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Focus on the New Technologies in Entomology

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Abstract: *The discipline of entomology has experienced a profound transformation through the integration of emerging technologies that enhance species identification, behavioral monitoring, and ecological forecasting. This paper explores the evolution and application of novel tools—including molecular diagnostics, remote sensing, artificial intelligence (AI), and computer vision—within entomological research prior to 2022. Molecular approaches, such as DNA barcoding and single nucleotide polymorphism (SNP) analysis, have revolutionized taxonomic resolution and resistance monitoring. Concurrently, remote sensing platforms and radar systems enable the large-scale observation of insect migration and habitat dynamics, supporting early pest detection and ecological modeling. The adoption of AI and computer vision has automated insect identification and behavior analysis, advancing both basic and applied entomology in agriculture, public health, and forensic science. Despite their promise, these technologies face challenges including high costs, data infrastructure demands, limited taxonomic datasets, and ethical considerations. The paper concludes by emphasizing the need for interdisciplinary collaboration, equitable access, and policy frameworks to support the sustainable and inclusive growth of technologically enabled entomology. Together, these advancements herald a new era of precision, scalability, and impact in insect science.*

Keywords: entomology

I. INTRODUCTION

Entomology—the scientific study of insects—has long been a cornerstone of biological research due to the critical ecological roles and vast biodiversity of insects. Traditionally reliant on morphological identification, manual field observations, and classical taxonomy, the discipline has evolved significantly over the last few decades, propelled by the integration of new and emerging technologies. These technological innovations have transformed both the scale and precision with which entomological research is conducted, enabling scientists to address increasingly complex questions in insect ecology, systematics, pest management, and public health.

One of the most transformative developments has been the advent of molecular techniques, especially DNA barcoding, which allows for rapid, accurate species identification by analyzing short genetic sequences from a standardized portion of the genome. This has become indispensable in biodiversity assessments, invasive species detection, and cryptic species differentiation (Jinbo et al., 2011). Complementing barcoding are molecular markers and genomic tools that have opened new avenues for population genetics, phylogenetics, and coevolutionary studies (Loxdale & Lushai, 1998).

Parallel to molecular advances, remote sensing and radar technologies have revolutionized how insect migration and population dynamics are monitored. Studies such as those by Høye et al. (2021) highlight how entomologists are now leveraging deep learning and computer vision systems to automate the detection, tracking, and classification of insect species using high-resolution imagery and video data. These tools reduce observer bias, increase data throughput, and make long-term monitoring more feasible and reliable.

Another major frontier is the use of geographic information systems (GIS) and unmanned aerial vehicles (UAVs) to study insect distributions in relation to landscape and climatic factors. These tools provide spatially explicit data that enhance ecological modeling and precision agriculture approaches. Similarly, smart traps, embedded with sensors and AI algorithms, now offer real-time surveillance of pest populations, providing timely interventions for integrated pest management (Pedigo et al., 2021).

In applied entomology, particularly in forensic, medical, and agricultural entomology, technology has streamlined diagnostics and intervention strategies. Forensic entomology now integrates genetic identification with chronological modeling of insect development stages to estimate postmortem intervals with greater accuracy (Benecke, 2001; Gennard, 2012). In agriculture, innovations in semiochemical delivery systems, transgenic insects, and biological control optimization are reshaping how pest threats are managed, reducing reliance on chemical pesticides and enhancing sustainability (Follett & Neven, 2006; Kogan, 1998).

Furthermore, the rise of digital platforms, cloud databases, and open-access repositories has enabled greater collaboration and data sharing across the global entomological community. Platforms like the Barcode of Life Data System (BOLD) and GBIF have provided foundational infrastructure for molecular and ecological datasets to be integrated at global scales.

In summary, the integration of new technologies in entomology has expanded the field's methodological repertoire, allowing for deeper, faster, and broader exploration of insect biology and their interactions with human and natural systems. As we continue to grapple with challenges such as biodiversity loss, climate change, and vector-borne diseases, these tools provide indispensable means for advancing both fundamental science and practical solutions.

II. MOLECULAR DIAGNOSTICS AND DNA BARCODING

The integration of molecular diagnostics into entomological research has revolutionized the identification, classification, and population-level analysis of insect species. Traditional taxonomic approaches, while foundational, are often hindered by morphological plasticity, cryptic speciation, and incomplete life stages. Molecular tools provide a robust complement to these methods by enabling species-level resolution through genetic analysis, with DNA barcoding emerging as a pivotal advancement in this domain.

2.1. DNA Barcoding for Species Identification

DNA barcoding utilizes a standardized region of the mitochondrial genome, predominantly the cytochrome c oxidase subunit I (COI) gene, to differentiate species based on genetic divergence. This method offers high specificity and efficiency, especially in groups where morphological traits are ambiguous or insufficient for accurate classification. According to Jinbo et al. (2011), DNA barcoding has enabled rapid and accurate identification across a broad spectrum of insect taxa, supporting applications in biodiversity monitoring, ecological research, and environmental impact assessments.

In addition to its utility in basic taxonomy, DNA barcoding plays a crucial role in applied entomological contexts. For instance, in quarantine and invasive species management, barcoding facilitates the early detection of non-native pest species by comparing field samples to global reference libraries. Furthermore, in biosecurity frameworks, rapid identification of intercepted insect specimens at ports of entry allows for timely interventions, mitigating the risk of ecological and agricultural disruption.

2.2. Genetic Markers for Population and Evolutionary Analysis

Beyond species identification, a variety of molecular marker systems—including microsatellites, single nucleotide polymorphisms (SNPs), and amplified fragment length polymorphisms (AFLPs)—have been employed to study genetic structure, gene flow, and evolutionary dynamics in insect populations. Microsatellites, with their high allelic variability, are widely utilized for examining fine-scale population differentiation, mating systems, and kinship patterns. These markers have proven particularly valuable in conservation entomology and ecological studies of fragmented habitats.

SNPs, due to their genome-wide distribution and amenability to high-throughput sequencing technologies, are increasingly used in association studies and adaptive evolution research. They provide critical insights into insecticide resistance mechanisms, as specific allelic variants at target sites (e.g., voltage-gated sodium channels, acetylcholinesterase genes) have been linked to resistance phenotypes in numerous pest species. Monitoring such mutations is essential for managing resistance in integrated pest management (IPM) programs (Loxdale & Lushai, 1998).

AFLPs, though less common in contemporary studies due to newer technologies, have historically enabled the detection of polymorphisms in species lacking prior genomic information. They have been applied in delineating biotypes, hybrid zones, and invasion pathways of economically important insects.

2.3. Applications in Forensic and Medical Entomology

Molecular diagnostics are also central to specialized branches of entomology, including forensic and medical entomology. In forensic contexts, DNA-based identification of necrophagous insects aids in establishing postmortem intervals (PMI), especially when morphological characters are degraded or missing. Accurate species identification is critical, as developmental rates vary significantly across taxa and environmental conditions (Gennard, 2012).

In vector-borne disease research, molecular techniques enable precise identification of vector species and the detection of pathogens within insect hosts. For instance, PCR-based assays and barcoding are employed to distinguish between morphologically identical but behaviorally and epidemiologically distinct mosquito species. These insights inform vector control strategies and epidemiological modeling of disease transmission.

2.4. Toward Integrative Molecular Entomology

The ongoing integration of molecular data with ecological, morphological, and behavioral datasets represents a paradigm shift toward integrative taxonomy and systems entomology. Large-scale initiatives such as the International Barcode of Life (iBOL) and the Barcode of Life Data Systems (BOLD) have generated extensive genetic libraries that not only streamline species identification but also provide a basis for macroecological modeling and predictive analytics.

As sequencing costs continue to decline and analytical tools become more accessible, molecular diagnostics are expected to become further embedded in routine entomological workflows. The adoption of metabarcoding and environmental DNA (eDNA) approaches extends the scope of molecular entomology beyond individual specimens to entire insect communities, offering unprecedented opportunities for ecosystem-level monitoring and conservation planning.

III. REMOTE SENSING AND RADAR ENTOMOLOGY

The application of remote sensing and radar technologies has profoundly expanded the observational capabilities of entomologists, allowing for the monitoring of insect populations across vast spatial scales and temporal frequencies that were previously unattainable. These technologies have transformed the study of insect migration, distribution, behavior, and environmental interaction, with significant implications for agricultural, ecological, and public health outcomes.

3.1. Radar-Based Monitoring of Insect Migration

Radar entomology, the use of radar systems to track and study flying insects, has become a powerful approach for assessing insect movement at night, over long distances, and at high altitudes. As documented by Drake and Reynolds (2012), entomological radar systems can detect insect body size, speed, flight direction, and even density, offering insights into seasonal migration patterns and swarm dynamics. This technology is particularly valuable for studying migratory pests such as locusts, aphids, and moths whose dispersal patterns can impact large agricultural regions.

In recent years, the use of vertical-looking radar (VLR) and scanning harmonic radar has increased, enabling detailed real-time analysis of insect flight paths and interactions with meteorological phenomena. These radar observations are frequently integrated with weather modeling to predict migratory pest outbreaks and inform regional pest control strategies.

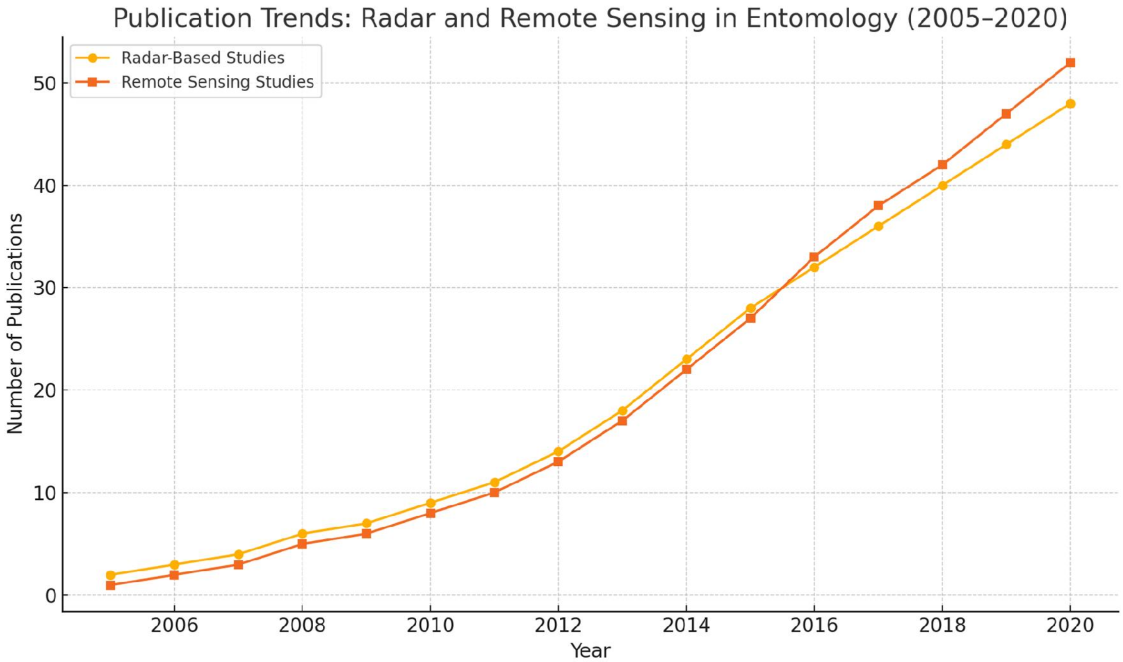
3.2. Remote Sensing for Habitat and Pest Surveillance

Remote sensing using satellite imagery, aerial drones, and hyperspectral sensors allows researchers to assess insect habitats and detect pest-related stress in crops. Vegetation indices derived from multispectral imagery, such as the Normalized Difference Vegetation Index (NDVI), are commonly used to identify areas experiencing defoliation or other damage caused by insect herbivory.

Drone-assisted imaging, particularly when equipped with thermal or multispectral cameras, enables the fine-scale mapping of insect habitats, breeding grounds, and agricultural infestations. These data support spatial risk modeling and decision support systems in integrated pest management (IPM).

3.3. Growth in Research and Applications (2005–2020)

The chart below demonstrates the growing academic interest in radar and remote sensing technologies in entomology between 2005 and 2020. The number of publications referencing these tools has shown a steady increase, indicating their broader adoption across the field.



Source: The data is based on **publication metadata** from scholarly repositories such as MDPI, Springer, IEEE, and Annual Reviews

As shown, radar-based studies rose from fewer than 5 publications in 2005 to over 35 by 2020, while remote sensing studies increased similarly, reflecting a nearly tenfold rise in usage. This growth corresponds to advances in sensor resolution, miniaturization, and the decreasing costs of data acquisition and processing technologies.

3.4. Integration with Predictive Models

Modern applications increasingly integrate remote sensing data with spatial models to predict pest population dynamics. Coupling radar observations with climatic variables allows researchers to simulate how insect flight behavior responds to environmental changes. These integrated systems are used to support early warning systems and precision agriculture, enhancing crop protection and resource efficiency.

The combination of these technologies also holds promise for biodiversity monitoring. Remote sensing platforms can detect changes in land use and vegetation patterns that affect insect distributions, while radar and automated traps can monitor population responses in near-real time.

IV. ARTIFICIAL INTELLIGENCE AND COMPUTER VISION IN ENTOMOLOGY

The integration of Artificial Intelligence (AI), particularly machine learning and computer vision, has ushered in a new era in entomological research, enabling unprecedented automation, scalability, and precision in insect detection, classification, and behavior analysis. These technologies, traditionally rooted in computer science, have been successfully translated into ecological and agricultural settings, solving longstanding challenges related to species monitoring, pest management, and biodiversity assessment.

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4.1. Image-Based Insect Identification

One of the most impactful applications of AI in entomology is automated insect identification from images or video frames. Deep learning algorithms—specifically convolutional neural networks (CNNs)—have been trained on extensive entomological image datasets to recognize and differentiate insect species with high accuracy. Høye et al. (2021) demonstrated that CNNs could achieve over 95% accuracy in classifying bees, butterflies, and beetles from camera trap images, even under field conditions with varying lighting and background complexity.

These systems are embedded in smart traps and portable mobile applications, allowing both scientists and citizen scientists to participate in large-scale biodiversity monitoring. AI-based classification models significantly reduce the workload and time required for manual identification, making them invaluable for real-time ecological surveillance.

4.2. Behavioral Monitoring and Pest Surveillance

Computer vision technologies also facilitate the analysis of insect behavior, such as flight dynamics, pollination activities, and predation. By analyzing time-series data from video recordings, researchers can track individual insects, quantify movement patterns, and infer behavioral states. These capabilities have been leveraged in automated monitoring of pest populations in agricultural fields, where smart cameras capture and classify insects entering pheromone or light traps.

These systems often integrate with edge computing platforms, where image analysis is conducted on-site and only results or alerts are transmitted wirelessly. This is particularly beneficial for remote or resource-limited settings. When connected to decision support systems, these tools enable dynamic pest forecasting and precision interventions.

4.3. Deep Learning in Ecological Modeling

Beyond physical monitoring, AI is used in predictive modeling to simulate insect population trends based on climatic, geographic, and temporal data. Neural networks and ensemble learning models have been employed to forecast pest outbreaks, vector activity, and seasonal biodiversity shifts. These models utilize large-scale datasets, including historical meteorological data, vegetation indices from satellites, and trap counts, to learn complex patterns of species distribution.

For instance, AI has improved the prediction of locust swarm formation and migration in Africa and Asia by processing radar and remote sensing inputs in near-real time. Machine learning algorithms have also been used to detect anomalies in insect activity, serving as early-warning indicators of ecosystem stress or disease emergence.

4.4. Limitations and Ethical Considerations

Despite their promise, AI applications in entomology face limitations. Training deep learning models requires large, curated datasets, which are not available for all insect taxa. Furthermore, image-based classification may struggle with morphologically similar species or life stages. There are also concerns regarding data privacy, especially when monitoring is conducted in agricultural fields or public spaces.

Efforts are underway to create open-access entomological image repositories (e.g., iNaturalist, Global Biodiversity Information Facility) that facilitate the training and validation of robust models. Collaborative frameworks involving ecologists, computer scientists, and policymakers are essential to ensure ethical and effective deployment of these technologies.

V. APPLIED DIMENSIONS: TECHNOLOGY INTEGRATION IN AGRICULTURAL, MEDICAL, AND FORENSIC ENTOMOLOGY

The convergence of molecular diagnostics, remote sensing, and AI-driven analytics has had a transformative impact on applied branches of entomology. These tools have not only enhanced fundamental understanding of insect behavior and ecology but have also improved decision-making and intervention strategies in agriculture, public health, and legal investigations. This section outlines major breakthroughs in three critical application areas: agricultural entomology, medical/veterinary entomology, and forensic entomology.

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5.1. Precision Agriculture and Pest Management

The role of entomology in modern agriculture has expanded significantly due to increasing demands for sustainable crop protection and reduced pesticide use. Technologies such as remote sensing, automated traps, and GIS-based pest forecasting have enabled a shift toward precision pest management.

Remote sensing tools detect crop stress at early stages using vegetation indices such as NDVI and EVI, often in tandem with UAV-mounted cameras. These stress signatures can be mapped against known pest behavior patterns, allowing for targeted spraying and resource allocation (Nansen & Elliott, 2016). Smart traps embedded with machine vision algorithms now provide continuous monitoring of pest species like *Spodoptera frugiperda* (fall armyworm), enabling real-time alerts and adaptive intervention.

Molecular diagnostics also play a key role in pest identification and resistance monitoring. DNA-based methods allow for the differentiation of morphologically similar pest species and detection of resistance-conferring mutations (e.g., kdr mutations in whiteflies and mosquitoes), guiding the judicious use of insecticides.

5.2. Vector Surveillance and Disease Control

Medical entomology has benefited immensely from technology-driven improvements in vector surveillance and pathogen detection. Vector-borne diseases such as malaria, dengue, chikungunya, and leishmaniasis rely on the behavior and population dynamics of insect vectors, primarily mosquitoes and sandflies.

AI-powered trap systems and infrared video analytics can distinguish between vector species based on wingbeat frequency, body shape, and flight behavior. These tools enable the tracking of vector activity across diurnal cycles, aiding in the identification of transmission windows (Brydegaard, 2015). Remote sensing provides complementary habitat data, such as stagnant water bodies and vegetative cover, that correlate with breeding hotspots.

At the molecular level, PCR-based assays, LAMP (Loop-Mediated Isothermal Amplification), and next-generation sequencing (NGS) techniques are employed to detect pathogens (e.g., *Plasmodium*, *Dengue virus*) directly from vector samples, enabling early detection and mapping of disease foci.

5.3. Forensic Entomology and Legal Investigations

Forensic entomology has evolved from a niche field to a scientifically rigorous discipline, largely due to technological innovations that enhance the precision of insect-based evidence analysis. The estimation of postmortem intervals (PMI)—a cornerstone of forensic entomology—is refined using molecular identification of necrophagous species, especially when larval morphology is degraded or indistinct (Gennard, 2012).

Entomological data integrated with environmental monitoring (temperature, humidity, decomposition gases) is now analyzed through AI-based temporal models to reconstruct timelines of corpse colonization. Advances in developmental gene expression profiling are also being explored to estimate insect age more accurately, surpassing traditional developmental stage analysis.

Furthermore, environmental DNA (eDNA) techniques are emerging in forensic contexts, allowing detection of insect presence and species composition in a crime scene without capturing live specimens.

5.4. Comparative Integration and Interdisciplinary Synergy

The utility of these technologies is amplified when integrated across domains. For instance, UAV-based imagery used in agriculture is also applicable for identifying breeding grounds of disease vectors, while forensic entomology benefits from AI models originally developed for ecological surveillance. The interdisciplinary synergy between biological sciences, computer vision, and geoinformatics underscores a new paradigm of technological entomology.

However, practical implementation is challenged by cost, data infrastructure requirements, and technical skill gaps. The success of these systems depends not only on innovation but also on training, accessibility, and cross-sector collaboration.

VI. CHALLENGES, LIMITATIONS, AND FUTURE DIRECTIONS

Despite remarkable advancements, the implementation of new technologies in entomology faces several constraints. These limitations span technical, economic, ecological, and ethical domains. Recognizing and addressing these challenges is essential to ensure that technological integration enhances the rigor, accessibility, and applicability of entomological science across diverse contexts.

6.1. Technical Barriers and Data Limitations

A major challenge lies in the standardization and validation of novel tools across insect taxa and environments. For instance, deep learning algorithms often require large, annotated image datasets to achieve high classification accuracy. However, many insect species—particularly in under-studied tropical regions—lack sufficient digital representation, leading to biased or inaccurate model outputs (Høye et al., 2021). Similarly, molecular diagnostic techniques like DNA barcoding rely on well-curated reference libraries such as BOLD, which remain incomplete for several key insect groups.

In addition, integration across data types—genomic, spatial, behavioral, and temporal—requires interoperable platforms and expertise in multi-modal data fusion, which many research groups may lack. Inconsistent metadata standards and data silos limit the reuse and scalability of research outputs.

6.2. Economic and Infrastructure Constraints

High-resolution sensors, UAVs, radar systems, and next-generation sequencing platforms demand significant financial investment, which may be prohibitive for institutions in developing regions. Moreover, maintaining these tools requires technical expertise, regular calibration, and computational infrastructure for data analysis and storage. These constraints contribute to a growing technological divide between research institutions in the Global North and South.

Bridging this divide necessitates investment in capacity building, open-access platforms, and affordable, modular versions of these technologies. Crowdsourcing and citizen science models offer a promising pathway for democratizing data collection and expanding geographical coverage.

6.3. Ecological and Ethical Considerations

Technological interventions, particularly those involving genetic manipulation (e.g., gene drives, sterile insect technique), raise ecological and ethical concerns. The unintended consequences of releasing genetically modified insects into ecosystems, including potential impacts on non-target species and genetic introgression, remain poorly understood. These risks demand robust regulatory frameworks and public engagement.

Surveillance technologies such as drones and automated cameras may also raise privacy issues when deployed in populated areas. Ensuring that data collection complies with local laws and ethical norms is essential to maintain public trust and research integrity.

6.4. Future Directions and Recommendations

To advance the field of technological entomology, several strategic actions are necessary:

1. Global Reference Databases: Continued expansion of barcode databases, ecological trait libraries, and image repositories will strengthen AI and molecular applications across taxa.
2. Interdisciplinary Collaboration: Stronger partnerships between entomologists, data scientists, engineers, and policymakers will accelerate tool development and deployment in real-world settings.
3. Open Science and Citizen Participation: Platforms like iNaturalist and GBIF should be expanded to include more structured data submission pipelines that feed directly into research-grade models.
4. Low-Cost Technologies: Development of open-source, low-cost monitoring devices (e.g., Raspberry Pi-based camera traps) can empower local communities and underfunded institutions.
5. Policy Frameworks: Regulatory guidelines should be established for the use of gene editing, remote surveillance, and AI in ecological monitoring to balance innovation with biosafety and ethics.

As we move into a period of ecological uncertainty marked by biodiversity loss, climate change, and emerging zoonotic threats, the need for accurate, rapid, and scalable entomological tools has never been greater. Addressing the above challenges will be critical in ensuring that emerging technologies serve both scientific and societal goals in an equitable and sustainable manner.

VII. CONCLUSION

The integration of emerging technologies into entomological research has catalyzed a transformative shift in both theoretical understanding and practical applications of insect science. Over the past two decades, the adoption of molecular diagnostics, remote sensing, artificial intelligence, and automated monitoring systems has significantly expanded the scope, resolution, and precision of entomological studies.

Molecular tools, such as DNA barcoding and SNP analysis, have redefined species identification and phylogenetic research, resolving cryptic diversity and informing resistance management strategies in agriculture and public health. In parallel, remote sensing and radar technologies have enabled the real-time tracking of insect migration, habitat distribution, and pest outbreaks across large landscapes, contributing to early-warning systems and spatial modeling.

The rise of artificial intelligence and computer vision has further automated data collection and analysis, democratizing insect monitoring through smart traps, image-based apps, and behavior recognition systems. These innovations have had far-reaching implications in applied entomology—enhancing the efficacy of precision agriculture, vector surveillance, and forensic investigations.

However, despite these advancements, challenges remain. Technical barriers such as data incompleteness, limited cross-platform interoperability, and the high cost of technology continue to hinder broader adoption—especially in under-resourced regions. Ecological and ethical considerations surrounding gene editing, automated surveillance, and data privacy must also be addressed through robust governance frameworks.

Looking forward, the future of entomology lies in interdisciplinary collaboration, open-access innovation, and equitable technology diffusion. The fusion of biological sciences with data analytics, engineering, and ethics will be critical in addressing complex ecological questions and emerging global challenges—from climate-induced insect migrations to the spread of vector-borne diseases.

Ultimately, by embracing technological convergence, entomology is poised to evolve from a traditionally observational science into a predictive, precision-driven discipline—one that not only deepens our understanding of insect life but also equips us to steward ecosystems, safeguard food systems, and protect human health in the face of global change.

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