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Original Article**AI Meets Taxonomy: Can Artificial Intelligence Identify Every Insect on Earth?****Mude Pavan Kalyan¹**

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ABSTRACT

Artificial intelligence (AI) is rapidly transforming insect taxonomy, a discipline traditionally dependent on expert knowledge, meticulous morphological observations and decades of taxonomic experience. As global insect diversity continues to outpace our ability to identify and describe species, AI offers an innovative solution by combining computer vision, machine learning, deep learning and genomic data to accelerate species recognition. Modern AI-powered systems can analyze high-resolution images, detect subtle morphological differences, process millions of biodiversity records, and even integrate DNA barcodes to improve classification accuracy. These technologies are revolutionizing biodiversity surveys, ecological monitoring, agricultural pest management, museum digitization and citizen science initiatives. However, AI is not replacing taxonomists; instead, it is becoming an intelligent partner that enhances scientific discovery while reducing identification time and improving accessibility. This article explores how artificial intelligence is reshaping insect taxonomy, examines its current achievements and limitations and discusses whether AI can ultimately help document Earth's extraordinary insect diversity.

Keywords: Artificial intelligence; Insect taxonomy; Computer vision; Machine learning; Biodiversity monitoring.

INTRODUCTION

On a summer evening, a farmer notices an unfamiliar insect feeding on young soybean leaves. Traditionally, identifying the species would require collecting the specimen, consulting taxonomic keys, examining minute anatomical characters under a microscope and perhaps sending it to a specialist hundreds of kilometers away. The process could take days or even weeks. Today, however, the same insect can often be photographed using a smartphone, uploaded to an artificial intelligence (AI)-powered application and identified within seconds with remarkable accuracy. What once demanded years of taxonomic training is increasingly becoming accessible through the power of machine learning and computer vision. This transformation represents one of the most exciting developments in modern biological sciences. Insect taxonomy the science of discovering,

describing, naming and classifying insects has traditionally relied on careful examination of morphological characters such as wing venation, antennae, mouthparts, genitalia and body segmentation. While this approach has built the foundation of entomology for more than two centuries, it faces unprecedented challenges today. Scientists estimate that Earth may harbor between 5 and 10 million insect species, yet fewer than one-quarter have been formally described. At the current pace of taxonomic research, documenting this diversity could require several centuries. Meanwhile, habitat destruction, climate change, invasive species, and environmental degradation threaten many insects before they are even discovered. Compounding this challenge is the taxonomic impediment a global shortage of professional taxonomists, insufficient funding for systematic research and the overwhelming volume of unidentified specimens housed in museums and research collections. Many experienced insect taxonomists are approaching retirement, while relatively few young scientists are entering this highly specialized field. Consequently, biodiversity surveys, ecological monitoring programs, agricultural pest diagnostics and conservation initiatives increasingly struggle to obtain rapid and accurate species identifications.

Artificial intelligence is emerging as a powerful ally in addressing these challenges. Unlike traditional computer programs that rely solely on predetermined instructions, AI systems can learn directly from vast datasets of insect images, DNA sequences, ecological records and taxonomic information. Using sophisticated algorithms, they recognize complex morphological patterns, continuously improve their performance through training and make predictions with impressive speed and accuracy. Recent advances in deep learning have enabled AI models to distinguish insect species that differ by only subtle anatomical characteristics features that may challenge even experienced entomologists. The integration of AI into taxonomy extends far beyond simple image recognition. Modern systems can automate specimen sorting in museums, analyze wing venation patterns, identify insects from environmental DNA (eDNA), predict evolutionary relationships using genomic data, and monitor insect populations through autonomous camera traps and acoustic sensors. Citizen scientists now contribute millions of georeferenced insect observations annually through AI-assisted mobile applications, dramatically expanding global biodiversity databases and accelerating species discovery. Importantly, AI is not replacing human expertise. Taxonomy involves far more than assigning names to organisms; it requires understanding evolutionary relationships, ecological interactions, geographic variation and the rules of biological nomenclature. Instead, AI functions as an intelligent assistant, handling repetitive tasks, processing enormous datasets and enabling taxonomists to focus on complex scientific questions that require expert judgment. As advances in computing, genomics, robotics and biodiversity informatics continue to converge, AI is redefining how scientists explore the insect world. The question is no longer whether artificial intelligence can assist taxonomy, but rather how far this technological revolution can go. Could AI eventually identify every insect species on Earth? Or will the extraordinary complexity of insect diversity always require the irreplaceable insight of human taxonomists? The answers are beginning to emerge from one of the most fascinating intersections of biology and technology.

The Taxonomic Crisis: Why Insect Science Needs Artificial Intelligence

To appreciate why artificial intelligence has become so important, one must first understand the enormous scale of the taxonomic challenge facing modern biology. Insects are the most diverse group of animals on Earth, accounting for more than 75% of all described animal species. They occupy virtually every terrestrial and freshwater habitat, pollinate crops, recycle organic matter, regulate pest populations and sustain countless food webs. Yet despite centuries of scientific exploration, our knowledge of insect diversity remains surprisingly incomplete. Current estimates suggest that only about one million insect species have been formally described, while several million remain unknown to science. Tropical rainforests, mountainous ecosystems, underground habitats, and even urban environments continue to yield hundreds of new species each year. Many insects are highly specialized, occupying narrow ecological niches or existing only in isolated geographic regions. Others are so small that they escape routine observation altogether. Tiny parasitoid wasps, minute beetles, fungus gnats, and soil-dwelling springtails often require microscopic examination before their distinguishing characteristics become visible.

The process of formally describing a new insect species is meticulous and time-consuming. Taxonomists must compare specimens with existing descriptions, examine type material preserved in museums, document diagnostic morphological characters, analyze molecular evidence when available, prepare illustrations or photographs, determine nomenclatural validity under the International Code of Zoological Nomenclature (ICZN) and publish peer-reviewed descriptions. Completing this process for a single species may require months of careful investigation. Meanwhile, museums worldwide house tens of millions of unidentified insect specimens, many collected decades ago during biodiversity surveys but never thoroughly examined. These collections represent an extraordinary scientific resource, yet their immense size far exceeds the capacity of available specialists. Every drawer of pinned insects potentially contains undescribed species awaiting discovery. The challenge is intensified by what biologists call the taxonomic impediment. Across the world, the number of trained insect taxonomists has declined steadily over recent decades. Many experts specialize in only one family or genus, reflecting the immense complexity of insect classification. As senior specialists retire, fewer young researchers possess the extensive morphological expertise required to replace them. Simultaneously, funding increasingly favors molecular biology, biotechnology and applied agricultural research, leaving traditional taxonomy relatively under-supported despite its foundational importance. This shortage has practical consequences extending far beyond academic research. Farmers depend on rapid identification of emerging pest species before outbreaks become economically devastating. Conservation biologists require accurate species inventories to identify biodiversity hotspots and protect endangered insects. Quarantine agencies must distinguish invasive species from harmless native insects at international borders. Public health officials need timely identification of disease vectors such as mosquitoes and sand flies. Delays or errors in identification can have significant ecological, agricultural, and economic consequences. Climate change adds further urgency. Rising temperatures are altering insect distributions worldwide, allowing numerous species to expand into previously unsuitable regions. New agricultural pests, invasive species and vector-borne diseases

are emerging in areas where they were historically absent. Rapid identification has therefore become increasingly critical for early detection and effective management.

Artificial intelligence offers an unprecedented opportunity to overcome many of these limitations. Instead of requiring every specimen to be examined individually by a specialist, AI systems can rapidly screen thousands of images, group similar specimens, identify likely species and prioritize unusual individuals for expert review. Rather than replacing taxonomists, AI dramatically increases their efficiency, enabling specialists to focus on describing genuinely new species and resolving complex taxonomic problems. Another major advantage lies in scalability. Once trained on sufficiently large datasets, AI algorithms can analyze millions of images in a fraction of the time required by human observers. High-throughput imaging systems installed in museums now automatically photograph pinned specimens, while machine-learning algorithms extract morphological information directly from digital images. Similar technologies operate in automated insect traps, camera networks, and agricultural monitoring systems, generating continuous biodiversity data with minimal human intervention. Citizen science has also become a powerful driver of AI-assisted taxonomy. Platforms such as iNaturalist, Observation.org and BugGuide receive millions of insect photographs annually from nature enthusiasts worldwide. AI algorithms provide preliminary identifications, while expert users verify records and continuously improve the training datasets. This collaboration between artificial intelligence and public participation has dramatically expanded the geographic and taxonomic coverage of biodiversity observations, often leading to new distribution records and even the discovery of undescribed species. Ultimately, the taxonomic crisis is not simply about identifying insects more quickly; it is about preserving humanity's ability to understand and conserve Earth's extraordinary biodiversity before it disappears. Artificial intelligence represents one of the most promising tools available to address this challenge. By accelerating species identification, improving data accessibility and enhancing collaboration between experts and the public, AI is helping transform taxonomy from a discipline constrained by limited human capacity into one empowered by computational innovation.

How Artificial Intelligence Learns to Recognize Insects

The remarkable ability of artificial intelligence (AI) to identify insects is rooted in one of the most significant breakthroughs in computer science machine learning. Unlike conventional software, which follows fixed instructions programmed by humans, machine-learning systems improve their performance by learning from examples. Instead of telling a computer precisely how to identify every butterfly, beetle, or mosquito, scientists provide thousands or often millions of labeled images from which the algorithm discovers distinguishing features on its own. Over time, the system becomes increasingly accurate, recognizing patterns that are often too subtle for the human eye. At the heart of modern insect identification lies deep learning, a branch of AI inspired by the architecture of the human brain. Deep-learning models consist of multiple interconnected computational layers that progressively analyze visual information. The earliest layers detect simple features such as edges, colors and textures. Intermediate layers recognize more complex structures including wing veins, antennae, body segmentation, and leg arrangements. The deepest layers combine these observations into a complete representation of an insect, enabling the model to predict its identity with impressive precision. Among the most widely used deep-learning

architectures are Convolutional Neural Networks (CNNs). CNNs have become the gold standard for biological image recognition because they excel at identifying spatial patterns regardless of variations in lighting, orientation or background. When presented with a photograph of a butterfly, for example, a CNN does not merely compare the image to stored templates. Instead, it analyzes thousands of visual characteristics simultaneously from wing symmetry and color patterns to body proportions and venation before assigning the specimen to its most probable taxonomic group. Training such systems requires enormous datasets. Researchers compile millions of accurately identified insect photographs from museum collections, biodiversity databases, scientific publications, and citizen science platforms. Each image serves as a teaching example. During training, the algorithm repeatedly compares its predictions with the correct identifications, gradually adjusting millions of internal parameters until classification errors are minimized. After sufficient training, modern CNNs can identify many common insect groups with accuracies exceeding 95 % under controlled conditions. Recent advances extend beyond simple image classification. Object detection algorithms, such as YOLO (You Only Look Once) and Faster R-CNN, can simultaneously locate and identify multiple insects within a single photograph. These systems prove invaluable for ecological monitoring, where camera traps may capture dozens of insects visiting flowers, crops or light traps. Instead of manually examining thousands of images, researchers can obtain automated counts, species identifications, and behavioral observations within minutes. Another emerging technology is vision transformers (ViTs), which combine computer vision with transformer-based architectures originally developed for natural language processing. Vision transformers analyze relationships among different image regions rather than relying solely on local visual features. Early studies suggest that ViTs may outperform conventional CNNs for highly diverse insect groups, particularly when distinguishing closely related species exhibiting subtle morphological differences.

AI-Powered Tools Transforming Insect Identification

The practical impact of AI becomes evident through the growing number of applications now available to scientists, agricultural professionals, conservationists and the general public. These tools have democratized insect identification, making expert-level assistance accessible through smartphones, tablets and web-based platforms. One of the most influential platforms is iNaturalist, a global citizen science initiative that combines AI with expert validation. Users simply photograph an insect using a smartphone and upload the image to the application. The integrated AI model immediately suggests possible identifications based on millions of previously verified observations. Experienced taxonomists and community experts then confirm or refine these identifications, continually improving both the database and the AI model itself. Today, iNaturalist contains hundreds of millions of biodiversity observations, representing one of the world's largest repositories of biological images. Similarly, Observation.org and ObsIdentify employ AI-assisted recognition to document insect diversity across Europe and other regions. These platforms support biodiversity inventories, ecological monitoring, and conservation planning by generating georeferenced occurrence records that are instantly accessible to researchers worldwide. Agriculture has become another major beneficiary of AI-based insect recognition. Farmers increasingly rely on smartphone applications capable of identifying economically important pests

directly from field photographs. Instead of waiting for laboratory diagnoses, growers receive rapid preliminary identifications that support timely pest management decisions. AI systems trained on regional pest databases can distinguish aphids, whiteflies, thrips, leaf miners, armyworms, fruit borers and numerous other agricultural pests with high accuracy, enabling earlier intervention and reducing unnecessary pesticide applications. In public health, AI-assisted mosquito identification has become an important component of disease surveillance. Accurate discrimination among species of *Anopheles*, *Aedes* and *Culex* mosquitoes is essential because each group transmits different pathogens. Automated recognition systems now assist surveillance programs by rapidly classifying captured mosquitoes from digital images, supporting early detection of vector-borne disease outbreaks. Researchers are also developing AI systems capable of identifying insects from wing venation alone. Wing patterns often remain highly conserved within species, functioning as natural fingerprints. Specialized algorithms analyze vein intersections, branching patterns and geometric relationships, achieving remarkable success in groups such as bees, mosquitoes, dragonflies, and fruit flies. These methods are particularly valuable when body coloration or other external features have faded during specimen preservation.

Artificial Intelligence in Museums and Digital Taxonomy

Natural history museums contain an estimated two to three billion insect specimens, making them among the world's largest repositories of biological knowledge. These collections document centuries of biodiversity exploration, including numerous extinct, endangered and undescribed species. However, only a fraction of these specimens has been digitized or thoroughly studied. Artificial intelligence is dramatically accelerating museum digitization efforts. Automated imaging systems now photograph thousands of pinned specimens each day using robotic cameras capable of producing high-resolution, multi-angle images. Machine-learning algorithms subsequently extract labels, measure body dimensions, identify morphological structures and organize specimens into searchable digital databases. Optical character recognition (OCR) algorithms automatically transcribe handwritten specimen labels, many of which date back more than a century. These labels often contain invaluable information regarding collection locality, habitat, host plants and historical distribution. AI substantially reduces the labor required to digitize these records while preserving irreplaceable historical data. Micro-computed tomography (micro-CT) further complements AI by generating three-dimensional digital models of insects without damaging fragile specimens. These virtual reconstructions allow researchers to examine internal and external anatomy from any angle, revealing diagnostic structures inaccessible through traditional microscopy. AI algorithms can automatically segment anatomical features, measure morphological traits and compare specimens with unprecedented precision. Together, these technologies are transforming museums from static collections into dynamic digital resources that support global taxonomic research.

When Genomics Meets Artificial Intelligence

The future of taxonomy increasingly lies at the intersection of AI and genomics. While photographs provide valuable morphological information, DNA sequences reveal evolutionary relationships invisible to external appearance. Integrating these complementary datasets produces more robust

species identification systems than either approach alone. DNA barcoding, particularly sequencing of the mitochondrial cytochrome c oxidase subunit I (COI) gene, has become a standard method for species identification. AI algorithms now analyze barcode sequences alongside morphological images, ecological information, and geographic distributions to improve taxonomic accuracy. Machine-learning models can rapidly classify unknown DNA sequences, identify cryptic species, detect sequencing errors, and predict evolutionary relationships using massive genomic datasets. As reference libraries such as the Barcode of Life Data System (BOLD) continue expanding, AI-assisted genomic taxonomy will become increasingly powerful. This integration is particularly valuable for immature life stages. Larvae, eggs and pupae often lack the diagnostic morphological features present in adults, making visual identification extremely difficult. Combining genomic data with AI overcomes this limitation, enabling accurate identification throughout an insect's life cycle.

Challenges, Limitations, and the Future of AI in Taxonomy

Despite remarkable progress, artificial intelligence is not infallible. AI systems are only as reliable as the data used to train them. Poor-quality photographs, insufficient representation of rare species, inaccurate labels and taxonomic inconsistencies can reduce classification accuracy. Models trained primarily on common species may struggle when encountering undescribed insects or populations from poorly sampled regions. Closely related species often differ only in microscopic structures, such as male genitalia or minute wing characteristics, that remain difficult to capture in ordinary photographs. Consequently, many taxonomic groups still require expert examination under high-powered microscopes before definitive identification can be achieved. Another concern involves algorithmic bias. Most publicly available training datasets originate from Europe and North America, whereas tropical regions contain the greatest insect diversity. AI systems may therefore perform less effectively in biodiversity hotspots where training data remain limited. Expanding high-quality image libraries from underrepresented regions will be essential for creating globally applicable identification models. Taxonomy also encompasses much more than identification. Describing a new species requires detailed morphological diagnosis, comparison with type specimens, nomenclatural decisions, ecological interpretation and publication following the International Code of Zoological Nomenclature. These tasks require scientific reasoning, critical evaluation and expert judgment that AI cannot currently replace. Nevertheless, the future is extraordinarily promising. Advances in multimodal AI will integrate photographs, DNA sequences, acoustic signals, geographic information, ecological metadata and environmental DNA into unified identification systems. Autonomous drones, robotic field stations, smart insect traps and real-time biodiversity monitoring networks may soon provide continuous surveillance of insect populations across entire landscapes. Rather than replacing taxonomists, AI is becoming an indispensable collaborator accelerating routine tasks while allowing experts to focus on scientific discovery, evolutionary interpretation and biodiversity conservation. In this partnership between human expertise and computational intelligence lies the future of insect taxonomy.

CONCLUSION

Artificial intelligence is ushering in a new era of insect taxonomy by combining computational power with centuries of taxonomic knowledge. Through advances in computer vision, deep

learning, genomics and biodiversity informatics, AI is making insect identification faster, more accurate and more accessible than ever before. From recognizing agricultural pests in farmers' fields to digitizing museum collections and uncovering cryptic species through genomic analyses, AI is transforming every stage of taxonomic research. Yet, despite its remarkable capabilities, artificial intelligence is not replacing human taxonomists. The discovery, description and classification of new species still depend on expert interpretation, evolutionary understanding, and rigorous scientific validation. Instead, AI serves as an intelligent partner that enhances efficiency, accelerates biodiversity research and expands global participation through citizen science. As algorithms become more sophisticated and biological databases continue to grow, the collaboration between humans and artificial intelligence will play a pivotal role in documenting, understanding and conserving the extraordinary diversity of insects before it is lost.

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