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Advances, challenges, and future directions in entomological research

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Abstract

Insects are the Earth's most diverse animal group and play critical roles in ecosystems and agriculture, yet global trends show dramatic declines in many insect populations. This scholarly review examines future challenges and innovations in entomological research, assuming a global scope and a 1030 year timeframe. After a historical overview highlighting pioneers (such as Merian, Linnaeus, Kirby, Fabre, Darwin, Wilson, von Frisch and Carson) and key milestones, the report analyses cutting-edge technologies and interdisciplinary approaches now transforming the field. Emerging tools include high-throughput DNA sequencing (e.g. metabarcoding, environmental DNA), CRISPR gene drives, AI-powered image and sound recognition, drone and sensor networks and robotics. These tools greatly expand monitoring and experimental capabilities, but each has limitations requiring integration with classical methods. A comprehensive table catalogues emerging technologies and their applications. Major current and future threats to insect biodiversity and agriculture are assessed (climate change, habitat conversion, agrochemical pollution, invasive species, pathogens, etc.), alongside their impacts on ecosystem services. Another table compares these threats in terms of biodiversity loss and agricultural risk. The review identifies urgent research gaps and priority questions, ranging from the taxonomic impediment (80%+ of insects remain undescribed) to the consequences of tipping points in insect communities. A third table summarises research priorities (e.g. funding taxonomy, open data standards, novel monitoring of neglected groups, understanding insect resilience). Finally, implementation pathways and stakeholder roles are discussed: governments, NGOs, industry, farmers, academia and citizens all have roles in funding, regulation, technology deployment and monitoring. The review article uses an academic tone and is intended for researchers and policymakers. It concludes that tackling insect declines and leveraging new science will require a concerted, interdisciplinary effort and sustained investment.

Keywords: entomology, insect biodiversity, emerging technologies, conservation, climate change, integrated pest management, monitoring, genomics, citizen science, insect decline

Introduction

Entomology, the scientific study of insects is a vital discipline underpinning agriculture, ecosystem science and public health. Insects pollinate crops, decompose organic matter, control pests and serve as food for many wildlife species. Global food security, ecosystem resilience and human well-being depend on healthy insect populations^[62]. However, mounting evidence indicates a rapid global decline in insects. Recent reviews report that 40-50% of insect species are declining and one-third are threatened with extinction. In Europe, long-term monitoring in protected areas has revealed losses of over 75-90% of flying insect biomass in recent decades^[80]. North America shows similar trends, with significant declines in pollinators such as native bees and monarch butterflies. Tropical regions, though less well monitored, likely face comparable pressures from deforestation and climate change. These declines have alarming consequences for agriculture and ecosystems. For example, pollinator losses jeopardise fruit, vegetable and oilseed production worldwide^[45]. A recent analysis by the UN showed that insects are disappearing eight times faster than birds or mammals, threatening the services they provide. In response, the entomological research community is rapidly adopting new

technologies and strategies. The next decade will see unprecedented data generation and analytical power applied to insects. High-throughput DNA sequencing (barcoding and metabarcoding) can identify species from bulk samples or environmental DNA (eDNA), tackling the “taxonomic impediment” that has long stalled knowledge of insect diversity^[10]. Machine learning and computer vision can automate species identification from images and sounds, alleviating the shortage of taxonomic experts. Remote sensors (radar, LIDAR, satellite imaging) and Internet of Things (IoT) networks of smart traps and acoustic monitors enable continuous, non-lethal tracking of insect movement and abundance in space and time. In pest management, precision agriculture using drones, sensors and AI is shifting control from blanket spraying to data-driven targeted interventions^[81]. At the same time, genetic tools like CRISPR-based gene drives and RNA interference (RNAi) are being developed to suppress or modify pest species with high specificity. These innovations promise to revolutionise entomology, but they raise challenges of integration, standardisation and ethical governance. This report provides a deep, comprehensive analysis of these issues^[23]. We start by reviewing the history of entomology, noting key milestones and contributors. We then assess emerging technologies and interdisciplinary methods, summarising their applications. Major current and future threats to insect biodiversity and agriculture are analysed. We identify critical research gaps and priority questions that the field must address^[82]. We also present tables that compare emerging tools, threats, research needs and stakeholder pathways. Finally, we discuss funding and implementation strategies, emphasising that safeguarding insect diversity will require coordinated action by scientists, policymakers, industry, farmers and the public^[63]. Our target audience includes entomology researchers, conservation biologists, agricultural scientists and policymakers. The analysis is grounded in recent literature and global perspectives. We assume a timeframe of roughly the next 1030 years, reflecting rapid technological change and the urgency of biodiversity goals. The tone is academic and analytical, yet accessible to decision-makers. No direct citations are provided in text, but the content is informed by current reviews and official reports^[46].

History of Entomology: Notable Scientists and Contributions

- Entomology has ancient roots, but emerged as a formal science only in the last few centuries. In ancient times, insects were noted in culture and early natural history. For example, the Egyptians revered the scarab beetle. Greek philosopher Aristotle (384-322 BCE) systematically described insect metamorphosis and anatomy, laying early foundations for the study of insects. However, the concept of spontaneous generation (insects arising from non-living matter) persisted for millennia until observational evidence refuted it^[64].
- The invention of the microscope in the 17th century opened new dimensions. Italian scientists like Marcello Malpighi (1628-1694) studied insect tissues, revealing structures such as spiracles and tracheae under magnification. Around this time Maria Sibylla Merian (1647-1717), a pioneering entomologist and artist, published detailed studies of insect life cycles^[83]. In her landmark 1705 work *Metamorphosis Insectorum Surinamensium*, Merian documented the complete metamorphosis of many New World caterpillars into butterflies, disproving myths of spontaneous generation. Her illustrations and descriptions of larval host plants and behaviour remain a classic milestone^[1, 47].

- The 18th century brought the era of classification. Carl Linnaeus (1707-1778) published his *Systema Naturae* (10th edition, 1758), which formalised the binomial nomenclature and included many insect genera. Linnaeus’s taxonomy enabled scientists to systematically name and compare species. One of his students, Johan Christian Fabricius (1745-1808), became one of history’s most prolific entomologists, describing thousands of insect species by grouping them according to mouthparts. Meanwhile, in England, William Kirby (1759-1850), often called the “Father of English Entomology”, co-wrote *Introduction to Entomology* (1815-1826) with William Spence. This four-volume work became the foundational text of modern entomology, combining classification with insect behaviour and natural theology. As Kirby wrote, there is “delight in nature” and systematic study of insects^[84].
- The 19th century saw further advances. British naturalist Jean-Henri Fabre (1823-1915) conducted in-depth behavioural experiments on wasps, bees and other insects, publishing vivid accounts that inspired later ethologists. Charles Darwin (1809-1882) indirectly influenced entomology: his theory of evolution by natural selection explained the adaptive significance of insect traits (e.g. mimicry in butterflies). Darwin’s work also encouraged collectors and naturalists to study speciation and biodiversity among insects. In 1859, Darwin’s *Origin of Species* provided an evolutionary framework that guided insect taxonomy and ecology^[24, 65].
- In the late 19th and early 20th century, entomology became professionalised. In the United States, Thomas Say and John Lawrence LeConte pioneered American insect taxonomy. J. H. Comstock (1840-1931) authored *An Introduction to Entomology* (1885) and later entomology textbooks, educating generations of entomologists. Karl von Frisch (1886-1982) made seminal discoveries in insect behaviour by decoding the honeybee “waggle dance” (communication of flower location). Other important figures included Charles Valentine Riley (1843-1895), a pioneer in pest control and E.O. Wilson (1929-2021), a myrmecologist who founded the field of sociobiology studying ants^[48].
- Women also made important contributions. Maria Sibylla Merian has already been noted as an early female naturalist. In the 20th century, entomologists such as Miriam Rothschild and Rachel Carson (1907-1964), though not focused solely on taxonomy, raised awareness of chemical ecology and conservation. Carson’s *Silent Spring* (1962) famously highlighted the dangers of pesticides to insects and ecosystems^[25, 11].
- In the mid-to-late 20th century, genetics and ecology transformed entomology. Thomas Hunt Morgan’s fruit fly genetics (1900s) established insects as model organisms in biology. Advances in microscopy, chemical analysis and radioisotope tracing revealed insect physiology and migration patterns^[67]. The later 20th century also saw the rise of integrated pest management (IPM) and biological control as applied entomology. More recently, the insect genome era has dawned: projects like the i5K initiative (to sequence 5,000 insect genomes) have begun to uncover the genetic basis of insect diversity. Notable modern figures include Jan Sapp for evolutionary biology of symbioses and insect physiologist Thomas Eisner for chemical ecology^[44, 66].

Emerging Technologies and Innovations in Entomology

Modern entomology is being transformed by an array of powerful tools from biotechnology, information technology and engineering. These emerging technologies vastly expand the scale, speed and detail of insect research. A number of novel monitoring methods provide unprecedented coverage in space, time and taxonomy^[49]. In parallel, advances in genetics and synthetic biology offer new ways to manipulate insect populations for control and conservation. The following categories summarise key technologies and their applications. Table 1 (below) compares many emerging tools and their uses^[2].

Digital sensing and monitoring

High-resolution imaging and acoustic sensing are allowing continuous, automated insect surveys. Automated camera traps equipped with light sources can attract and photograph insects in flight or on landing. For example, researchers have deployed autonomous traps that use LEDs and cameras to capture images of night-flying moths and other^[68]. The Internet of Things (IoT) further integrates sensors. Networks of battery-powered traps and environmental sensors (measuring temperature, humidity, CO₂, etc.) can sample insect presence and context in farmland and wild habitats^[85]. For instance, traps equipped with optical counters count beetle or locust entries and wirelessly upload counts. IoT sticky traps or panel traps can even incorporate small cameras or eDNA samplers. Data from widespread sensor grids (including remote sites) can feed into cloud databases for big-data analysis of insect distributions and phenology^[26, 12].

Machine learning and computer vision

The explosion of digital cameras and computing has spurred AI applications in entomology. Deep neural networks are trained on labeled insect images to recognize species, caste or life stage with high accuracy. Apps like iNaturalist or insect-specific platforms allow amateurs and professionals to upload photos, AI suggests identifications, while experts confirm them, vastly expanding digitised specimen records. This citizen-science backbone leverages millions of field observations. In research, convolutional neural networks applied to camera trap photos can count insects or even discern sex or behaviour. Similarly, audio classification algorithms can detect mosquito species by their distinct flight sounds. These methods are reducing reliance on human experts for routine identification^[27].

Genomic and molecular methods

DNA-based tools revolutionise insect detection and taxonomy. Traditional morphology is slow, DNA barcoding and metabarcoding allow rapid identification. In DNA barcoding, a standard gene region (e.g. COI) is sequenced from an individual insect, revealing its species when compared to a reference library. Environmental DNA (eDNA) expands this further: insects leave DNA traces in water, soil or even air. For example, air samplers can collect trace DNA from flying insects to infer community composition. Bulk samples (e.g. mixed trap catches) can be metabarcode: DNA from all individuals in the sample is extracted and sequenced, producing a species inventory without manual sorting. These methods make large-scale biodiversity assessments feasible. The Barcode of Life Data System now contains sequences for hundreds of thousands of insect species worldwide and this database is growing^[3].

Advances in genomics are also applied in population genetics and adaptation studies. Entire insect genomes (from model organisms to pests) are being sequenced, enabling analysis of genes for pesticide resistance, thermal tolerance or vector

competence. With CRISPR/Cas9 gene editing, entomologists can knock out or modify genes in pest insects in the lab to study function or to develop genetic control strategies^[50]. For instance, CRISPR is used to engineer mosquitoes with reduced capacity to carry diseases or agricultural pests with fertility defects. Beyond editing single genes, gene drives are an emerging frontier. Engineered gene drives use selfish genetic elements to bias inheritance of a trait through a population^[86]. In theory, a gene drive inserted into mosquitoes could spread a gene making them unable to transmit malaria. While not yet field deployed (due to ecological and ethical concerns), laboratory studies have demonstrated gene drives in fruit flies and mosquitoes. These powerful tools could transform pest suppression or conservation (e.g. spreading an allele that resists an invasive species), but they require rigorous modelling and governance^[51].

Biotechnology and biocontrol

Advances in biological control include RNA interference (RNAi) and symbiont engineering. RNAi-based biopesticides deliver double-stranded RNA that silences essential pest genes, offering target-specific control. Companies are developing sprayable RNAi for crop pests that degrade quickly in the environment^[69]. Another approach is manipulating insect microbiomes: many insects host beneficial bacteria. For example, the bacterium *Wolbachia* is used to suppress mosquito populations or block dengue virus, *Wolbachia*-infected mosquitoes breed with wild ones, spreading the trait of disease resistance. Synthetic biology is also used to produce pheromones or attractants (semiochemicals) at scale, enabling more effective trapping or behavioural control^[28].

Robotics and miniaturised devices

Inspired by insects, robotics research has produced tiny flying drones that mimic flight patterns. While still emerging, these devices may serve both as pollination aids (drone pollinators) and as mobile sensors to follow insect swarms. Microelectromechanical systems (MEMS) now allow insect-borne tags: miniature RFID or harmonic radar tags can be glued to larger insects (e.g. bees, beetles) to track individual movement over hundreds of meters. Such tags have illuminated pollinator foraging routes and migrations. In the next decade, nano-sensors (e.g. electronic noses) could even sense insect pheromones or pathogens in the field in real time^[70].

Data science and modelling

Underlying all these tools is big-data analysis. Global biodiversity databases (e.g. GBIF, Global Biodiversity Information Facility) aggregate occurrence records from millions of insect specimens and observations. Climate and land-use data layers, combined with species occurrence, allow predictive species distribution models (SDMs) to forecast range shifts under climate change. Machine learning can also forecast outbreaks by learning from historical data (weather, cropping patterns, past pest outbreaks). These *in silico* tools are becoming integral to entomological planning^[13].

The rapid pace of innovation also creates integration challenges. Each technology has limitations: for instance, camera traps may miss small or cryptic insects, acoustic monitors identify only those species that produce sound, DNA methods require reference libraries, AI, models can be biased by training data. To harness the full potential, multiple technologies must be combined for example, linking eDNA surveys with smart traps and local experts in an integrated monitoring program. Standardising data formats and sharing information openly will be key^[4, 29].

Table 1: Emerging Technologies and Applications in Entomology [87, 30, 43, 71]

Technology / Tool	Application & Use
Computer vision (image recognition)	Automated species ID from photos (camera traps, smartphone apps)
Acoustic monitoring (microphones)	Detecting insects by sound (flight buzz, calls, e.g. mosquitoes)
Weather radar / LIDAR	Tracking mass insect movements (migrations, swarms)
Environmental DNA (eDNA)	Survey species by DNA in soil, water, air
DNA metabarcoding	Identify all species in bulk sample via sequencing
Genomic sequencing	Whole-genome data for phylogeny, population genetics, adaptation
CRISPR gene editing	Functional studies, potential gene drive development
RNA interference (RNAi)	Species-specific pest control via gene silencing sprays/traps
Symbiont engineering (e.g. Wolbachia)	Altering insect endosymbionts to reduce disease/pests (mosquitoes)
Internet of Things (IoT) networks	Smart traps and sensors for real-time field monitoring

Each of these technologies is advancing rapidly. For example, precision agriculture now uses drones with multispectral cameras to detect early crop stress from insect damage. Insects often prefer plants under drought or nutrient stress, so anomalies in plant reflectance can signal pest hotspots [52]. Farmers can then apply pesticides or biological controls only where needed, vastly reducing chemical use and cost. Researchers are also using exoskeletal sensors attached to larger insects (like bees) to monitor temperature and motion inside hives or nests. Laboratory automation is improving too: microfluidic devices can sort small insects or mosquito larvae by genetic traits, speeding up experiments [42, 14].

Major Current and Future Threats to Insect Biodiversity and Agriculture

Entomology's importance is underscored by the severe threats facing insects worldwide. Insects are subject to a complex array of pressures from human activities and environmental change. These threats not only imperil insect populations, but also jeopardise the ecosystem services insects provide (such as pollination, biological control, decomposition) [31]. Table 2 summarises the major threats, their impacts on insect biodiversity and agriculture and illustrative examples. Many threats are already accelerating.

- Habitat loss and fragmentation:** This is the single largest driver of insect declines. Conversion of forests, grasslands and wetlands to agriculture or urban areas removes or fragments insect habitat. Monoculture farming (with extensive tillage and pesticide use) vastly reduces floral resources and nesting sites for pollinators and predators. Urban development eliminates leaf litter, dead wood and native flora, disrupting life cycles [88, 53]. Fragmentation isolates populations, making them prone to extinction. In agriculture, intensive land use means fewer wild pollinators and natural enemies of pests. For example, intensive soybean and wheat fields in North America have seen declines in beneficial bees and predatory beetles. Conversely, diverse landscapes with hedgerows, wildflower strips and forest patches support richer insect communities. Future urban expansion and biofuel crop production may further shrink insect habitats. Restoring corridors and green spaces is urgent to mitigate this threat [15].
- Climate change and extreme events:** Rising temperatures, altered precipitation and more frequent extreme weather events (droughts, floods, heatwaves, wildfires) are reshaping insect ecology. Many insects are ectothermic and highly sensitive to temperature. In tropical insects, which often live near their thermal limits, even small warming can cause mortality. Altered seasonality disrupts lifecycles for instance, if a pollinator emerges before its host flower blooms, both suffer. Climate change also facilitates the

expansion of some pest insects into new regions (e.g. tropical mosquitoes moving poleward) [5, 32]. Meanwhile, beneficial insects may lose suitable range. Extreme weather can cause mass die-offs, as seen in heatwaves killing swarms of butterflies or bees. Interaction of climate stress with other pressures (such as drought plus pesticide exposure) can synergistically magnify losses [72]. Adaptive capacity varies: some short-generation insects (like fruit flies) can evolve thermal tolerance within decades, but long-lived insects may lag. Future climate unpredictability means entomologists must develop models to predict new pest outbreaks and conservation needs [54, 16].

- Agricultural pesticides and pollutants:** Widespread use of insecticides (especially systemic chemicals like neonicotinoids) is a critical threat. These chemicals decimate target pests but often harm non-target insects such as bees, butterflies and aquatic larvae [41, 89]. Neonicotinoids, for instance, contaminate pollen and nectar, impairing bee navigation, immunity and reproduction. Even sublethal doses weaken insect communities over time. Other pesticides (fungicides, herbicides) and contaminants (heavy metals, plasticizers) can poison insects or reduce food quality [55]. Light pollution is also significant: artificial nocturnal light (streetlights, screens) disorients moths and fireflies, reduces mating and feeding and even attracts predators. Air and water pollution (soot, ozone, run-off chemicals) harm larvae of aquatic insects, a key part of food webs [73]. Together, chemicals cause "insecticide treadmill" effects pests evolve resistance (as in mosquitoes resistant to pyrethroids), requiring ever-more potent agents, which further injure ecosystems. Agricultural reliance on chemicals is likely to remain a major challenge, emphasizing the need for integrated pest management.
- Invasive species and disease:** Global trade and travel have introduced invasive insects that outcompete or prey on native species (e.g. Argentine ants in California). Invasive plants alter habitats and reduce native host plants. Pathogens and parasites (fungal infections, viruses, nematodes) spread more easily in stressed insect populations [90]. A prime example is the spread of the Varroa mite, which transmits viruses among honeybees worldwide, contributing to colony collapse. Crop pests also spread (e.g. fall armyworm moving from the Americas to Africa/Asia). Invasive or emerging diseases of insects (like Ash dieback affecting wood-boring beetles indirectly) add to the threat. The combined effect is reduced resilience of native insect communities [74].
- Habitat degradation (other forms):** Beyond outright loss, degradation (polluted or degraded habitat) reduces insect carrying capacity. For instance, loss of host plant diversity, eutrophication of soils (fertiliser runoff favouring weeds

over wildflowers) and removal of dead wood all remove critical resources^[92]. Even protected areas can lose quality if surrounding land is degraded, limiting dispersal. Agricultural intensification creates pesticide-laden, monocultural environments where generalist pests flourish but specialists vanish. Noise pollution may interfere with acoustic insects (like crickets and cicadas). In addition, global climate policies like ‘30 by 30’ conservation targets may paradoxically exclude insects if not carefully designed to include habitats supporting invertebrates^[91].

6. **Socioeconomic and knowledge gaps:** Although not a direct ecological threat, the shortage of taxonomists and monitoring programs is a crisis in itself. The “taxonomic

impediment” means most insect diversity is not formally known or monitored. Without data, declines can go undetected until severe. Lack of funding for entomology means fewer career entomologists and fewer conservation initiatives. This human factor is a threat because it hampers any response to ecological threats^[17, 56].

These threats interact in complex ways. For instance, climate change can intensify the impact of habitat loss and chemical exposure can make insects more vulnerable to extreme weather. Likewise, threats to insects often feedback to agriculture: fewer pollinators reduce crop yields, while pesticide-resistant pests can cause crop failures^[75, 6].

Table 2: Major Current and Future Threats to Insect Biodiversity and Agriculture^[40, 18, 33]

Threat	Impact on Insect Biodiversity	Impact on Agriculture & Ecosystems
Habitat loss/fragmentation	Widespread loss of species and local extinctions, reduced population sizes, loss of host plants and nesting sites.	Decline of pollinators and natural enemies, crop yields fall, increased pest outbreaks due to lack of predators.
Loss of floral diversity	Many herbivorous/pollinating insects suffer, simplified food webs.	Reduced pollination services, need for hand pollination in some crops.
Agricultural intensification	Homogeneous landscapes support fewer insect species, chemical/soil disturbance kills life.	Short-term high yields, but long-term pest outbreaks, collapse of natural pest control, pollination deficits.
Overexploitation	Direct depletion of insects used by humans (e.g. wild silkworms, edible insects) can threaten populations.	Loss of traditional food sources, potential cultural/economic impacts.
Emerging threats (future)	Risks from novel technologies (e.g. GMO escapes, nanopesticides) could harm non-target insects, growing light & noise pollution.	New pest complexes, regulatory gaps, unclear ecological risks.
Knowledge/Monitoring gap	Invisible decline: many species lost before discovery, lack of baseline data.	Poorly informed policies, delayed responses.

Research Gaps and Priority Questions

Given these challenges and the range of new tools available, the entomological community has identified several urgent research gaps and priority questions. Filling these gaps is essential to guide conservation and sustainable agriculture^[39].

Taxonomy and Systematics: The “taxonomic impediment” remains a fundamental obstacle. Estimates suggest 80-90% of insect species on Earth are still undescribed. Without baseline taxonomic knowledge, we cannot even quantify declines. Priorities include massively increasing funding and training for insect taxonomy, especially in biodiverse regions with many endemic species^[76]. Integrating molecular methods (DNA barcoding, genomic data) with classical morphology can speed up species descriptions. Digitising and curating museum collections (many specimens of unknown identity) is also crucial. In addition, we need global networks of entomological surveys, from citizen science to standardized field programs, to map where species occur and how numbers change^[57].

- **Monitoring and Data Integration:** There are severe monitoring deficits, especially outside Europe/North America. We lack long-term data on population trends for most insect taxa. Research should develop cost-effective, standardized monitoring protocols deployable worldwide for example, Malaise trap networks with automated counts and barcoding^[93]. Novel monitoring technologies (as described above) must be evaluated and integrated into regular surveys. A priority question is how to achieve interoperable, open databases of insect observations and genetic data. Modern entomology must embrace open-data standards and collaborative platforms to enable meta-analysis of trends^[19, 34].
- **Ecological Function and Interaction:** Much about insect ecology remains poorly understood. What are the key roles of less-studied groups (e.g. soil insects, dung beetles, non-

bee pollinators)? How do insect communities structure ecosystem processes? Fundamental “blue sky” research on insect life-histories, nutrition and trophic interactions is needed. Related questions include: how do insect-plant and insect-insect interactions (pollination networks, predator-prey) reorganize under global change? For example, if a pollinator declines, can other species fill its role or does the plant fail? Understanding these dynamics is critical for predicting ecosystem responses^[77].

- **Anthropogenic Impact Analysis:** We need to clarify the drivers of insect decline and their relative contributions. Which factors (climate, land use, chemicals, light pollution, etc.) are most important in specific contexts? Studies should aim to disentangle these influences (e.g. by comparing gradients of pesticide use and habitat change)^[94]. Consequences of changes must also be studied: for example, what threshold of insect loss causes significant crop pollination shortfall or bird declines? The concept of ecological tipping points is a priority: at what point does insect community change cause ecosystem collapse? Research on insect resilience (recovery potential) is also vital. How quickly can populations rebound if conditions improve and what factors limit recovery?^[35]
- **Conservation Strategies:** There is a gap between general conservation ideas (like protected areas or flower strips) and evidence-based insect conservation. Key questions include: which management interventions most effectively support insects at different scales? For example, how effective are different pollinator corridor designs in agricultural landscapes? How should urban planning incorporate insects (green roofs, street vegetation, pollinator gardens)? There is growing interest in “rewilding” (restoring natural habitats at landscape scale), insect entomology must assess its impacts on invertebrates versus targeted agri-environment schemes. Developing optimized conservation action plans for insects

(akin to IUCN Red List strategies for vertebrates) is a large gap. Engaging applied entomologists (extension agents, farmers) in creating conservation-friendly pest management (like encouraging natural enemies rather than using broad-spectrum pesticides) is also a priority ^[7].

- **Technological and Methodological Gaps:** Each emerging tool has limitations to overcome. Examples include: building comprehensive DNA reference libraries for all insect orders, developing acoustic recognition for thousands of species, miniaturising sensor tags for small insects and standardising AI algorithms. Research needs to evaluate biases of methods (e.g. which species are missed by camera vs trap vs DNA) and create hybrid protocols. There is also a need for low-cost technologies suitable for use in developing countries, as many biodiversity hotspots lack resources. Creating community-driven databases of insect traits and vulnerabilities would help global analyses ^[78].
- **Societal and Policy Engagement:** Entomology must better connect with society and policymakers. How can entomologists effectively communicate the value of insects? What education and outreach strategies most increase public support for insect conservation? There are gaps in stakeholder-engaged research: e.g., involving farmers, citizen scientists and indigenous communities in setting research agendas. Funding and policy questions are also research topics: what incentives or regulations (such as pesticide taxes, habitat protection laws or sustainable agriculture subsidies) are most effective for promoting insect-friendly practices? ^[36]

Government research agencies and international bodies:

National science foundations, environmental ministries and supranational programs (e.g. EU Horizon Europe, UN biodiversity funds) must prioritise entomology in funding. This means allocating grants for basic research (genomics, monitoring technology) and applied projects (IPM, habitat restoration) ^[38]. Governments can also implement policies that incentivise insect-friendly practices: for example, agricultural subsidies for farmers maintaining flower strips or regulations reducing harmful pesticides ^[58]. International agreements like the Convention on Biological Diversity can include insect-specific targets. The Global Biodiversity Framework (post-2020 targets) could incorporate insect indicators. Agencies like the United Nations Environment Programme (UNEP) and Intergovernmental Science-Policy Platform on Biodiversity (IPBES) can promote insect monitoring initiatives globally ^[20].

- **Academic and research institutions:** Universities and research institutes conduct much of the innovation. They should foster interdisciplinary programs combining entomology with computer science, engineering, climate science and social science. Academic consortia can build large shared infrastructure (e.g. genomic sequencing centers, sensor networks) and databases. Institutions can also offer training grants and workshops to build capacity in underrepresented regions ^[8].
- **Non-Governmental Organisations (NGOs) and conservation groups:** NGOs (like WWF, The Xerces Society, Conservation International) can implement practical conservation projects (restoring pollinator habitats, running citizen monitoring schemes) and lobby for insect-friendly policies. They often have strong outreach capacity to educate the public about insects. NGOs can help translate research into action by collaborating with communities and governments ^[79].

- **Private sector and industry:** Agricultural companies, tech companies and biotech firms have roles. For example, agrochemical industries can invest in developing safer pest management products (e.g. RNAi sprays, pheromone traps) and phase out the most harmful pesticides. Tech companies can support citizen science platforms (smartphone apps) or provide AI services for species ID ^[59]. Companies developing IoT devices for agriculture can incorporate insect monitoring features. Private investment in start-ups focused on entomological technology (drones, robotics) can accelerate innovation. Corporate sustainability initiatives (e.g. airline carbon offsets) could fund insect habitat projects ^[37].
- **Farmers and land managers:** As on-the-ground stewards, farmers are critical implementers of insect-friendly practices. Through training and incentives, farmers can adopt integrated pest management (e.g. using biological controls, crop rotation, minimal tillage) that reduce pesticide harm to beneficial insects. Farmers' associations can partner with researchers to co-design trials of pollinator habitats, monitoring pest populations and implementing precision spraying. Agronomists should include insects in soil health and crop health assessments ^[60].
- **Citizen scientists and educators:** Engaging the public directly can vastly expand data collection. Programs like garden butterfly counts, pollinator planting initiatives and bio-blitzes make people stakeholders in insect science. Volunteers can run simple traps, count insects and submit data via apps. Schools and universities can incorporate insect research projects, raising awareness. Education campaigns highlighting the importance of insects for food security and ecosystem health can shift attitudes and behaviour (e.g. reducing insecticide use in home gardens) ^[21].
- **International research collaborations:** Insect biodiversity knowledge is heavily skewed toward wealthier countries. Partnerships between researchers in developed and developing regions can help fill geographic gaps. Collaborative networks (like the Global Entomology Coalition, insect-focused chapters of IPBES) can pool resources. Development agencies can support entomology capacity-building in biodiversity hotspots ^[61].
- **Media and public communication:** Science communicators and media organisations can help translate entomological findings for policy-makers and the public. Documentaries, news stories and social media campaigns focusing on pollinator health or insect decline can generate political will. Highlighting economic case studies (e.g. value of pollination to crop yield or costs of pest damage) can motivate funding decisions ^[22, 9].

Conclusion

Entomology is poised at a critical juncture. On one hand, the accelerating decline of insects globally presents an urgent crisis. Declines driven by habitat loss, climate change, pollution and other anthropogenic factors threaten ecosystems, agriculture and ultimately human well-being. On the other hand, unprecedented technological and methodological innovations offer hope. Advances in genomics, artificial intelligence, remote sensing and robotics are expanding our capacity to study, monitor and even manipulate insect populations. The future of entomology will be defined by how effectively these tools are harnessed to overcome the challenges. This review has shown that an integrated, global approach is needed. Historical perspective

reminds us that entomology has always advanced by blending observation with new technology (from Linnaeus's microscope to Fabre's experiments). Today's breakthroughs are no different: they combine classical expertise with cutting-edge science. To succeed, entomologists must collaborate across disciplines and continents. Data silos must be broken down through open standards and shared platforms. Conservation and agriculture policies must incorporate entomological insights, ensuring that land-use planning and farming practices support insect diversity. The proposed tables serve as a guide for stakeholders: Table 1 outlines technologies that researchers and practitioners should adopt and refine, Table 2 highlights the threats that policies must address, Table 3 identifies the knowledge gaps that science must fill, Table 4 suggests how funding and collaboration can be organised. Examples of actions include establishing global insect monitoring networks (using both automated traps and citizen science), funding a new generation of taxonomists and informaticians, retooling agriculture to favor beneficial insects and preparing frameworks for emerging biotechnologies (like gene drives) through international dialogue. The timeframe considered (next 1030 years) is ambitious, but necessary. Many insect declines are already underway and climate impacts will intensify. Quick action is required to document and halt declines before ecosystem functions collapse. Yet the same timeframe promises rapid technology maturation. By 2035, it is plausible that thousands of insect genomes will be sequenced, AI systems will identify most common species from wingbeat sounds and affordable sensors will monitor farms and forests in real time. Entomologists must be ready to interpret and apply this data deluge. In sum, the future of entomology depends on integrating innovation with conservation urgency. Advancing research on insect biology and ecology must go hand-in-hand with societal efforts to protect habitats and reduce pollutants. Entomology can no longer be a niche scientific pursuit, it must be central to environmental and agricultural policy. The challenges are great, but so are the opportunities. With concerted effort, the coming decades can see entomology rise to safeguard insect life and, by extension, the health of our planet.

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