effect could even be "rescued" by co-administering a second drug that targets an overlapping pathway (Simola et al., 2016).

Bottlenecks in Studying Epigenetics

Though these mechanisms sound fascinating, practical field deployment and accurate exploration are formidable challenges. Techniques such as bisulfite sequencing, methylation-sensitive amplification polymorphism, and chromatin immunoprecipitation remain expensive and technically demanding for routine use outside well-funded laboratories. Off-target effects are a genuine concern for both RNAi and CRISPR-based epigenome editing, and the ecological and ethical implications of deliberately manipulating heritable information in wild or semi-wild insect populations are only beginning to be discussed seriously. Most of the studies are from a handful of model species: *Drosophila, Tribolium, Apis mellifera*, and *Nasonia*, while economically important non-model pests remain comparatively understudied.

Road Ahead

Insecticide resistance research is increasingly treating epigenetic marks as a mechanism in their own right rather than a footnote to genetic mutation. RNAi and epigenome-editing platforms are converging on field-ready delivery systems and species like the whitefly, already central to virus transmission and resistance concerns in agriculture, are emerging as genuinely useful epigenetic models rather than side notes to *Drosophila*. Epigenetics will not replace conventional pest management, but as a layer of biology that governs resistance, behaviour, symbiosis and development.

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GENERAL ARTICLE

The Chemical Language of Fruit Flies and Its Future in Pest Management

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Abstract

The Tephritidae family, commonly known as true fruit flies, encompasses over 5000 species and 500 genera distributed globally. The most economically important species belong to the genera Zeugodacus, Bactrocera, Anastrepha, Ceratitis, and Rhagoletis. These flies significantly threaten fruit production, causing losses ranging from 10% to 30%. Effective communication in these flies involves the exchange of species- and sex-specific cues. Long-distance communication involves pheromones, which might be emitted by one or both sexes. In contrast, medium-to-short communication involves cuticular hydrocarbons (CHCs) with limited volatility and host marking pheromones (HMPs) deposited on fruits after oviposition. Studying the chemical ecology of fruit flies leads to the development of new methods for effective management. Practical applications of this knowledge include mass trapping, monitoring, and direct population management methods such as lure-and-kill and push-pull strategies, which pave the way for advanced approaches such as the Sterile Insect Technique (SIT). The microbiome-mediated semiochemical emissions open novel breakthroughs for better understanding and eco-friendly management of fruit flies. Recent progress in elucidating the molecular basis of olfaction (odorant-binding proteins and olfactory receptors) and CHCs holds significant potential for advancing artificial olfaction. This progress could drive the creation of novel attractants effective at medium and long ranges. To fully realize this potential, future research must focus on gaining a comprehensive understanding of all semiochemical communication modalities within the target species.

Keywords: Fruit flies, Semiochemicals, Cuticular hydrocarbons, Odorant binding proteins, Reverse chemical ecology

Introduction

Fruit flies belonging to the family Tephritidae are not just a nuisance in the kitchen fruit bowl, but they also represent one of agriculture's most economically significant groups of pests, comprising around 5000 species from 500 genera globally. The most economically important species belong to the genera *Zeugodacus* Hendel, *Bactrocera* Macquart, *Anastrepha* Schiner, *Ceratitis* Macleay, and *Rhagoletis* Loew, causing economic losses ranging from 10-30% (Papadopoulos et al., 2024). What makes this family biologically remarkable, however, is not simply its diversity but the sophistication of its communication system. Long before humans understood the concept of "chemical signalling", fruit flies had already built an entire social order around it using odour to find mates, claim territory, avoid competition, and warn off rivals. This effective communication in these flies involves the exchange of species- and sex specific cues. Insect semiochemicals are a diverse group of compounds that drive key behavioral and physiological responses by regulating chemical communication. Depending on the relationship between the emitter and receiver, these molecules are classified as either pheromones, which

mediate interactions within a single species, or allelochemicals, which facilitate communication between different species.

In Tephritids, three broad classes dominate the conversations including long-range volatile sex pheromones and aggregation pheromones, host marking pheromones deposited on fruit after egg laying and cuticular hydrocarbons (CHCs) that coat insect body and mediate close-contact recognition (Scolari et al., 2021; Fig. 1). Understanding how these "dialects" work and how it can be intercepted or exploited can play an important role in selecting their best management strategies. For each of these three groups, characterizing the tissues responsible for their production and their chemical identities is crucial for fruit fly management. Furthermore, using analytical, electrophysiological, and behavioral methods to uncover their ecological role directly enhances monitoring strategies.

Three "Chemical Dialects" of Fruit Flies

Long-distance sex pheromones are typically airborne and used to locate mates over long distances (Figure 1). Cuticular hydrocarbons (CHCs), by contrast are low-volatile compounds that persist on the body surface or on surfaces that insect touch and are read only at close range or through direct contact (Fig. 1). Host-marking pheromones (HMPs) occupy a third category entirely: they are not really for "communication" in the conventional sense but a form of chemical memory, deposited on a fruit after oviposition so that other females including the one that laid the eggs can detect it later and avoid re-infesting an already-occupied resource (Scolari et al., 2021; Fig. 1). Together, these three systems shape nearly every major life event in a fruit fly's existence including courtship, mating, egg-laying and even species recognition.

Choreography of Courtship: Mating Signalling

Reproduction in fruit flies unfolds like a carefully staged chemical drama. Males gather in leks, arenas where they compete purely through sexual signalling, without controlling resources or offering parental care, by performing wing vibration, buzzing, and head rocking to court freely choosing females (Benelli et al., 2014).

Courtship frequently includes trophallaxis, in which males offer oral, genital, or transdermal "gifts." In *Anastrepha ludens* commonly known

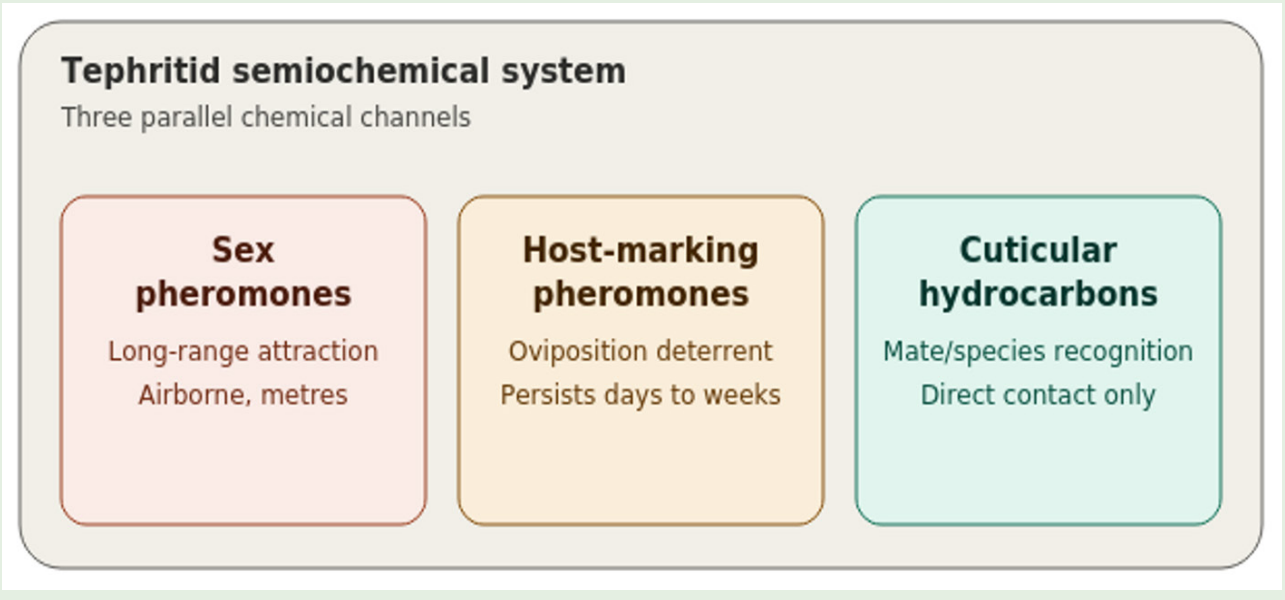


Fig. 1. The three parallel chemical channels of the Tephritid semiochemical system

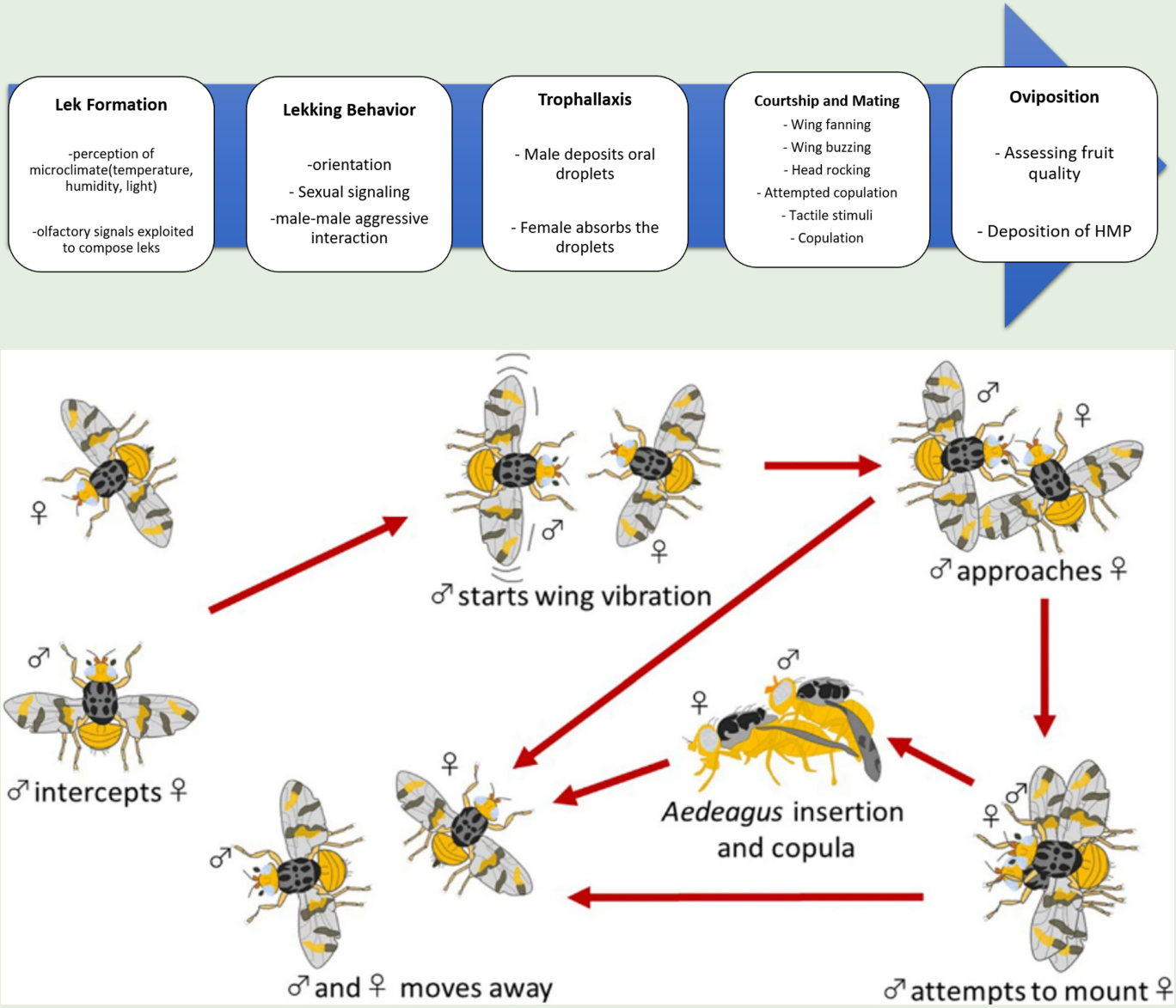


Fig. 2. Role of fruit fly chemicals in courtship

as Mexican fruit fly, males regurgitate more than females, hinting that these secretions may serve multiple roles; from harvesting environmental bacteria and neutralizing ingested toxins to producing oral pheromones (Guillén et al., 2019). As courtship intensifies, volatile chemicals guide long-distance attraction, while less volatile cuticular hydrocarbons take over during close contact, shaping mate acceptance and copulation itself (Clarke, 2019; Fig. 2). Once mated, females undergo a rapid behavioral switch, abandoning pheromone-driven mate-seeking for host-plant cues, and rely on mechanoreceptors, hygroreceptors and gustatory receptors on the ovipositor to make highly species-specific, context-sensitive oviposition decisions (Leal & Zucoloto, 2008).

From Signal to Strategy: Semiochemicals in Integrated Pest Management

Monitoring of Tephritid Population and Early Outbreak Detection

Early detection of small pest populations is critical for delimiting outbreaks and implementing eradication measures while densities remain low. Highly effective attractants (Table 1) are therefore essential for adult trapping, a primary tool used

to (a) monitor the density and seasonality of established tephritid populations, (b) detect new exotic infestations, and (c) map the boundaries of detected outbreaks.

Push and Pull Approaches

A push-pull strategy (Fig. 3) employs a combination of behavior-modifying stimuli to manipulate the distribution and abundance of target insects. Pests are deterred from a protected resource (the "push") using host-masking stimuli or repellents. Simultaneously, they are lured toward a localized area (the "pull") using highly attractive stimuli, such as traps, facilitating their subsequent elimination.

Bacterial-Derived Semiochemicals in Fruit Fly Management

An increasingly promising and eco-friendly approach utilizes volatile organic compounds (VOCs) produced by bacteria associated with fruit flies or their parasitoids. Recent findings demonstrate that parasitoids, such as *Fopius arisanus*, respond to the host-marking pheromones (HMP) of target fruit fly species (Silva et al., 2012), and could pave the way for enhanced biological control strategies. To further improve the capacity of parasitoids to locate and parasitize tephritid pests in the field, intensified research is needed to elucidate the interactions between parasitoids and fruit fly semiochemicals, particularly oviposition-induced volatiles.

Integration of Sterile Insect Technique (SIT) and Male Annihilation Technique (MAT)

SIT campaigns achieve optimal efficacy when pest population densities are suppressed prior to the release of sterile males. Applying the Male Annihilation Technique (MAT), alongside inundative releases of biological control agents, can effectively reduce feral populations, making them ideal precursors to SIT implementation. Furthermore, in *Bactrocera* species, exposing

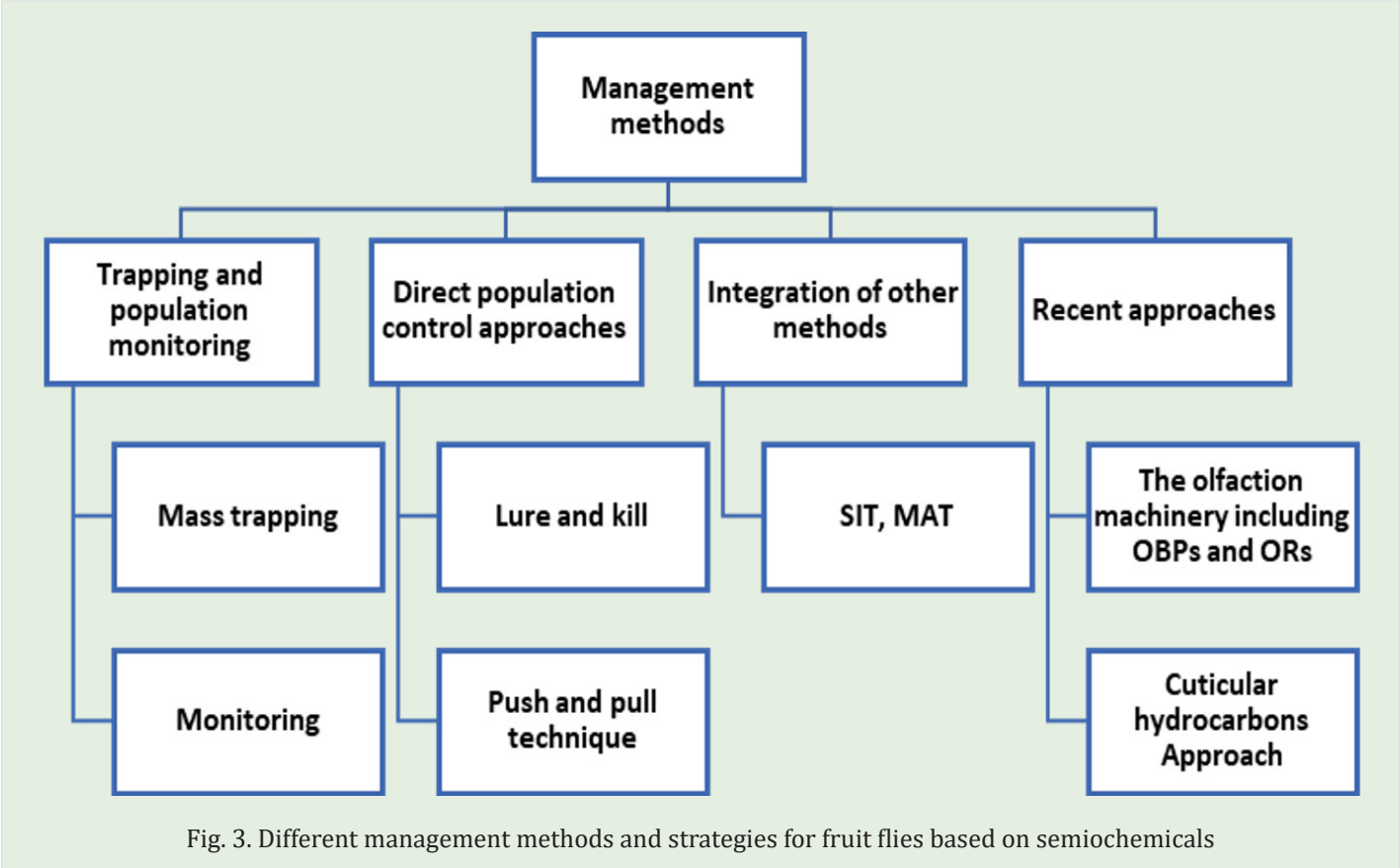


Fig. 3. Different management methods and strategies for fruit flies based on semiochemicals

Table 1. Different attractants used for different Tephritid flies.

Fruit flies	Attractants
Anastrepha spp	McPhail-type traps are standardly baited with torula yeast pellets or a hydrolyzed protein and borax mixture. Additionally, a two-component synthetic attractant consisting of ammonium acetate and putrescine is occasionally deployed in MultiLure traps, a McPhail variant.
Ceratitis capitata	To monitor female *C. capitata*, McPhail traps are typically baited with torula yeast, hydrolyzed protein with borax, or a three-component dry attractant comprised of ammonium acetate, putrescine, and trimethylamine.
Rhagoletis spp.	Although economically less significant, *Rhagoletis* spp. are primarily monitored using McPhail-style traps equipped with torula yeast pellets or the hydrolyzed protein and borax blend.
Bactocera spp.	For the detection of *B. dorsalis, B. invadens*, and *B. zonata*, traps are equipped with long-lasting methyl eugenol plugs, whereas cuelure is the standard attractant for *B. cucurbitae* and *B. tryoni*.

sterile males to plant-derived semiochemicals and synthetic lures before release has been shown to decrease their subsequent response to the attractants used in MAT field applications (Vargas et al., 2010).

Where This Is Heading: Emerging Frontiers

Microbiome-Engineered Rearing

Since gut bacteria are now known to shape both pheromone precursors and cuticular hydrocarbon profiles, deliberately engineering the microbiome of mass-reared flies could become a low-cost way to boost sterile males' mating competitiveness before release.

Reverse Chemical Ecology at Scale

Screening olfactory receptor and binding-protein libraries against candidate compounds, rather than waiting to stumble on them, promises faster discovery of narrowly species-specific attractants and repellents**.**

Biosensor-Based Surveillance

OBP (Odorant Binding Proteins) -based electronic sensors, still experimental, could eventually flag an incipient outbreak before a single conventional trap catch anything.

Combined SIT-MAT-Push-Pull Systems

As more cryptic species are resolved through pheromone and CHC chemistry, lure-and-kill, mating disruption, and SIT can all be layered into the same area-wide program with far less collateral impact on non-target insects.

Conclusion

Fruit flies inhabit a chemical universe that is almost entirely invisible to us, a universe of courtship signals, territorial markers, and identity badges written in molecules rather than sound or colour. What began as curiosity about how these insects find mates and avoid competing with their own offspring has, over five decades, matured into one of agriculture's most elegant control strategies. Instead of blanketing orchards with broad-spectrum insecticides, researchers are learning to speak the fly's own chemical language and quietly turn it against the pest itself. As microbiome science, reverse chemical ecology, and nano-sensor technology continue to converge with the semiochemical foundations already in place, the next generation of fruit fly management

looks less like chemical warfare and more like a conversational one, where humans have finally learned enough of the vocabulary to gently redirect.

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MINI REVIEW

El Niño and Indian Insect Biodiversity: Understanding Climate Variability and its Ecological Consequences

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Abstract

El Niño, the warm phase of the El Niño-Southern Oscillation (ENSO), is a major driver of global climate variability, influencing temperature, rainfall, and extreme weather events worldwide. In India, El Niño is commonly associated with weakened southwest monsoon rainfall, higher temperatures, and prolonged dry spells, with important implications for agriculture and biodiversity. As ectothermic organisms, insects are highly sensitive to climatic fluctuations, which affect their distribution, phenology, survival, and species interactions. Climatic anomalies associated with El Niño can alter insect community structure by promoting outbreaks of certain pest species while adversely affecting beneficial insects such as pollinators and natural enemies. These changes may disrupt ecosystem functioning and reduce the resilience of agricultural and natural ecosystems. This article summarizes the mechanisms of El Niño, its influence on the Indian climate, and its potential consequences for Indian insect biodiversity. It also highlights key research gaps and emphasizes the need for long-term monitoring and climate-informed conservation and pest management strategies in the face of increasing climate variability.

Key words: El Niño; ENSO; Indian monsoon; insect biodiversity; climate variability; climate change; insect ecology; ecosystem services.

Introduction

India is recognized as one of the world's megadiverse countries, harboring an extraordinary variety of insects that contribute significantly to ecosystem functioning, agricultural productivity, and biodiversity conservation. More than 63,000 insect species have been described from India, representing nearly 6-7% of the world's known insect fauna, although many species remain undocumented, particularly from biodiversity-rich regions such as the Himalaya, Western Ghats, North-East India and the Andaman and Nicobar Islands (Chandra & Gupta, 2013; Zoological Survey of India, 2023). These insects perform indispensable ecological functions including pollination, decomposition, nutrient recycling, biological control of pests, and maintenance of food webs, thereby supporting both natural ecosystems and agricultural landscapes.

The distribution, abundance and seasonal activity of insects are closely linked to climatic conditions. Since insects are ectothermic organisms, their growth, survival, reproduction and dispersal depend largely on environmental temperature,

rainfall and humidity (Bale *et al*., 2002). Even small changes in climate can influence the timing of insect emergence, alter species interactions, and modify population dynamics. Consequently, climatic variability has become one of the most important factors shaping insect biodiversity in the twenty-first century.

Among the various climate phenomena influencing weather patterns across the globe, El Niño is one of the most significant. Although it originates in the tropical Pacific Ocean, El Niño influences atmospheric circulation on a global scale, resulting in altered rainfall patterns, increased temperatures, droughts, floods and extreme weather events in many parts of the world, including India (Trenberth, 1997; IPCC, 2023). In India, El Niño is widely known for its association with weaker southwest monsoons, reduced rainfall and prolonged dry spells, all of which can have profound consequences for agriculture and biodiversity.

Insects respond rapidly to these environmental changes because of their short life cycles and high reproductive potential. Some species may benefit from warmer and drier conditions by increasing their populations or expanding their geographical range, whereas others may decline because of habitat degradation, reduced host plant availability or changes in humidity. Such responses can alter ecological interactions, influence pollination services, disrupt natural biological control and increase the incidence of insect pests in agricultural ecosystems (Deutsch *et al*., 2018; Wagner, 2020).With climate change expected to increase the frequency and intensity of extreme weather events, understanding the ecological consequences of El Niño has become increasingly important.

For India, where agriculture and biodiversity are closely linked to monsoon rainfall, studying the influence of El Niño on insect diversity is essential for developing climate-resilient conservation strategies, strengthening pest forecasting systems, and safeguarding the ecosystem services provided by insects. This article provides an overview of El Niño, explains its relationship with the Indian climate, and discusses its potential impacts on Indian insect biodiversity and the challenges ahead.

El Niño: Causes, Characteristics, and Global Climate Effects

Weather and climate are among the most important environmental factors influencing insect life. Seasonal rainfall, temperature, humidity and wind patterns determine where insects occur, how rapidly they develop, when they reproduce and how they interact with plants and other organisms. One of the most important natural climate phenomena affecting global weather is El Niño, which periodically alters atmospheric circulation and influences weather patterns across many parts of the world, including India (Trenberth, 1997).

The term El Niño, meaning *"The Little Boy"* or *"Christ Child"* in Spanish, was first used by fishermen along the coasts of Peru and Ecuador in South America. They observed that every few years, around Christmas, the normally cold waters of the eastern Pacific Ocean became unusually warm, resulting in a sharp decline in fish catches because nutrient-rich cold water no longer reached the ocean surface. This unusual warming event was later recognized as part of a large-scale ocean-atmosphere phenomenon known as the El Niño–Southern Oscillation (ENSO) (McPhaden *et al*., 2020).

ENSO is a naturally occurring climate cycle comprising three phases:

- **El Niño:** the warm phase, characterized by

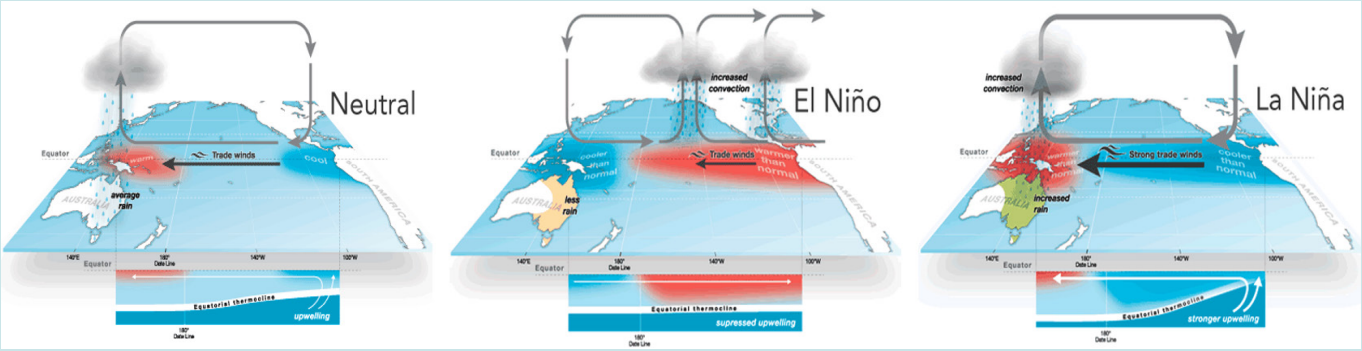


Figure 1. Neutral, El Niño and La Niña conditions in the equatorial Pacific.
Source: Adapted from the International Research Institute for Climate and Society (IRI), Columbia University, ENSO Essentials. (Available at: https://iri.columbia.edu/our-expertise/climate/enso/enso-essentials/)

above-average sea surface temperatures in the central and eastern equatorial Pacific Ocean.

- **La Niña**: the cool phase, characterized by below-average sea surface temperatures in the same region.
- **Neutral phase:** when oceanic and atmospheric conditions remain close to their long-term average.

These phases occur irregularly every 2 to 7 years, and each event usually lasts 9-12 months, although some may persist for more than a year depending on oceanic and atmospheric interactions (NOAA, 2024).

Under normal conditions, strong easterly trade winds blow across the tropical Pacific Ocean, pushing warm surface water towards Indonesia and northern Australia. As warm water accumulates in the western Pacific, cold, nutrient-rich water rises from deeper layers along the western coast of South America through a process known as upwelling. This upwelling supports highly productive marine ecosystems and one of the world's richest fisheries. Warm waters in the western Pacific also promote cloud formation and heavy rainfall over Southeast Asia and northern Australia.

During an El Niño event, the trade winds weaken or sometimes reverse. As a result, warm surface water moves eastward towards the central and eastern Pacific Ocean, while the upwelling of cold water along the South American coast becomes weaker. These changes alter the exchange of heat and moisture between the ocean and the atmosphere, disrupting normal atmospheric circulation known as the Walker Circulation. Consequently, rainfall patterns shift across the globe, causing floods in some regions and droughts in others (Trenberth, 1997; McPhaden *et al.*, 2020).

Although El Niño develops in the Pacific Ocean, its effects extend far beyond the Pacific through atmospheric teleconnections, whereby changes in one region influence weather in distant parts of the world. This explains why a warming event occurring thousands of kilometres away can influence the Indian monsoon, African droughts, Australian bushfires, South American floods and even cyclone activity in different ocean basins (IPCC, 2023).

It is important to note that El Niño is a natural climatic phenomenon and should not be confused with climate change. El Niño has existed for thousands of years as part of Earth's natural climate system. However, global warming caused by increasing greenhouse gas concentrations may intensify the impacts of El Niño by raising

background temperatures and increasing the frequency of extreme weather events. Recent climate projections suggest that strong El Niño events may become more frequent under future climate scenarios, potentially amplifying their effects on agriculture, biodiversity and water resources (Cai *et al*., 2015).

For India, El Niño is particularly significant because it often influences the strength of the southwest monsoon, which supplies nearly three-fourths of the country's annual rainfall. Variations in monsoon rainfall caused by El Niño can directly affect crop production, freshwater availability, forest ecosystems and insect populations. Since insects respond rapidly to changes in temperature and moisture, understanding the mechanisms behind El Niño is essential for predicting changes in insect biodiversity and developing effective conservation and pest-management strategies.

El Niño and the Indian monsoon: Why does it matter to India?

India's climate, agriculture and biodiversity are closely linked to the southwest monsoon, which contributes nearly 75-80% of the country's annual rainfall between June and September. The timing, distribution and intensity of monsoon rainfall determine water availability, crop production, forest productivity and the survival of countless plant and animal species. Among the various climatic factors influencing the Indian monsoon, El Niño has received considerable scientific attention because of its potential to weaken monsoon circulation and alter rainfall patterns (Gadgil & Gadgil, 2006; Kumar *et al*., 2006).

Although El Niño develops in the equatorial Pacific Ocean, changes in sea surface temperature influence atmospheric circulation over the Indian Ocean through large-scale teleconnections. During many El Niño years, the rising warm air and associated rainfall shift eastwards towards the central Pacific, weakening the atmospheric circulation that normally supports the southwest monsoon over the Indian subcontinent. Consequently, several parts of India experience below-normal rainfall, delayed monsoon onset, prolonged dry spells, and higher-than-average temperatures (Rasmusson & Carpenter, 1983; IPCC, 2023).

Historically, several severe droughts in India have coincided with strong El Niño events. For example, the El Niño years 1982-83, 1987, 2002, 2009, 2015-16 and 2023 were associated with rainfall deficits in many parts of the country, although the intensity of their impacts varied among regions (IMD, 2024). Reduced rainfall during these years affected agricultural production, reservoir storage, groundwater recharge and natural ecosystems. However, it is equally important to recognize that not every El Niño results in drought in India, and not every drought is caused by El Niño.

The relationship between El Niño and the Indian monsoon has become increasingly complex because other climatic systems also influence rainfall. One such important factor is the Indian Ocean Dipole (IOD), which refers to differences in sea surface temperature between the western and eastern Indian Ocean. During a positive IOD, warmer waters in the western Indian Ocean can enhance moisture transport towards India and partly compensate for the adverse effects of El Niño. Therefore, the final outcome depends on the combined influence of ENSO, IOD, regional atmospheric circulation and local weather systems (Saji *et al*., 1999; Ashok *et al*., 2001).

Besides reducing rainfall, El Niño often leads to higher surface temperatures across many parts of India. Increased temperatures accelerate

soil moisture loss through evaporation, intensify drought conditions and impose physiological stress on crops and natural vegetation. Water scarcity also affects flowering, fruiting and leaf production, which in turn influences herbivorous insects, pollinators and natural enemies. Thus, the ecological consequences of El Niño extend well beyond rainfall deficits and include widespread changes in terrestrial and freshwater ecosystems.

The effects of El Niño are not uniform across India. Northwestern and central India often experience stronger drought conditions, whereas some southern and northeastern regions may receive near-normal or even above-normal rainfall depending on regional weather patterns. Such geographical variation creates different ecological responses among insect communities, making long-term monitoring essential for understanding climate–biodiversity relationships.

For agriculture, changes in rainfall timing may be as important as changes in total rainfall. Delayed monsoon onset can postpone sowing, alter crop growth stages and modify the availability of host plants for insects. Similarly, prolonged dry periods followed by sudden heavy rainfall may create favourable conditions for certain pest species while adversely affecting beneficial insects such as pollinators and parasitoids. Consequently, climate variability influences not only insect abundance but also the complex ecological interactions among crops, insects and their natural enemies (Deutsch *et al*., 2018).

Recent seasonal forecasting by the India Meteorological Department (IMD) has significantly improved the country's ability to predict El Niño events several months in advance. These forecasts are increasingly used by agricultural agencies to develop contingency plans, advise farmers on crop management and strengthen pest surveillance programmes. Integrating climate forecasts with entomological observations will become increasingly important for anticipating insect outbreaks and conserving biodiversity under changing climatic conditions.

In summary, El Niño does not merely influence rainfall; it alters the entire environmental framework within which insects live. Changes in temperature, humidity, vegetation and water availability ultimately determine how insect populations respond. Understanding this climate–monsoon-insect relationship is therefore fundamental to assessing the future of India's insect biodiversity.

Indian Insect Biodiversity: Diversity, Distribution and Ecological Importance

India is one of the world's 17 megadiverse countries, supporting an extraordinary diversity of plants, animals and microorganisms. Its remarkable geographical variation, ranging from the snow-covered Himalayas to tropical rainforests, deserts, grasslands, wetlands, mangroves and island ecosystems, provides a wide array of habitats that support an exceptionally rich insect fauna. Although insects are often overlooked because of their small size, they represent the largest and most diverse group of animals in the country and play indispensable roles in maintaining ecological balance.

According to the Zoological Survey of India (ZSI), more than 63,000 insect species have been described from India, accounting for nearly half of the country's faunal diversity. However, entomologists estimate that the actual number is considerably higher, as many species, particularly those inhabiting tropical forests, high-altitude ecosystems and soil habitats, remain undiscovered or undescribed (Chandra & Gupta, 2013; ZSI, 2023).

Every year, numerous new insect species and new distributional records are reported from different parts of the country, indicating that India's insect diversity is still incompletely known.

The country's four global biodiversity hotspots-the Himalaya, Western Ghats-Sri Lanka, Indo-Burma (including North-East India) and the Nicobar Islands (part of Sundaland) harbour an exceptionally high number of endemic insect species. These regions possess unique climatic conditions, vegetation types and ecological niches that have promoted insect diversification over millions of years. Many species found in these hotspots occur nowhere else in the world and are therefore particularly vulnerable to habitat degradation and climate change.

Insects occupy almost every terrestrial and freshwater habitat in India. Butterflies and bees are abundant in forests and agricultural landscapes, dragonflies and damselflies thrive in wetlands and river ecosystems, termites dominate tropical soils, while beetles, ants, flies, moths, grasshoppers and true bugs perform a wide variety of ecological functions. Their abundance and diversity make insects one of the most important components of Indian biodiversity.

Beyond their remarkable diversity, insects provide numerous ecosystem services that are essential for both natural ecosystems and human society. Pollinating insects such as honey bees, solitary bees, butterflies, moths, hoverflies and beetles contribute significantly to the reproduction of flowering plants and many economically important crops. Approximately 75% of global food crops benefit, at least partly, from animal-mediated pollination, with insects contributing the largest share of this service (IPBES, 2016). In India, crops such as mustard, sunflower, apple, mango, cucurbits, cardamom and several vegetables depend substantially on insect pollination.

Insects also play a vital role in biological control by naturally suppressing populations of agricultural pests. Ladybird beetles, lacewings, praying mantids, predatory bugs, spiders and parasitoid wasps help regulate pest populations, reducing the need for chemical pesticides. Similarly, dung beetles, termites and numerous fly larvae accelerate the decomposition of organic matter, improve soil fertility and facilitate nutrient recycling. Aquatic insects contribute to freshwater ecosystem functioning by participating in decomposition, nutrient cycling and serving as food for fish and amphibians.

Despite their ecological importance, many insect populations are experiencing increasing pressure from habitat loss, pesticide use, pollution, invasive species and climate change. Among these factors, climatic variability is particularly significant because insects are ectothermic organisms whose physiology, growth, development and reproduction are directly influenced by environmental temperature and moisture (Bale *et al.*, 2002). Even relatively small changes in climate may alter their distribution, abundance and seasonal activity. India's diverse climatic zones further complicate insect responses to changing weather. Species adapted to cool Himalayan environments may decline under rising temperatures, whereas insects inhabiting arid and semi-arid regions may expand their geographical range. Likewise, prolonged droughts, irregular rainfall and heat waves associated with El Niño can alter flowering periods, host plant availability and freshwater habitats, ultimately affecting numerous insect groups simultaneously.

Understanding the richness and ecological significance of Indian insect biodiversity is therefore essential for appreciating how climate phenomena

such as El Niño may influence ecosystems. Since insects form the foundation of many terrestrial and freshwater food webs, changes in their diversity can have cascading effects on birds, reptiles, amphibians, mammals and ultimately human well-being. Conserving insect diversity is not only important for protecting wildlife but also for ensuring sustainable agriculture, food security and ecosystem resilience in a changing climate.

How does El Niño affect Indian Insect biodiversity?

Insects are among the first organisms to respond to changes in climate because they are ectothermic, meaning that their body temperature and physiological activities depend largely on the surrounding environment. Temperature, rainfall, humidity and seasonal weather patterns directly influence insect survival, reproduction, development, dispersal and interactions with host plants. Consequently, climatic anomalies associated with El Niño can substantially alter insect communities across India's diverse ecosystems (Bale *et al*., 2002; Parmesan, 2006; Ramaiah *et al*., 2022). The effects of El Niño on insects are rarely uniform. While some species may benefit from warmer temperatures and prolonged dry conditions, others may decline because of habitat degradation, reduced food availability or disruption of their life cycles. The overall impact depends on the ecological requirements of individual species and the intensity and duration of climatic changes.

Climate is one of the principal factors determining where insects can survive. During El Niño years, above-average temperatures and altered rainfall patterns may create favourable conditions for some insects to expand into new geographical areas, while others may disappear from regions that become unsuitable. Several insect species are already showing shifts in their geographical distribution in response to changing climatic conditions. In India, insects inhabiting cooler Himalayan ecosystems may gradually move to higher elevations, whereas species adapted to warmer climates may extend their range into northern states or higher altitudes. Such shifts may alter local biodiversity, introduce new pest species into agricultural systems and change interactions among insects, plants and natural enemies (Parmesan, 2006; Chen *et al*., 2011). Changes in insect distribution are particularly important for conservation because many endemic species occupying restricted habitats may have limited opportunities to migrate when climatic conditions become unfavourable.

Alteration of Life Cycles and Seasonal Activity

One of the earliest biological responses to climatic variability is a change in phenology, the seasonal timing of biological events such as emergence, mating, migration and reproduction.

Higher temperatures during El Niño often accelerate insect development, causing adults to emerge earlier than usual. Some species may complete their life cycle more rapidly and produce additional generations within a single year, whereas others may experience shortened adult longevity under prolonged heat stress (Bale *et al*., 2002; Ramaiah *et al*., 2022). Changes in seasonal activity can disrupt synchrony between insects and their environment. For example, herbivorous insects may emerge before their host plants produce sufficient foliage, while pollinating insects may become active before flowering begins. Such mismatches reduce survival, reproductive success and ecosystem stability (Forrest, 2016).

Effects on Pollinators

Pollinating insects are highly sensitive

to climatic fluctuations because their survival depends on the availability of flowering plants throughout the year. El Niño-induced droughts frequently reduce flowering intensity, nectar production and pollen availability, resulting in food shortages for bees, butterflies, moths, hoverflies and beetles (Potts *et al*., 2010). India supports more than 700 species of bees, including the well-known honey bees (*Apis* spp.) and numerous solitary bees that contribute significantly to crop pollination. Declines in pollinator abundance may reduce the productivity of crops such as mustard, sunflower, apple, mango, cucurbits, cardamom and several vegetables. Butterflies may also be affected because prolonged dry periods reduce the availability of larval host plants and nectar sources. Changes in flowering time may further disrupt the close relationship between butterflies and flowering plants, affecting both pollination and butterfly reproduction.

Effects on Agricultural Insects

Agricultural landscapes often experience rapid changes in insect populations following climatic disturbances. Warm temperatures associated with El Niño generally accelerate insect growth and reproduction, while drought-stressed crops may become more vulnerable to insect attack. In India, fluctuations in temperature and rainfall have been linked with outbreaks of aphids, whiteflies, thrips, stem borers, planthoppers and several lepidopteran pests in different cropping systems (Deutsch *et al*., 2018; Ramaiah *et al*., 2022). Delayed monsoon onset or irregular rainfall can alter sowing dates and crop growth stages, influencing the availability of suitable host plants and changing pest population dynamics. Conversely, some insects requiring moist environments may decline during prolonged drought, demonstrating that climate change can benefit certain species while adversely affecting others.

Effects on Natural Enemies

Predators and parasitoids provide valuable ecosystem services by naturally regulating populations of agricultural pests. However, these beneficial insects are often more sensitive to climatic variability than the pests they suppress. High temperatures and reduced humidity may decrease the survival and reproductive success of parasitoid wasps, lacewings, ladybird beetles and predatory bugs. Similarly, entomopathogenic fungi that infect insect pests require high humidity for successful transmission and therefore become less effective during prolonged dry conditions. Disruption of these natural biological control mechanisms may allow pest populations to increase rapidly, increasing dependence on chemical pesticides (Hance *et al.,* 2007; Ramaiah *et al.,* 2022).

Effects on Forest and Aquatic Ecosystems

India's forests support an enormous diversity of insects, many of which remain poorly studied. Drought conditions associated with El Niño may alter forest vegetation, reduce leaf production and increase tree stress, affecting herbivorous insects as well as their predators and parasitoids. Freshwater ecosystems are equally vulnerable. Reduced rainfall lowers water levels in rivers, streams, ponds and wetlands, affecting dragonflies, damselflies, mayflies, caddisflies and numerous other aquatic insects whose immature stages depend on freshwater habitats. These insects are important indicators of ecosystem health, and their decline may signal broader environmental degradation.

Ecological Consequences

Changes in insect biodiversity extend far beyond individual species. Since insects occupy multiple trophic levels, alterations in their

abundance can affect entire ecosystems. Reduced pollinator populations may lower seed production in wild and cultivated plants, while declines in decomposer insects can slow nutrient cycling. Similarly, changes in herbivore abundance may influence vegetation structure, and reductions in prey insects may affect birds, reptiles, amphibians and mammals that depend on them for food. Recent studies suggest that repeated climatic extremes can simplify insect communities by favouring a few climate-tolerant species while reducing populations of specialized and habitat-restricted insects (Harvey *et al*., 2023). Such changes may ultimately reduce ecosystem resilience and biodiversity.

Why Long-Term Monitoring is Essential?

Although the influence of El Niño on Indian agriculture has been extensively studied, its effects on insect biodiversity remain comparatively underexplored. India lacks long-term nationwide monitoring programmes for many insect groups, making it difficult to distinguish natural population fluctuations from climate-driven changes. Regular biodiversity surveys, museum collections, DNA barcoding, ecological monitoring and citizen science initiatives such as butterfly and dragonfly monitoring programmes can generate valuable information on changing insect distributions and population trends. Integrating these observations with climate data will improve our understanding of how El Niño and future climate change are reshaping India's insect biodiversity.

Implications for Agriculture, Biodiversity Conservation and Future Preparedness

The influence of El Niño on Indian insect biodiversity extends beyond changes in species abundance and distribution. Because insects play fundamental roles in pollination, biological control, decomposition and nutrient cycling, any climate-induced alteration in their populations can have cascading effects on agriculture, natural ecosystems and human well-being. Understanding these impacts is therefore essential for developing effective conservation strategies and strengthening climate resilience.

Implications for Indian Agriculture

Agriculture remains one of the sectors most vulnerable to climatic variability. During El Niño years, reduced and erratic rainfall often delays sowing, affects crop growth and modifies the availability of host plants for insect herbivores. Such changes can alter the timing of pest outbreaks, making them more difficult to predict and manage. Warmer temperatures may accelerate insect development, allowing some pest species to complete additional generations within a cropping season. At the same time, drought-stressed crops become physiologically weaker and more susceptible to insect attack. However, prolonged drought may also reduce the populations of insects that depend on moist habitats, demonstrating that climate effects differ among species and cropping systems (Deutsch *et al*., 2018).

Climate variability also affects beneficial insects. Pollinators may experience food shortages due to reduced flowering, while predators and parasitoids that naturally regulate pest populations may decline under adverse environmental conditions. Consequently, the balance between pests and their natural enemies may be disturbed, increasing the risk of pest outbreaks and greater reliance on chemical insecticides. These observations highlight the importance of integrating weather forecasts with pest surveillance so that farmers can adopt timely management practices and reduce unnecessary pesticide applications.

Conservation of Indian Insect Biodiversity

India's insect diversity is closely associated with its forests, grasslands, wetlands, agricultural landscapes and biodiversity hotspots. Climatic disturbances such as prolonged droughts, heat waves and irregular rainfall can alter these habitats, affecting both common and rare insect species. Particular attention should be given to endemic insects occurring in the Western Ghats, the Himalayas and North-East India, where many species occupy narrow ecological niches and may be unable to adapt rapidly to changing climatic conditions. Conserving natural habitats, restoring degraded ecosystems and maintaining ecological connectivity will improve the resilience of insect populations to future climate variability.

Pollinator conservation deserves special attention because bees, butterflies, hoverflies and other flower-visiting insects are essential for maintaining plant diversity and crop production. Protecting flowering plants, reducing indiscriminate pesticide use and conserving natural vegetation around agricultural fields can help sustain healthy pollinator communities even during periods of climatic stress.

Strengthening Insect Monitoring in India

Although India possesses immense insect diversity, long-term monitoring programmes remain limited for many insect groups. Regular surveys are essential to detect changes in species distribution, seasonal activity and population trends associated with climate variability. National biodiversity monitoring should include forests, agricultural ecosystems, wetlands, grasslands and protected areas. Museum collections maintained by institutions such as the National Pusa Collection (NPC), Zoological Survey of India (ZSI), the ICAR–National Bureau of Agricultural Insect Resources (NBAIR) and agricultural universities provide valuable historical records that can be compared with present-day observations to understand climate-driven changes in insect distributions. Citizen science initiatives have also become increasingly valuable. Butterfly monitoring programmes, dragonfly surveys, pollinator observation networks and biodiversity documentation through digital platforms have significantly improved our understanding of insect diversity across India. Public participation can complement scientific surveys by generating large-scale biodiversity data from different regions of the country.

Climate-Smart Pest Management

The growing influence of climate variability highlights the need for climate-smart Integrated Pest Management (IPM). Pest management strategies should increasingly incorporate seasonal weather forecasts, climate models and early warning systems. Advances in remote sensing, geographic information systems (GIS), artificial intelligence and ecological modeling now enable researchers to predict favourable conditions for pest outbreaks several weeks in advance. Such forecasting systems can help farmers optimize monitoring schedules, reduce unnecessary pesticide applications and adopt environmentally sustainable pest management practices. Strengthening collaboration among meteorologists, entomologists, ecologists and agricultural extension agencies will improve preparedness for future El Niño events and enhance the resilience of Indian agriculture.

Future Research Priorities

Despite considerable advances in climate science, many questions remain regarding the effects of El Niño on Indian insect biodiversity. Future research should focus on:

- Long-term monitoring of insect populations across different climatic zones.
- Assessing the responses of pollinators, predators, parasitoids and decomposers to changing climate.
- Understanding how changing rainfall patterns influence insect–plant interactions.
- Developing climate-based distribution models for economically important and threatened insect species.
- Integrating taxonomy, molecular tools, ecological modelling and climate science to improve biodiversity assessments.
- Investigating the combined effects of El Niño, habitat fragmentation and land-use change on insect communities.

Addressing these research priorities will help scientists better understand the ecological consequences of climate variability and develop evidence-based conservation strategies.

Conclusion

India's rich insect biodiversity is fundamental to ecosystem functioning, agricultural productivity, and food security through essential services such as pollination, biological control, and nutrient cycling. However, this biodiversity is increasingly vulnerable to climate variability, particularly the effects of El Niño, which alters temperature, rainfall, and monsoon patterns, thereby influencing insect phenology, distribution, abundance, and species interactions. These changes can favour certain pest species while adversely affecting pollinators and natural enemies, leading to disruptions in ecosystem services and ecological balance. As the frequency and intensity of extreme ENSO events are expected to increase under climate change, long-term ecological monitoring, climate-informed biodiversity conservation and pest forecasting, and interdisciplinary research will be essential for understanding insect responses and developing adaptive management strategies. Strengthening these efforts will be critical to conserving India's insect biodiversity and enhancing the resilience of its natural and agricultural ecosystems.

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MINI REVIEW

Importance of Hyperspectral Imaging for Hidden Pest Infestation Detection in Fruits, Vegetables and Grains

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Abstract

Hidden insect infestations in fruits, vegetables, and grains are a major cause of postharvest losses and pose significant challenges to food quality, quarantine inspection, and international trade. Since internal-feeding pests develop within host tissues without producing visible external symptoms, conventional inspection methods are often inadequate for their early detection. Hyperspectral imaging (HSI) has emerged as a powerful non-destructive technology that integrates imaging and spectroscopy to detect subtle biochemical, physiological, and structural changes associated with concealed insect infestation. By acquiring spectral information across the visible, near-infrared, and short-wave infrared regions, HSI enables rapid and accurate identification of infested commodities before visible damage occurs. The integration of machine learning and deep learning algorithms has further enhanced the sensitivity and automation of HSI-based detection systems. This review highlights the principles of hyperspectral imaging, its applications in detecting hidden pest infestations in major fruits, vegetables, and stored grains, recent advances in artificial intelligence-assisted analysis, and future prospects for precision agriculture and postharvest quality management. The technology offers considerable potential to improve pest surveillance, reduce postharvest losses, strengthen quarantine measures, and promote sustainable crop protection through rapid, non-invasive, and high-throughput detection systems.

Keywords: Hyperspectral imaging; hidden pest detection; concealed infestation; fruits; vegetables; grains; non-destructive sensing; precision agriculture; artificial intelligence.

Introduction

Global agricultural production is continually threatened by insect pests that cause significant losses both in the field and during postharvest storage (Shahbazi et al., 2025) Among these, hidden or concealed insect infestations represent one of the greatest challenges because they develop internally within fruits, vegetables, seeds, and grains without producing obvious external symptoms during the early stages of infestation (Souza et al., 2025). Internal feeders such as fruit borers, fruit flies, seed borers, grain weevils, and beetle larvae consume host tissues while remaining protected inside the commodity, making visual inspection ineffective. Consequently, infested produce often enters storage facilities and marketing channels unnoticed, leading to deterioration in quality, reduced shelf life, economic losses, and restrictions in international

trade due to quarantine concerns (Arya et al., 2026). Conventional methods used for detecting concealed infestations include manual inspection, destructive sampling, X-ray radiography, magnetic resonance imaging (MRI), computed tomography (CT), and acoustic sensing (Keerthana, et al., 2025; Patel et al., 2026). Although these techniques have contributed significantly to pest detection, each possesses inherent limitations (Table 1). Visual inspection is subjective and incapable of detecting internal infestations (Khan et al., 2025). Destructive sampling is labour-intensive and unsuitable for large-scale commercial screening. Similarly, CT and MRI provide excellent internal visualization but require expensive instrumentation, specialized facilities, and prolonged scanning times that limit their practical application in routine agricultural inspection. Hyperspectral imaging (HSI) has emerged over the past two decades as one of the most promising non-invasive technologies for early detection of hidden insect infestations (Cheng et al., 2025). Unlike conventional imaging systems that capture only three colour bands (red, green, and blue), hyperspectral imaging simultaneously acquires hundreds of contiguous narrow spectral bands across the visible (VIS), near-infrared (NIR), and short-wave infrared (SWIR) regions (Hong et al., 2026). Each pixel within the image contains a complete reflectance spectrum that represents the biochemical and structural characteristics of the sampled tissue. Since insect feeding induces subtle physiological, biochemical, and structural changes long before visible symptoms appear, hyperspectral imaging can detect these alterations with remarkable sensitivity. Consequently, HSI has become an indispensable tool in precision agriculture, smart postharvest management, food safety, and quarantine inspection (Doruchowski et al., 2025).

Principle of Hyperspectral Imaging

Hyperspectral imaging combines the principles of digital imaging and spectroscopy into a single analytical platform capable of collecting both spatial and spectral information simultaneously. Traditional imaging records only spatial information, whereas spectroscopy measures only the spectral characteristics of a sample without preserving its spatial distribution. Hyperspectral imaging integrates both approaches by generating a three-dimensional dataset known as a hyperspectral cube or hypercube, consisting of two spatial dimensions (x and y) and one spectral dimension (λ) (Li et al., 2025; Silva et al., 2025). Each material interacts with electromagnetic radiation in a unique manner depending on its chemical composition, moisture content, cellular architecture, and surface characteristics. When incident light strikes a biological sample, part of the radiation is absorbed while the remainder is reflected, transmitted, or scattered. These interactions generate characteristic spectral fingerprints that can be measured across hundreds of wavelengths (Luo et al., 2025). Healthy plant tissues exhibit spectral signatures determined by pigments such as chlorophyll, carotenoids, anthocyanins, water molecules, carbohydrates, proteins, cellulose, lignin, and waxes. When insects infest plant tissues, their feeding activity disrupts cellular organization, alters moisture distribution, stimulates defensive metabolism, and accelerates tissue degradation (Raghav et al., 2026). These biochemical changes modify the reflectance spectrum of the tissue. Because hyperspectral imaging measures reflectance continuously across hundreds of wavelengths, even minute physiological alterations associated with early insect infestation become detectable before any visual symptoms are evident.

Table 1. Comparison of Hyperspectral Imaging with Traditional Detection Methods for Hidden Pest Detection

Parameter	Visual Inspection	Destructive Sampling	X-ray Radiography	CT/MRI Imaging	Acoustic Sensing	Hyperspectral Imaging (HSI)
Detection principle	External visual symptoms	Cutting/ opening commodity	X-ray penetration to visualize internal structures	Cross-sectional internal imaging	Detection of insect feeding or movement sounds	Detection of biochemical and structural changes through spectral signatures
Nature of method	Non-destructive	Destructive	Non-destructive	Non-destructive	Non-destructive	Non-destructive
Detection of hidden infestation	Very poor	Excellent	Good	Excellent	Moderate	Excellent
Early detection before visible symptoms	No	Limited	Moderate	Moderate	Limited	Excellent
Detection basis	Visible damage	Direct observation of insects	Density differences	Internal anatomical structures	Acoustic emissions	Physiological, biochemical, moisture, and structural alterations
Spatial information	Yes	Yes	Yes	Yes (3D)	No	Yes
Spectral/ Chemical information	No	Limited	No	Limited	No	Yes (hundreds of spectral bands)
Automation potential	Low	Low	Moderate	Moderate	Moderate	Very high using AI and deep learning
Screening speed	High	Low	Moderate	Low	Moderate	High
Suitability for large-scale commercial inspection	Moderate	Poor	Moderate	Poor	Moderate	Excellent
Need for sample destruction	No	Yes	No	No	No	No
Equipment cost	Very low	Low	High	Very high	Moderate	High (decreasing with technological advances)
Operational complexity	Low	Low	Moderate	High	Moderate	Moderate to High
Labour requirement	High	High	Moderate	High	Moderate	Low after automation

Compatibility with AI/ML	Minimal	Minimal	Moderate	Moderate	Moderate	Excellent (SVM, CNN, ResNet, Vision Transformers, etc.)
Major limitations	Cannot detect internal infestation; subjective	Time-consuming; unsuitable for commercial screening	Limited biochemical information	Expensive equipment, specialized facilities, slow scanning	Influenced by insect activity & environmental noise	Large datasets require advanced computation and specialized sensors

Physiological Basis of Hidden Pest Detection

Hidden insect infestation triggers a cascade of physiological and biochemical responses within host tissues. Feeding larvae consume internal cells, resulting in destruction of vascular tissues, degradation of starch reserves, breakdown of cell walls, reduction in chlorophyll concentration, moisture loss, oxidation of phenolic compounds, and accumulation of stress-related metabolites (Sonowal et al., 2026). Simultaneously, insect respiration and metabolic waste products alter the internal gaseous environment of the host tissue. These processes produce measurable changes in optical properties. Cell collapse increases light scattering, while moisture depletion alters absorption characteristics within the near-infrared region. Changes in carbohydrate metabolism influence reflectance in wavelengths associated with C-H, O-H, and N-H molecular bonds. Furthermore, oxidative stress induced by insect feeding stimulates synthesis of phenolics, flavonoids, terpenoids, and volatile organic compounds (VOCs), all of which contribute to distinctive spectral signatures (Pfordt and Paulus, 2025). Consequently, hyperspectral imaging serves as an indirect indicator of insect activity by detecting these physiological alterations rather than imaging the insects themselves. This capability explains why HSI can identify concealed infestations several days before visible damage or emergence holes become apparent.

Spectral Regions Used in Hidden Pest Detection

The effectiveness of hyperspectral imaging largely depends on the spectral region employed for data acquisition. Different wavelength ranges provide complementary information regarding the biochemical composition and structural characteristics of agricultural commodities (Yan et al., 2026) (Table 1). The visible region (400–700 nm) primarily reflects pigment composition, including chlorophylls, carotenoids, and anthocyanins. Early insect feeding often causes pigment degradation, making this region valuable for detecting physiological stress (Elmaidomy et al., 2026). The near-infrared region (700–1000 nm) provides information related to cellular architecture, internal tissue structure, and scattering properties. Since concealed insect feeding disrupts cellular organization, this spectral range is particularly useful for identifying internal damage (Huang et al., 2025). The short-wave infrared region (1000–2500 nm) is sensitive to molecular vibrations associated with water, carbohydrates, proteins, lipids, cellulose, and lignin (Raghav et al., 2026). Hidden insect infestation modifies these biochemical constituents through tissue degradation, making SWIR wavelengths highly informative for detecting internal infestations. Modern hyperspectral systems often combine VIS-NIR and SWIR imaging

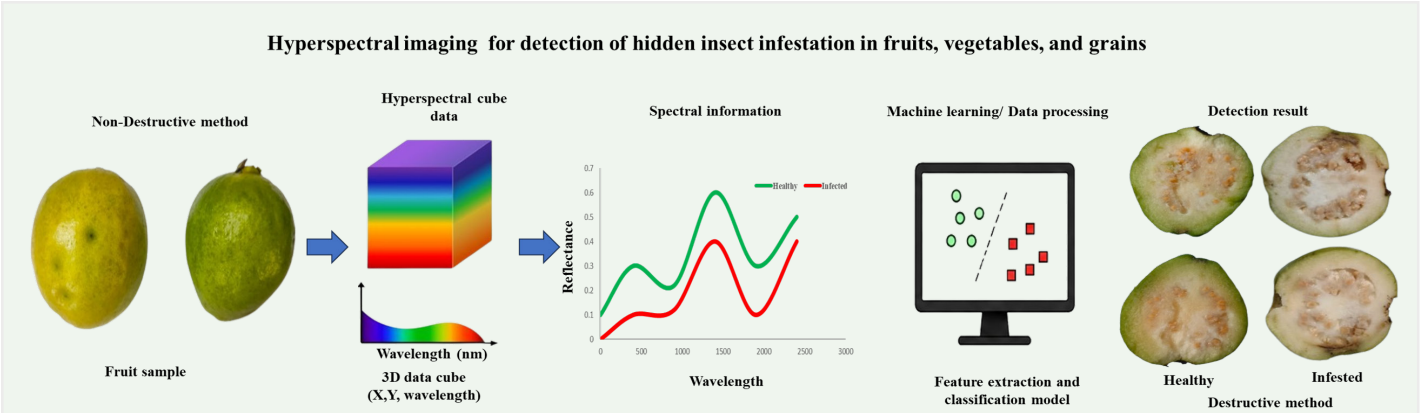


Figure 1. Workflow for hyperspectral imaging–based detection of concealed fruit fly infestation in guava fruits.

to maximize detection accuracy across diverse commodities (Faqeerzada et al., 2025).

Applications in Fruit Crops

Fruit crops represent one of the most important applications of hyperspectral imaging because many economically important pests develop entirely within fruits. Fruit fly larvae, fruit borers, seed borers, and internal-feeding moth larvae remain concealed until late developmental stages, making quarantine inspection particularly challenging (Table 1). In apples, hyperspectral imaging has successfully detected codling moth infestations by identifying localized changes in moisture distribution, tissue density, and biochemical composition (Shao et al., 2026). Similar success has been achieved for citrus fruits infested by fruit flies, where larval feeding alters internal pulp structure without producing immediate external symptoms (Xie et al., 2026). In mango, HSI has demonstrated remarkable sensitivity for identifying infestation by Oriental fruit fly (*Bactrocera dorsalis*). Larval feeding causes degradation of pulp tissues, reduction in moisture content, and increased enzymatic activity, all of which generate characteristic spectral changes detectable during early infestation (Chaudhary et al., 2025). Litchi presents a particularly challenging case because larvae of the litchi fruit borer (*Conopomorpha sinensis*) develop inside developing fruits, causing substantial economic losses while remaining externally invisible. Conventional grading frequently fails to distinguish healthy fruits from infested ones. Hyperspectral imaging offers significant potential for early detection of concealed larval infestation by monitoring spectral changes associated with tissue degradation, moisture redistribution, and metabolic alterations. Such technology could substantially improve export quality inspection and reduce postharvest losses in litchi-producing regions (Zhao et al., 2026).

Applications in Vegetables

Hidden infestations are equally important in vegetables (Table 1), particularly in crops such as tomato, brinjal, potato, onion, pepper, and cucurbits. Internal feeders consume fruit tissues, reduce market quality, and accelerate microbial infections (Xie et al., 2026). Hyperspectral imaging enables early recognition of these infestations through detection of localized physiological stress. In tomatoes, larval feeding by fruit borers alters chlorophyll degradation patterns and water distribution, producing distinct spectral responses. Similarly, wireworm infestation in potato tubers induces starch degradation and tissue necrosis that become detectable through near-infrared imaging long before external lesions develop (Yang et al.,

Table 2. Applications of Hyperspectral Imaging for Detection of Hidden Pest Infestations in Fruits, Vegetables, and Grains

Sl no	Commodity	Hidden pest	Nature of infestation	Spectral range (nm)	Hyperspectral imaging approach	Data analysis / AI model	Major findings
1	Apple	Codling moth (*Cydia pomonella*)	Larvae tunnel inside fruit pulp and seed cavity	400–900	Diffuse reflectance HSI	LDA, Decision Tree, KNN, PLS-DA, ANN	Successfully discriminated healthy and infested fruits; classification accuracy >85% depending on model. (University of Kentucky)
2	Mango	Oriental fruit fly (*Bactrocera dorsalis*)	Internal larval feeding within pulp	400–1000	Reflectance and absorbance HSI	Discriminant Analysis (DA)	Early detection before visible symptoms with accuracies approaching 99%. (PMC)
3	Orange	Internal fruit fly infestation	Internal pulp degradation	400–1000	Reflectance HSI	PCA, Binary Regression	100% discrimination between healthy and infested samples under experimental conditions. (PMC)
4	Grapefruit	Citrus leafminer (*Phyllocnistis citrella*)	Internal leaf mining	450–930		Spectral Information Divergence (SID)	Detection accuracy of approximately 95%. (PMC)
5	Jujube	*Carposina niponensis*	Internal fruit infestation	900–1700		Binary Regression	Healthy and infested fruits classified with >93% accuracy. (PMC)
6	Tomato	Tomato fruit borer (*Helicoverpa armigera*)	Internal fruit feeding	VIS–NIR		SVM, CNN	Detects biochemical changes associated with larval feeding before external symptoms become obvious. (PubMed)
7	Potato	Wireworms	Internal tunnelling in tubers	VIS–NIR/ SWIR		PLS-DA, Random Forest	Sensitive to internal tissue degradation and moisture redistribution. (PubMed)
8	Brinjal	Shoot and fruit borer (*Leucinodes orbonalis*)	Internal fruit damage	VIS–NIR		CNN	Potential for identifying concealed larval infestation through tissue spectral changes. (PubMed)
9	Litchi	Fruit borer (*Conopomorpha sinensis*)	Internal seed and pulp feeding	VIS–NIR/ SWIR		Deep learning (potential)	High potential for quarantine inspection by detecting internal tissue degradation and moisture changes before visible damage; commercial application remains an active research opportunity. (PMC)

10	Wheat	Rice weevil (*Sitophilus oryzae*)	Larvae develop completely inside kernels	VIS–NIR	Kernel-level HSI	Spectral preprocessing + feature selection + machine learning	Enables nondestructive identification of hidden infestations at different developmental stages. (PMC)
11	Wheat	Lesser grain borer (*Rhyzopertha dominica*)	Internal kernel feeding	NIR HSI	Reflectance HSI	ANN, SVM	Detects concealed infestation through changes in kernel spectra. (PubMed)
12	Maize	Maize weevil (*Sitophilus zeamais*)	Internal grain infestation			Backpropagation Neural Network	Accurate discrimination of infested kernels using selected wavelengths. (PMC)
13	Rice	Rice weevil (*Sitophilus oryzae*)	Internal grain feeding	VIS–NIR		Deep learning, SVM	Early detection before adult emergence, reducing storage losses. (PubMed)
14	Pulses	Pulse beetles (*Callosobruchus spp.*)	Larval feeding inside seeds	VIS–NIR		PLS-DA, Random Forest	Potential for rapid seed screening and quality grading. (PMC)

2025). Because vegetable quality depends heavily on internal texture and freshness, HSI provides valuable information not only for pest detection but also for simultaneous quality assessment during postharvest grading.

Applications in Stored Grains

Stored grain ecosystems present ideal conditions for concealed insect infestations because many beetles complete their larval development entirely within individual kernels (Table 1). Species such as the rice weevil (*Sitophilus oryzae*), maize weevil (*Sitophilus zeamais*), granary weevil (*Sitophilus granarius*), lesser grain borer (*Rhyzopertha dominica*), and pulse beetles (*Callosobruchus* spp.) cause severe postharvest losses worldwide (Kaliramesh et al., 2013; Chelladurai et al., 2014). Hyperspectral imaging detects internal grain infestation by measuring changes in moisture content, kernel density, starch composition, and protein degradation resulting from larval feeding. Studies have consistently reported classification accuracies exceeding 90–95% when hyperspectral imaging is integrated with machine learning algorithms. Such systems enable rapid, non-destructive screening of thousands of kernels, making them highly suitable for grain storage facilities, seed certification laboratories, and quarantine inspection services.

Integration with Artificial Intelligence

One of the major strengths of hyperspectral imaging lies in its compatibility with artificial intelligence and machine learning (Table 2). Each hyperspectral image contains enormous amounts of spectral information, often comprising hundreds of wavelengths for every pixel. Manual interpretation of such datasets is impractical (Hong et al., 2026). Machine learning algorithms including Support Vector Machines (SVM), Random Forests, Partial Least Squares Discriminant Analysis (PLS-DA), Artificial Neural Networks (ANN), and K-Nearest Neighbours (KNN) efficiently classify healthy and infested samples based on spectral signatures. More recently, deep learning architectures such as Convolutional Neural Networks (CNNs), 3D-CNNs, ResNet, EfficientNet, and Vision Transformers have further improved classification accuracy

by automatically learning complex spatial–spectral relationships without extensive feature engineering. The combination of hyperspectral imaging and deep learning has enabled automated detection systems capable of real-time operation on industrial sorting lines, significantly advancing precision agriculture and intelligent food processing.

Future Perspectives

Future developments in hyperspectral imaging are expected to transform agricultural pest management. Advances in sensor miniaturization are leading to portable hyperspectral cameras suitable for handheld field diagnostics. Drone-mounted hyperspectral sensors are enabling rapid orchard-scale surveillance, while robotic harvesting systems equipped with hyperspectral cameras can simultaneously assess fruit maturity, quality, and pest infestation. Emerging technologies such as explainable artificial intelligence, cloud computing, Internet of Things (IoT), and digital twins will further enhance decision-making by integrating hyperspectral data with environmental, meteorological, and crop management information. Multisensor platforms combining hyperspectral imaging with thermal imaging, Raman spectroscopy, fluorescence imaging, and X-ray imaging are expected to provide even greater diagnostic accuracy for complex pest detection scenarios. As computational efficiency improves and instrument costs decline, hyperspectral imaging is likely to become a routine component of smart agriculture, precision horticulture, postharvest quality control, and biosecurity surveillance.

Conclusion

Hyperspectral imaging has revolutionized the detection of hidden insect infestations by providing a rapid, accurate, and non-destructive means of assessing the internal health of agricultural commodities. Its ability to detect subtle biochemical and structural changes induced by concealed insect feeding offers significant advantages over conventional inspection methods, enabling intervention before visible damage becomes apparent. The integration of hyperspectral imaging with machine learning and artificial intelligence has further enhanced its potential for automated, real-time pest detection across fruits, vegetables, and stored grains. With continued advances in sensor technology, computational methods, and portable imaging systems, hyperspectral imaging is poised to become a cornerstone of next-generation precision agriculture, supporting sustainable pest management, minimizing postharvest losses, strengthening quarantine systems, and improving global food security.

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FIELD NOTE

The Invasive Mealybug *Hypogeococcus pungens* (Hemiptera: Pseudococcidae): Continues Its Spread in India

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India has witnessed numerous insect introductions and invasions in recent decades, many of which involve sap-sucking pests, with scale insects (Hemiptera: Coccomorpha) constituting the majority. *Hypogeococcus pungens* Granara de Willink, 1981 (Hemiptera: Sternorrhyncha: Pseudococcidae) is a Neotropical (South America) origin mealybug (Poveda-Martinez et al., 2019) and represents complex of at least five cryptic species with strong host specific associations (Poveda-Martinez et al. 2020). It has been reported from 23 countries on 23 different host plants belonging to 18 genera in 5 plant families, Amaranthaceae, Apocynaceae, Cactaceae, Malvaceae and Portulacaceae (García Morales et al., 2016). The mealybug was introduced from Argentina to Queensland, Australia and also released in South Africa as biological control agent for control of invasive cacti. Although its introduction was initially considered successful for invasive cacti weed management, the mealybug subsequently emerged as an important threat to ornamental plants, other native cacti and other plant species in many parts of the world.

Joshi et al. (2024) reported the mealybug for the first time from India (Andhra Pradesh, Karnataka, and Tamil Nadu), along with three new host records: *Alternanthera brasiliana*, *A. ficoidea*, and *Portulaca* sp. (Amaranthaceae). Recently, Poorani and Thanigairaj (2026) reported *Alternanthera sessilis* (L.) R.Br. ex DC, a widespread weed and leafy vegetable, as an additional host from Tamil Nadu. During recent field surveys in Magadi (Ramanagara District) and Chintamani (Chikkaballapura District), Karnataka, we collected the mealybug from different host plants for further study. The specimens were identified based on permanent slide mounts using the descriptions provided by Joshi et al. (2024). The specimens studied are preserved in ICAR-NIM collections of the ICAR-NBAIR, Bengaluru.

Under field conditions, *H. pungens* can be readily recognized by its characteristic colonization pattern, forming dense, cottony white masses in the axillary regions of host plants. Slide-mounted adult females are distinguished by a combination of diagnostic characters: body round to oval; antennae seven-segmented; three circuli present between abdominal segments IV and V; claw lacking a denticle; and both claw and tarsal digitules distinctly clubbed (Fig. 1A).

Based on available literature, five species of *Alternanthera* (*A. paronychioides*, *A. pungens*, *A. brasiliana*, *A. ficoidea*, and *A. sessilis*) and

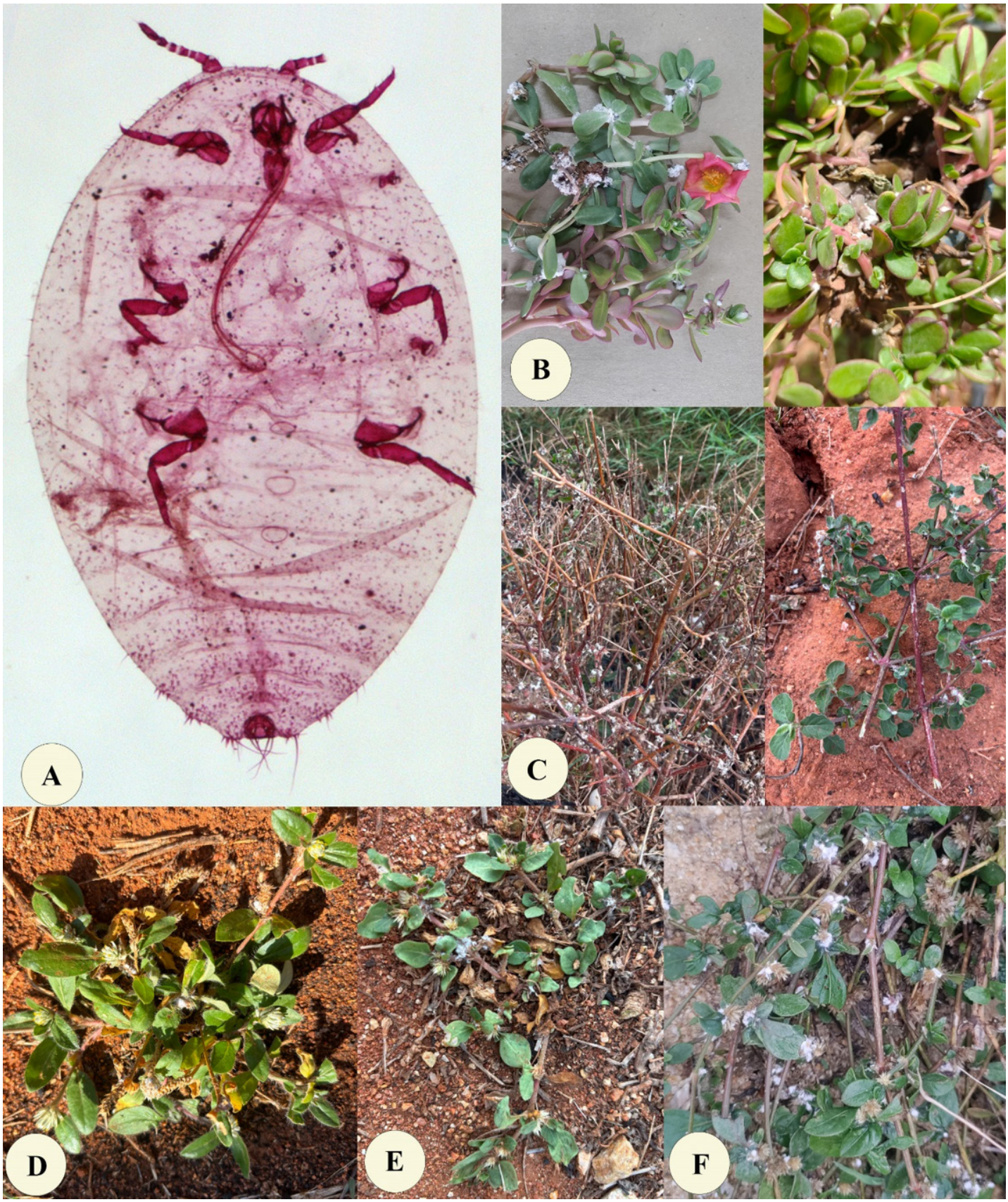


Fig. 1: A. *Hypogeococcus pungens* Granara de Willink, Mounted female; B-F. Host plants: B. *Portulaca umbraticola* Kunth (Portulacaceae); C. *Achyranthes aspera* L. (Amaranthaceae); D. *Gomphrena celosioides* Mart. (Amaranthaceae); E. *Alternanthera pungens* Kunth (Amaranthaceae); F. *Alternanthera sessilis* (L.) R.Br. ex DC (Amaranthaceae).

Gomphrena globosa (Amaranthaceae), together with two species of *Portulaca* (*P. oleracea* and *P. quadrifida*) (Portulacaceae), have been reported as host plants of *H. pungens* (Garcia Morales et al., 2016; Joshi et al., 2024; Poorani & Thanigairaj, 2026). Subsequent surveys revealed a continued expansion of this invasive mealybug in southern India, accompanied by the colonization of additional host plants. The present study reports three new host plant records: *Achyranthes aspera* L. (Fig. 1C), *Gomphrena celosioides* Mart. (Fig. 1D) (Amaranthaceae) and *Portulaca umbraticola* Kunth (Portulacaceae) (Fig. 1B), thereby indicating expansion of the known host range of *H. pungens* in India and documenting its first association with the genus *Achyranthes* (Amaranthaceae). In addition, the occurrence of *H. pungens* on *A. pungens* (Fig. 1E) and *A. sessilis* (Fig. 1F) in Karnataka confirms its continued spread within the region.

Feeding by dense population of *H. pungens* on stems, nodes, and axillary shoots causes severe deformation, chlorosis, stunting, and dieback, often leading to complete desiccation of susceptible weed hosts and substantial aesthetic damage to ornamental plants in landscapes and nurseries. In addition to ornamental species, several of its recorded host plants are common weeds, some of which are also valued as leafy vegetables and medicinal plants in traditional Indian systems of medicine, such as *Alternanthera sessilis, Achyranthes aspera* and *Gomphrena celosioides*. The ability of *H. pungens* to exploit both cultivated ornamentals and widespread weed hosts is likely to facilitate its establishment, persistence, and dispersal across agricultural, urban, and natural ecosystems. These findings provide updated information on the distribution and host range of *H. pungens* in India and highlight the need for continuous surveillance, early detection, and effective phytosanitary measures to limit its further spread and minimize its potential economic, ecological, and horticultural impacts.

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FIELD NOTE

A Note on the Occurrence of *Pieris canidia* (Lepidoptera: Pieridae) on Garden Nasturtium from Northeast India

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Abstract

The Asian Cabbage White, *Pieris canidia* (Sparrman, 1768) (Lepidoptera: Pieridae), is primarily known to utilise plants of the family Brassicaceae as larval hosts. During a field survey in January 2026 on the campus of ICAR–Indian Agricultural Research Institute, Assam, larvae of *P. canidia* were observed feeding on the leaves of Garden Nasturtium, *Tropaeolum majus* L. (Tropaeolaceae), grown in pots. The larvae were reared and the adults were identified based on external morphology and examination of the female genitalia. The observation confirms the utilisation of *T. majus* as a larval host by *P. canidia* and adds to the growing list of non-brassicaceous plants utilised by this species. The present observation also provides an updated review and analysis of the trophic spectrum of known larval host plants of *P. canidia*, encompassing both brassicaceous and non-brassicaceous hosts.

Keywords: Host-plant association; Larval feeding; Trophic spectrum; Tropaeolaceae; *Tropaeolum majus*; Pierinae; Host range; Assam; Butterfly ecology

Introduction

The genus *Pieris* Hübner, 1819 was established with *Papilio brassicae* Linnaeus, 1758, described from Sweden, as its type species. The genus currently comprises approximately 38 species worldwide (Häuser et al. 2026), of which 10 species are recorded from India (Smetacek 2025). The larvae of *Pieris* are predominantly associated with plants of the order Brassicales, particularly members of the family Brassicaceae (the mustard or cabbage family). Brassicaceous plants are characterised by the presence of glucosinolates and other secondary metabolites that serve as chemical defences against herbivory. Larvae of *Pieris* have evolved specialised physiological mechanisms that enable them to tolerate, detoxify, and utilise these compounds, facilitating their exploitation of brassicaceous hosts. However, host-plant use varies among *Pieris* species, with individual species exhibiting preferences for particular groups of brassicaceous plants. Such host-plant specificity is influenced, at least in part, by differences in the chemical composition of their host plants (Braby & Trueman 2006; Okamura et al. 2019).

Although members of *Pieris* are strongly associated with Brassicaceae, several species are known to utilise plants outside their principal host-plant family. Host-plant associations can vary geographically and among closely related species, and occasional records on non-brassicaceous plants may provide useful insights into the ecological plasticity of these butterflies. Published records indicate that the larvae of *P. canidia* utilise a range of brassicaceous plants, but non-

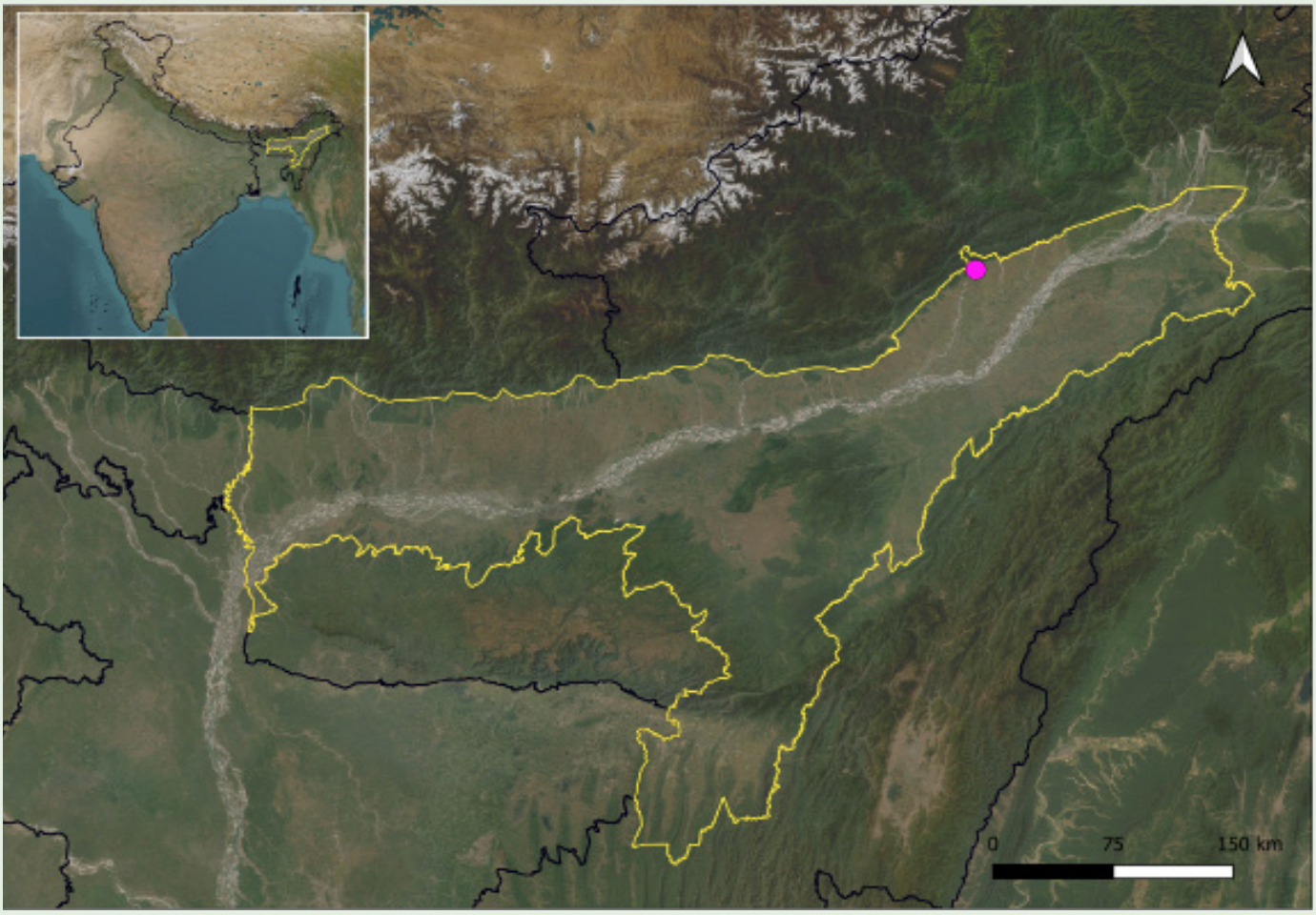


Figure 1. Map depicting the survey location, ICAR–Indian Agricultural Research Institute, Assam, India

brassicaceous hosts belonging to Cleomaceae, Apocynaceae, Tropaeolaceae and Amaranthaceae have also been documented (Thapa et al. 2025). Among these, records involving Tropaeolaceae are particularly noteworthy because Garden Nasturtium, *Tropaeolum majus* L., is a commonly cultivated ornamental plant and is taxonomically distant from the principal brassicaceous hosts of *Pieris*.

During a field survey on the campus of ICAR–Indian Agricultural Research Institute, Assam, we encountered larvae of *P. canidia* feeding actively on potted *T. majus*. The larvae were collected and reared to adults, allowing confirmation of their identity. The present observation also provides an updated review of the known larval host plants of *P. canidia* and an analysis of its trophic spectrum, encompassing both brassicaceous and non-brassicaceous hosts.

Taxonomic Position

Class Insecta Linnaeus, 1758

Order Lepidoptera Linnaeus, 1758

Superfamily Papilionoidea Latreille, 1802

Family Pieridae Swainson, 1820

Subfamily Pierinae Swainson, 1820

Tribe Pierini Swainson, 1820

Genus *Pieris* Hübner, 1819

Type species*: Papilio brassicae* (Linnaeus, 1758); by original designation.

Species ***Pieris canidia* (Sparrman, 1768)**

Common name: Indian Cabbage White or Asian Cabbage White.



Figure 2. Caterpillars of *Pieris canidia* on leaves of Garden Nasturtium.

Subspecies

Pieris canidia is represented by two recognised subspecies in India: *Pieris canidia* subsp. *canis* Evans, 1912, distributed in Kerala, Karnataka and Tamil Nadu; and *Pieris canidia* subsp. *indica* Evans, 1926, recorded from Ladakh, Jammu and Kashmir, Northeast India, Delhi, Rajasthan, Punjab, Haryana, Uttar Pradesh, Bihar, Odisha, Chhattisgarh, Madhya Pradesh and Gujarat (Smetacek 2025).

Observation and Examination

During field surveys conducted in January 2026 on the campus of ICAR–Indian Agricultural Research Institute (ICAR–IARI), Assam (Figure 1), caterpillars were observed (Figure 2) feeding on the leaves of Garden Nasturtium, *Tropaeolum majus* L. (Tropaeolaceae), grown in pots. Approximately one to three larvae were observed on each plant, causing irregular defoliation of the leaves. Late-instar caterpillars were collected and reared on

fresh leaves of the same host plant in a rectangular plastic container (22 × 15 × 6 cm) at room temperature until pupation and adult emergence. The larvae pupated (Figure 3) after approximately 5–7 days, and adults (Figure 4) emerged 8–10 days later.

Adult specimens were examined under a Quasmo® SZB 65A stereo-zoom microscope. Female genitalia were prepared by macerating the abdomen in 10% KOH for 5–7 minutes, followed by rinsing and cleaning in 50% ethanol. Images of the live caterpillar, pupa and adult habitus were



Figure 3. Pupae of *Pieris canidia*



Figure 4. Adult Habitus of *Pieris canidia* (scale bar: 1 cm)

taken using a Sony® DSC-HX400V digital camera equipped with a Raynox® DCR-250 macro lens. Images of the female genitalia were obtained using a Quasmo® ULTRACAM 5.0 MP microscope camera (UC-5) attached to the same microscope. Multiple images were captured at different focal depths and subsequently stacked and post-processed using Adobe Photoshop®. The dissected genitalia were preserved in glycerol in a vial and stored with the corresponding specimen. The examined specimens are deposited in the insect reference collection of ICAR–Indian Agricultural Research Institute, Assam. The collection locality map (Figure 1) was prepared using QGIS v. 3.24.3 (Tisler) (QGIS Development Team 2022). A bipartite network illustrating the trophic spectrum of the species and its subspecies was generated using RAWGraphs 2.0 (alluvial diagram module) and subsequently post-processed in Adobe Illustrator® v. 27.0 (Windows).

Material Examined

1 (female), India: Assam, Gogamukh, IARI–Assam campus, 27°30'09"N, 94°17'54"E, 127mt., 10.i.2026, Kishore Chandra Sahoo (IARI–Assam–LEP–PIE–01); 1 (female), same as previous, 16.i.2026 (IARI–Assam–LEP–PIE–02).

Diagnosis

The species closely resembles *Pieris rapae* (Linnaeus, 1758), but can be distinguished by the following combination of female genitalial characters (Figure 5): corpus bursae large and spherical; signum nearly bilobed, disc-shaped, and bearing radially arranged, tooth-like scobinations; and a crescent-shaped sclerotized patch present at the junction of the corpus bursae and ductus bursae (Kirti et al. 2020).



Figure 5. Female genitalia of *Pieris canidia*

Host Range

The Asian Cabbage White, *Pieris canidia*, is principally associated with plants of the family Brassicaceae during its larval stage. However, its larvae have also been reported to utilise non-

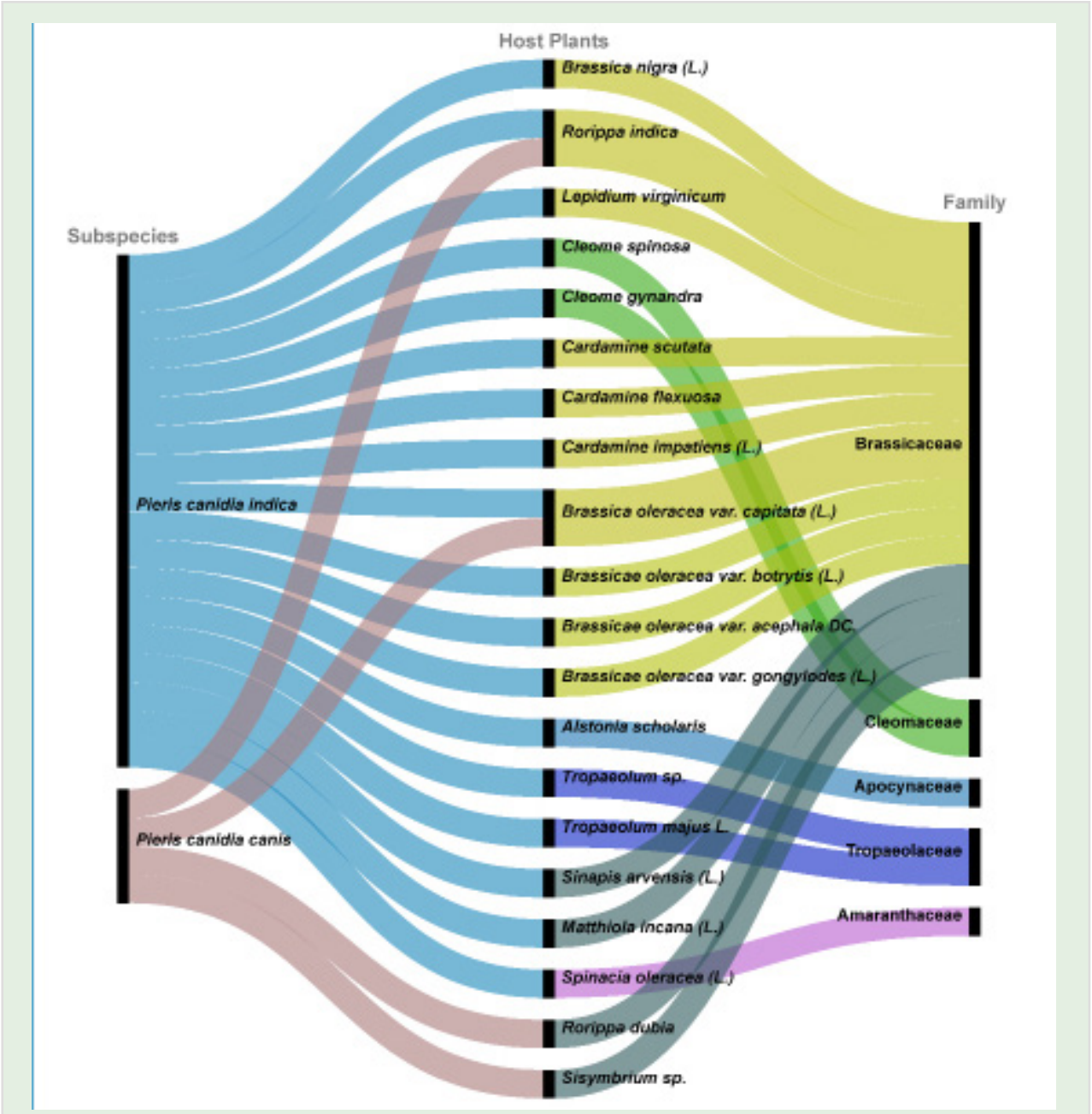


Figure 6. Associated host plants and trophic spectrum of the two different subspecies of *Pieris canidia.*

brassicaceous host plants belonging to the families Cleomaceae, Apocynaceae, Tropaeolaceae and Amaranthaceae. Thapa et al. (2025) recently summarised the known larval host plants associated with the two recognised subspecies of *Pieris canidia*. The currently documented host-plant records are presented in Table 1 and Figure 6.

Conclusion

The present observation documents the feeding and successful development of *Pieris canidia* on Garden Nasturtium, *Tropaeolum majus*, in Assam. Although *P. canidia* is predominantly associated with Brassicaceae, its ability to utilise plants from different families indicates a degree of flexibility in larval host selection. The successful rearing of larvae to adults and confirmation of the adults through female genitalia examination provide reliable evidence for this association. Further observations from different localities and systematic host-plant surveys may reveal whether

Table.1 Host plants of the two subspecies of *Pieris canidia* (Updated after Thapa et al. 2025).

Subspecies	Host Plants	Family	References
Pieris canidia indica	*Brassica nigra* (L.)	Brassicaceae	Karmakar et al. 2018; Robinson et al. 2023
	Rorippa indica	Brassicaceae	Robinson et al. 2023
	Lepidium virginicum	Brassicaceae	Robinson et al. 2023
	Cleome spinosa	Cleomaceae	Robinson et al. 2023
	Cleome gynandra	Cleomaceae	Robinson et al. 2023
	Cardamine scutata	Brassicaceae	Robinson et al. 2023
	Cardamine flexuosa	Brassicaceae	Robinson et al. 2023
	Cardamine impatiens (L.)	Brassicaceae	Smetacek & Smetacek, 2011
	Brassica oleracea var. *capitata* (L.)	Brassicaceae	Robinson et al. 2023; Rasool & Mir, 2023
	Brassicae oleracea var. *botrytis* (L.)	Brassicaceae	Rasool & Mir, 2023
	Brassicae oleracea var. *acephala* DC.	Brassicaceae	Rasool & Mir, 2023
	Brassicae oleracea var. *gongylodes* (L.)	Brassicaceae	Rasool & Mir, 2023
	Alstonia scholaris	Apocynaceae	Robinson et al. 2023
	Tropaeolum sp.	Tropaeolaceae	Robinson et al. 2023
	Tropaeolum majus L.	Tropaeolaceae	**Present Study**
	Sinapis arvensis (L.)	Brassicaceae	Mukherjee & Mondal, 2023
	Matthiola incana (L.)	Brassicaceae	Thapa et al. 2025
	Spinacia oleracea (L.)	Amaranthaceae	Thapa et al. 2025
Pieris canidia canis	*Brassica oleracea* var. *capitata* (L.)	Brassicaceae	Wynter-Blyth 1957; Kunte, 2000; Robinson et al. 2023
	Rorippa dubia	Brassicaceae	Nitin et al. 2018
	Rorippa indica	Brassicaceae	Nitin et al. 2018
	Sisymbrium sp.	Brassicaceae	Nitin et al. 2018

the use of *T. majus* is a localised association or represents a more widespread but previously overlooked host-plant relationship of *P. canidia*.

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BUG STUDIO

14TH INDIAN ENTOMOLOGIST PHOTO CONTEST

The Indian Entomologist Photo Contest aims to promote insect photography among photographers, professionals, amateur entomologists, and laymen. The theme for the 14th edition of the photo contest was "Insects and aspects related to insect life." The contest was open from the 20th May, 2026 until 31st June, 2026. Each participant was asked to submit one good photograph that meet a few specified formats, as well as a filled-in application form in which he or she must include his or her details, caption, description, photograph specifications and a declaration of the ingenuity of the photograph. We received an overwhelming response from 63 participants, who submitted a total of 65 images. The photos were initially screened by Bug Studio associate editors for the prescribed standards and overall image quality and further sent to three independent and anonymous external reviewers to judge the best three photos. Based on the reviewer results, the final evaluation was done by a committee of independent members under the oversight of the three editorial board members. During the complete review process, the entries were assessed based on the following criteria: quality (clarity, lighting, depth of field, composition), relevance of the subject matter (theme, rareness of subjects), creativity and originality. To ensure a blind review, the details of the photographer were hidden, and the evaluators were only presented with the photograph, caption, description and technical specifications.

The following are the winner for 14th Indian Entomologist photo contest:

- The first place was won by Mr. Rahul Babanrao Bhende from Wardha district Maharashtra, who captured incredible photo of Mating Pair of Grey pansy, *Junonia atlites* (Lepidoptera).

- The second place was won by Mr. Dharmendrasinh Padhiyar from Surat, Gujarat for his incredible close up photo of Jewel beetle (Buprestidae: Coleoptera).

- The third place was won by Dr. S.S Suresh from Kottayam, Kerala for capturing a proximate photo of Bark mantis interacting with Diacamma ant and horsehair worm.

Congratulations to the winners, and we acknowledge all the participants who took an interest in 14th Indian Entomologist photo contest and sent their entries!!

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First place: Mating Pair of Grey pansy, *Junonia atlites* (Lepidoptera) submitted by Mr. Rahul Babanrao Bhende from Wardha district Maharashtra, India.



Second place: A close up shot of Jewel beetle (Buprestidae: Coleoptera) by Mr. Dharmendrasinh Padhiyar from Surat, Gujarat, India.



Third place: Proximate photo of Bark mantis interacting with Diacamma ant and horsehair worm by Dr. S.S Suresh from Kottayam, Kerala, India.

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STUDENT CORNER

Durgesh Kailas Narwade

1. Please introduce yourself briefly with your current degree, institution, department, and area of specialization.

Ans: I am Mr. Durgesh Kailas Narwade, a Ph.D. student in Entomology at the Department of Entomology, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra. I am working under the supervision of Dr. B. V. Deore, Residue Analyst at AINP on Pesticide Residues and Contaminants, MPKV, Rahuri. My areas of specialization include Integrated Pest Management (IPM), biopesticides, pesticide residue analysis, and advanced analytical techniques such as LC-MS/MS and GC-MS/MS. My current research focuses on the chemical management of thrips in pomegranates and the residue dynamics of insecticides used for their protection, with the goal of developing effective pest management strategies while ensuring food safety and promoting sustainable agriculture.

2. What inspired you to pursue a PhD in Entomology?

Ans: My interest in entomology began during my undergraduate studies, but it grew significantly during my M.Sc. research at the Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. There, I worked on managing the sucking pest complex and *Earias vittella* in okra using a sequential pest-management strategy. This research taught me about the complex interactions between insects, host plants, and pesticides and emphasized the importance of studying pesticide residues, especially dissipation kinetics and pre-harvest intervals (PHI), to ensure food safety and



sustainable crop protection.

While examining the challenges in India's pomegranate industry, I found that thrips infestation and pesticide residue violations are major issues affecting farmers' income and export opportunities. I believe that entomological research can help create practical, science-based solutions that balance effective pest management with food safety. Working with Dr. B. V. Deore, in a well-equipped pesticide residue laboratory, further increased my interest and motivated me to pursue a Ph.D. in this field.

3. Can you explain your research in simple terms for students and general readers? Why is this research important in the present context of entomology, agriculture,

biodiversity, or pest management?

Ans: Pomegranate is a key export fruit crop in India, with Maharashtra as the top producer. A major issue in its cultivation is the chilli thrips, *Scirtothrips dorsalis*, which causes severe fruit damage and economic loss. Farmers often rely on frequent insecticide use to control this pest, but overuse can lead to pesticide residues in fruits, affecting food safety and export opportunities.

This study aims to fill several gaps in pomegranate pest management. First, despite heavy pesticide use in pomegranate farming, there has been no detailed study on pesticide use patterns and farmers' knowledge and practices in Maharashtra's main pomegranate-growing areas. Understanding these practices is crucial for identifying gaps in knowledge and promoting safer pesticide use. Second, because pomegranate is a key export product, monitoring pesticide residues is vital to meet food safety standards and protect consumer health. Therefore, I am assessing pesticide residues in both farm-harvested and market-collected pomegranates to create baseline data and evaluate the dietary risk to consumers.

Another focus of my research is the testing of new insecticides for thrips control. Currently, only one insecticide is officially approved by the Central Insecticides Board and Registration Committee (CIB&RC) for managing S. dorsalis in pomegranate. The long-term use of conventional insecticides has increased the risk of reduced effectiveness and resistance in these thrips. Therefore, identifying effective alternative insecticides is crucial. Finally, I am studying how these new insecticides break down after their application. As there are no data on residue dissipation and pre-harvest intervals (PHI) for these insecticides in pomegranates, this study will help establish scientifically validated waiting periods, allowing farmers to produce safer fruits while meeting food safety standards.

In simple terms, my research seeks to answer practical questions: Are farmers using pesticides correctly, are the available insecticides still effective against thrips, and when can pomegranates be safely harvested after spraying. The answers to these questions will help farmers improve pest management, support safer food production, and boost India's pomegranate export potential.

4. What are the major challenges you have faced during your research and how did you overcome them?

Ans: Like many research scholars, I faced several challenges during my Ph.D. One major challenge was the analysis of pesticide residues. Pomegranate is challenging to work with because its natural compounds can interfere with residue analysis. To obtain accurate and consistent results, the trials were repeated, and the analytical method was optimized. Another challenge was studying *Scirtothrips dorsalis*. This insect is very small, so understanding its biology and assessing field populations required patience, careful observation, and attention to detail. In addition to laboratory work, I conducted farmer surveys in different districts, performed field experiments, and collected fruit samples for residue analysis. Balancing these tasks with academic responsibilities is sometimes demanding. However, with proper planning and the support of my supervisor, Dr. B. V. Deore and encouragement from the FMC Science Leaders Fellowship, I overcame these challenges and successfully advanced my research.

5. Have you used any modern tools or techniques in your research? If yes, how have they enhanced your study?

Ans: Yes. My research used advanced tools such as LC-MS/MS and GC-MS/MS to identify

pesticide residues in pomegranates. These tools are highly sensitive and can detect even trace amounts of pesticide residues, which is crucial for residue studies.

6. How do you see your research contributing to real-world applications such as sustainable agriculture, conservation, or policy making?

Ans: I hope that my research will make pomegranate farming safer and more sustainable. By studying how farmers use insecticides, we can identify gaps in pesticide use and improve awareness through better training and extension programs. Residue monitoring and dietary risk assessment will provide scientific proof of the safety of pomegranate fruits for consumers and support the survey results. Bio-efficacy and residue dissipation studies will also help identify effective insecticides and suitable pre-harvest intervals, allowing farmers to control thrips effectively while lowering the risk of pesticide residue issues. Overall, I hope this study helps produce safer food and boosts the export potential of Indian pomegranates.

7. After completing your degree, what career path do you wish to pursue?

Ans: I want to build a career in agricultural entomology research and teaching. My aim is to work on integrated pest management, pesticide residue analysis, biopesticides and food safety. I hope to create practical solutions that will help farmers.

8. What message would you like to give to young students interested in pursuing a career in entomology?

Ans: Entomology is an interesting subject because insects affect almost every part of farming and our environment. If you enjoy observing nature and solving real-world problems, this field offers endless opportunities. My advice to young students is simple: do not seek fame or recognition. Instead, be honest with yourself and enjoy your work. Develop a true love for your subject, stay connected with nature, and keep learning continuously. Research takes time, and not every experiment will yield the expected result, but every success and failure teaches you something valuable. Stay curious, keep asking questions and trust the process. Great discoveries often begin with a simple observation and a curious mind.

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Payel Kar

1. Please introduce yourself briefly with your current degree, institution, department, and area of specialization.

Ans: Hi, I am Payel Kar, 3rd Year PhD scholar, Department of Agricultural Entomology, Bidhan Chandra Krishi Viswavidyalaya. My area of specialisation is the taxonomy and biology of soil mites (they have the potential to become good biocontrol agents).

2. What inspired you to pursue a PhD in Entomology?

Ans: The short answer is I fell in love with insects. The long one is, it happened during my undergraduate days, we all remember those ENT 101 practical, and I wanted to pursue that. I love



learning about new things, and my PhD work allows me to apply them in real time. I enjoy doing research, every aspect of it, from going on wild-goose-chases on the internet to track down a specific information to being in the field.

3. Can you explain your research in simple terms for students and general readers? Why is this research important in the present context of entomology, agriculture, biodiversity, or pest management?

Ans: My research is on finding soil mites from the hills, which have not been explored yet. It falls under mostly the fundamental science of taxonomy, but it has application as well, the mites that I am looking for are predators, they feed on soil insects. They can be utilised as biocontrol agents, they are already being sold commercially in other countries, I hope through my research they come into focus and are explored more. Also, the most important thing I think I am doing, is documentation, because it is the first step of biodiversity conservation. The rate at which organisms are going extinct is alarming and conservation is the need of the hour. If we do not know what organisms dwell in our soils and what role they play, how can we take measures to conserve them. At my core, I am a naturalist and I believe that every organism should be able to live on this planet, regardless of their so-called "usefulness" to humans.

4. What are the major challenges you have faced during your research and how did you overcome them?

Ans: The challenge I have faced are multifaceted, first, this is a relatively new area, so not much work has been conducted, I am developing protocols as I go, while this is exiting, the failures and roadblocks are also proportional to that excitement. Secondly, lack of awareness, most people do not understand on which organisms I am working on, the plant mites are relatively known, owing to their status as devastating pests, soils mites are a whole new beast altogether, Thirdly, mindset, within our fraternity, many of are the opinion, what use of taxonomy is and having to justify this becomes tedious and disappointing after a point, don't get me wrong, I will be speaking about this till I can speak no more, but the blatant disregard, sometimes gets my spirits down. But not all is doom and gloom, I have received overwhelming support from my peers and professors as well, inside and outside my university, and that love and support overshadows everything.

So, how did I overcome these challenges, simply just by persevering, by clinging on to my conviction even in the darkest of days and also, I have a very good support system, my father supports me in every endeavour and he always encourages me, my friends are there to listen to my rants whenever I am frustrated, which is often. I have a very good

academic environment, the members of Acarology Lab, BCKV and Prof. Krishna Karmakar, they have provided me with such an environment that doing work does not feel like it.

5. Have you used any modern tools or techniques in your research? If yes, how have they enhanced your study?

Ans: I frequently use 3 tools-

a. Research Rabbit, to look up and organise my literature review, it is a very useful tool to keep all your papers in one place.

b. R studio to code for graphs and statistical analyses in my ecology studies, and I would like to thank the ESI who first got me started on this software through the training organised by them. The ease of use and the control over the variables makes it an excellent tool.

c. QGiS, to make the survey maps.

6. How do you see your research contributing to real-world applications such as sustainable agriculture, conservation, or policy making?

Ans: I see my research contributing to 2 fields- Conservation and Sustainable agriculture. If I can develop a good mass multiplication method, then it could be the first step towards commercialisation and popularisation of these mites as biocontrol agents. And I hope the documentation of their rich biodiversity in the hills leads to some conservation of the hills themselves, they support a huge diversity and the complex ecosystem, each and every organism needs to be conserved. I hope my research and the resulting articles puts these under-rated critters into the spotlight that they deserve.

7. After completing your degree, what career path do you wish to pursue?

Ans: I want to pursue teaching, my dream job is becoming a professor, I would love to educate, raise awareness in the young minds and instill in them a deep empathy and appreciation for mother nature. And it does not need saying that I would love to continue my ongoing research as well.

8. What message would you like to give to young students interested in pursuing a career in entomology?

Ans: Go for it! If you love learning, if you love these critters, go for it. Keep an open mind, and an open heart and these insects will teach you more about life them self-help books can.

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Loganathan R

1. Please introduce yourself briefly with your current degree, institution, department, and area of specialization.

Ans: I'm Loganathan R, currently pursuing a Ph.D. in Entomology at the Division of Entomology, ICAR-Indian Agricultural Research Institute, New Delhi and specializing in Apiculture.

2. What inspired you to pursue a PhD in Entomology?

Ans: When I was a child, I loved catching and watching fireflies at night. I never imagined that this curiosity would one day become my passion. During my undergraduate studies, Dr. K. Samiayyan and Dr. A. Kalyanasundaram sparked my interest in Entomology, which eventually inspired me to pursue a Ph.D. in the field.



I completed my master's degree at the College of Agriculture, Central Agricultural University, Imphal. My master's research focused on the management of the pulse beetle, *Callosobruchus chinensis* L., using indigenous plant powders and oils on green gram under stored conditions, under the guidance of Dr. Khumukcham Ibohal Singh.

Currently, my doctoral research focuses on investigating the invasion risk of the small hive beetle, Aethina tumida Murray, in India. I am conducting this research under the supervision of Dr. Sachin S. Suroshe, Project Coordinator, AICRP on Honeybees and Pollinators, Division of Entomology, ICAR-Indian Agricultural Research Institute, New Delhi.

3. Can you explain your research in simple terms for students and general readers? Why is this research important in the present context of entomology, agriculture, biodiversity, or pest management?

Ans: Recently, the small hive beetle (*Aethina tumida* Murray) was reported for the first time in North 24 Parganas, West Bengal, India. This invasive pest poses a serious threat to honey bee colonies and the beekeeping industry. My research focuses on identifying its invasion origin and assessing its potential impact on apiculture in India. The findings will help strengthen quarantine measures and support the development of timely management strategies to prevent its establishment and spread, thereby protecting honeybees and ensuring sustainable crop pollination.

4. Have you used any modern tools or techniques in your research? If yes, how have they enhanced your study?

Ans: Yes. I am using CRISPR-based diagnostics to develop a rapid field detection kit for the small hive beetle (*Aethina tumida*). Compared with conventional laboratory-based methods, this approach enables faster, highly sensitive, and species-specific detection, making it suitable for on-site surveillance.

5. How do you see your research contributing to real-world applications such as sustainable agriculture, conservation, or policy making?

Ans: My research will support the early detection of the small hive beetle and identify areas at risk of invasion under changing climate conditions. This will contribute to strengthening quarantine regulations and biosecurity policies, helping to prevent the establishment and spread of this invasive pest. Ultimately, it will promote sustainable apiculture and protect honeybees and other vulnerable pollinators from one of the most destructive pests affecting beekeeping.

6. After completing your degree, what career path do you wish to pursue?

Ans: After completing my Ph.D., I aspire to become an agricultural research scientist, focusing on pollinator health and pest management.

7. What message would you like to give to young students interested in pursuing a career in entomology?

Ans: Entomology is a fascinating field. Stay curious, enjoy the learning journey, inspire others, and use your knowledge to support farmers and protect our ecosystems, just as insects do.

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Articles submitted should not have been published elsewhere and should not be currently under consideration by another journal/ magazine. Interested authors are advised to follow the author guidelines of Indian Journal of Entomology for reference citations and to follow as closely as possible the layout and style, capitalization and labelling of figures. All papers are subject to peer review and may be returned to the author for modification as a result of reviewers reports. Manuscripts are acknowledged on receipt and if acceptable proofs are sent without further communication. Minor editorial alterations may be made without consulting the author. Make sure to submit the photographs of high quality in .jpg format. For those who want to contribute commentary and feature articles please contact editors before submission.

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IE is intended to publish following categories of Articles.

Commentary – We encourage opinions or critical analysis of current entomological happenings. Submissions should be no more than 5,000 words in length.

Reviews – two types of reviews will be published a. invited review (editorial team will contact eminent entomologists to contribute) and b. peer reviewed review (any author/s can submit a comprehensive reviews on modern entomological developments).

Feature articles – these must be of broad interest to biologists, amateur and professional entomologists. These articles should be no longer than approximately 5,000 words. Articles should contain high quality photographs.

Natural histories & short research articles with focus on insect life cycle, occurrence etc. and have the same requirements as feature articles. Submissions should be up to 5,000 words in length.

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Student corner – students working on interesting topics of entomology to share their views and opinions about their research work. Can submit with personal photograph; it should not be more than 1,000 words in length.

We encourage entomologists to contact us if you have any interesting story to share about insects. Contributions to be sent to the Managing Editor, in digital format (MS Word) as an e-mail attachment to indianentomologist@gmail.com

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