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Artificial intelligence in entomology research: Species identification, behaviour, disease vector analysis and data processing

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Abstract

This review explores the integration of artificial intelligence (AI) in entomological research, highlighting its potential to revolutionize the field. Traditional methods of entomology, while still valuable, are increasingly complemented by AI-driven approaches. The paper discusses current AI applications in automated species identification, behavioural tracking and monitoring, disease vector analysis, and data collection and processing. These technologies offer enhanced accuracy, efficiency, and scale in studying insect biology, ecology, and behaviour. However, challenges persist, including data scarcity, model interpretability, and deployment in resource-limited settings. The review also examines future directions for AI in entomology, emphasizing its potential in climate change research, pest management, and disease vector control. The integration of AI with other emerging technologies holds promise for advancing entomological research and conservation efforts. The paper concludes by stressing the importance of collaborative efforts between entomologists and AI specialists to develop tailored solutions that address the field's unique challenges while maintaining the foundational principles of entomology.

Keywords: Artificial intelligence, entomology, species identification, disease vector analysis, data processing, biodiversity conservation

Introduction

Entomology is the scientific study of insects, encompassing their biology, ecology, behaviours, and interactions within ecosystems. It plays a crucial role in understanding and preserving biodiversity, particularly given that insects constitute the most diverse and ecologically important group among all animals [13].

The significance of entomology in biodiversity is multifaceted. Insects are integral to earth's ecosystems, playing vital roles in pollination, decomposition, and as both predators and prey [24]. They contribute significantly to soil health, nutrient cycling, and plant growth, making them essential for maintaining ecological balance [24]. Entomological research also has implications for human well-being, as insects intersect with socio-economic, cultural, and public health sectors [24]. While entomology is crucial for biodiversity conservation, there are challenges in public perception. The lack of human appreciation for insects' importance, coupled with general disregard and dislike, presents a significant impediment to their conservation [22]. This perception barrier, along with the "taxonomic impediment" (only about 7-10% of insects are scientifically described), needs to be overcome for effective biodiversity conservation [22].

This review paper aims to provide a comprehensive overview of artificial intelligence (AI) applications in entomology, highlighting their current state and future directions. It begins by emphasizing the importance of entomology in biodiversity conservation and ecosystem management, followed by a discussion of traditional entomological research methods and their limitations. The paper then explores current AI applications in entomology, including automated species identification, behavioural tracking and monitoring, disease vector analysis, and data collection and processing. Additionally, it examines the challenges and limitations of implementing AI in entomological research. The review identifies future needs and potential directions for AI integration in entomology, focusing on areas such as climate change research, pest management, and disease vector control. Finally, it emphasizes the importance of interdisciplinary collaboration between entomologists and AI specialists to develop tailored solutions for the field's unique challenges.

A present review study attends following aspects in this paper: A. Traditional method of entomology research; B. Traditional methods of entomological research have faced several limitations and challenges; C. Current Applications of AI in Entomology; D. Behavioural Tracking and Monitoring; E. Disease Vector Analysis; F. Data Collection and Processing with AI; G. Challenges and Limitations of AI in Entomology and H. Future Needs and Directions of AI in Entomology.

A. Traditional method of entomology research

Traditional methods of entomological research have long been the foundation of the field, providing valuable insights into insect biology, behaviours, and ecology. These methods primarily include specimen collection and observation [23]. Researchers have relied on field sampling, manual identification, and morphological analysis to study insect species and their distributions. However, it's interesting to note that while these traditional approaches remain important, they are increasingly being complemented by advanced technologies. For instance, environmental DNA (eDNA) analysis offers a non-invasive alternative to traditional specimen collection, allowing researchers to monitor elusive or endangered insect species [23]. Similarly, artificial intelligence and machine learning are now being employed for automated species identification, potentially surpassing traditional morphological identification methods in terms of accuracy and speed [8]. While traditional entomological methods continue to play a crucial role, the field is rapidly evolving. The integration of new technologies and approaches, such as NGS-based methods [16], citizen science initiatives [2], and molecular techniques [14], is transforming entomological research. This evolution is enabling researchers to address more complex ecological questions and tackle grand challenges facing entomology in the 21st century, including the need for global-scale data synthesis and rapid sharing of research outputs [4].

B. Traditional methods of entomological research have faced several limitations and challenges

Offline research methods in the field of sexualities have been associated with methodological difficulties such as biases, limited access to hidden groups, and prohibitive costs [7]. These challenges have prompted researchers to explore alternative approaches, including online methods, to address these limitations. In the context of citizen science and amateur entomology, quality control of data remains an issue for some projects [2]. Traditional methods may struggle to balance the goals of researchers, participants, and supporting institutions, potentially affecting the reliability and usefulness of collected data. The advent of new technologies has highlighted some limitations of traditional entomological research methods. For instance, AI-based species identification methods using deep learning neural network models have been shown to outperform traditional morphological identification methods in terms of accuracy and speed [8]. This suggests that traditional identification techniques may be less efficient and potentially less accurate in certain scenarios. Furthermore, the scale of biodiversity and environmental analyses has shifted from individuals and indicator species to large-scale studies of communities and ecosystems, which traditional methods may struggle to, accommodate [16]. The emergence of NGS-based methods has enabled the study of bulk samples and environmental DNA, offering a broader perspective that traditional approaches may not easily achieve.

C. Automated species identifications of insects using AI

Automated species identification of insects has become increasingly important in various fields, including agriculture, environmental monitoring, and entomology. Computer vision and machine learning techniques have shown promising results in accurately classifying large numbers of closely related insect species [5]. These methods can handle complex tasks such as identifying fruit flies (Diptera: Tephritidae) and mosquitoes (Diptera: Culicidae) with high accuracy [5, 25]. Interestingly, different approaches have been developed to tackle this challenge. Some systems use global feature extraction and dimension reduction techniques [26], while others employ convolutional neural networks (CNNs) for image-based classification [3]. The AFIS1.0 system, for instance, combines automated image identification with manual verification, achieving an 87% classification success rate for fruit flies [25]. In contrast, a CNN-based approach for identifying plant bug species demonstrated expert-level accuracy, even for taxonomically challenging groups. Automated insect species identification has made significant progress, with various methods showing high classification rates. These systems offer potential solutions for non-destructive, real-time monitoring of insects [3] and can provide valuable insights into insect behaviour and ecology [3]. However, challenges remain, such as handling class imbalance and improving performance on diverse datasets [3]. As these technologies continue to evolve, they are likely to revolutionize insect systematics and contribute to more efficient pest management and biodiversity monitoring.

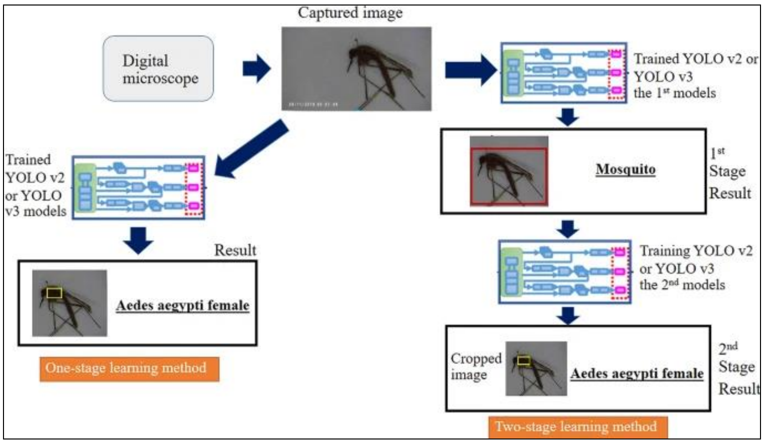
D. Behavioural Tracking and Monitoring

Artificial intelligence (AI) and machine learning techniques have revolutionized behavioural tracking and monitoring of insects, offering unprecedented accuracy and efficiency in entomological research. These advanced technologies enable researchers to study insect behaviours, movement patterns, and population dynamics with greater precision and on larger scales than ever before. AI-based systems have been developed for tracking and recognizing various insect species, including honey bees and moths. For instance, a planar bee tracking system using neural networks can track individual bees in closed mazes, while a spatial bee tracking system combines neural networks and tracking algorithms to identify and track flying bees in open environments [19]. Similarly, an open-source machine learning pipeline has been created for automated monitoring of moths via camera traps, including object detection, classification, species identification, and individual tracking [10]. Interestingly, these AI-powered tracking systems are not limited to controlled laboratory settings. The Insect Classification and Tracking algorithm (ICT) has been successfully deployed in the field, achieving an average precision of 89% for correctly classified insect tracks of eight different species [3]. This system can provide real-time classification and tracking, uploading summary data on insect identity and movement to a server daily, offering valuable insights into insect phenology, abundance, foraging behaviours, and movement ecology.

AI and machine learning have significantly enhanced our ability to track and monitor insect behaviours across various environments and species. These technologies offer non-destructive, continuous, and efficient methods for collecting and analyzing large-scale entomological data [9]. As these tools continue to evolve, they promise to provide even more accurate and comprehensive insights into insect behaviours, ecology, and population dynamics, contributing to critical areas such as biodiversity conservation, pest management, and climate change research.

E. Disease Vector Analysis

Deep learning and artificial intelligence techniques are increasingly being applied to analyze and predict vector-borne disease outbreaks caused by insects and other arthropods. Convolutional neural networks (CNNs) and artificial neural networks (ANNs) have shown promising results in classifying and predicting outbreaks of diseases like chikungunya, malaria, and dengue across the Indian subcontinent, with prediction accuracies of 88% and 86% respectively [17, 18]. Conventional strategies for managing vector-borne pathogens focus on keeping vector populations below a threshold based on the basic reproductive ratio (R0), bio-economic approaches that balance ecological and economic trade-offs may be more cost-effective [6]. This highlights the importance of considering both biological and economic factors when developing AI-based vector control strategies. AI and machine learning techniques offer powerful tools for analyzing large amounts of medical data related to vector-borne diseases and predicting future outbreaks. These approaches can potentially improve upon traditional methods of assessing vector populations, which are often time-consuming and labour-intensive [11]. As research in this field progresses, integrating AI with ecological and economic considerations may lead to more effective and sustainable strategies for controlling disease vectors and the pathogens they transmit.

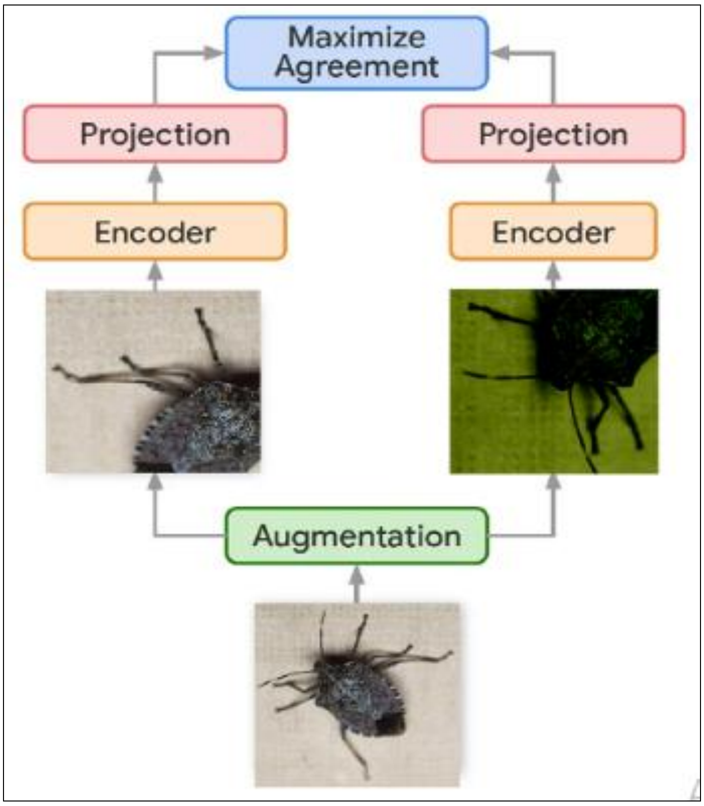


(**Source:** https://www.nature.com/articles/s41598-021-84219-4#citeas)

Fig 1: Illustration of Deep Learning for Species and Gender Identification of Mosquito Vectors.

F. Data Collection and Processing with AI

Artificial intelligence (AI) has revolutionized data collection and processing related to insects, offering innovative solutions for species identification, pest management, and ecological research. AI-powered tools like AInsectID Version 1.1 have demonstrated remarkable accuracy in insect species identification, achieving a validation accuracy of 99.65% using the ResNet101 convolutional neural network model [20]. This software integrates transfer learning and hyper-parameter optimization to improve prediction performance, particularly addressing challenges posed by insect mimics. In agricultural settings, AI and IoT techniques have shown promising results in detecting, classifying, and counting cotton insect pests and beneficial insects, with accuracy rates ranging from 70% to 98% [12]. AI has shown great potential in insect-related applications, there are still limitations to overcome. For instance, the detection and characterization of immature and predatory insects remain challenging, and only a few species have been targeted for detection and classification by AI and IoT systems [12]. Additionally, factors such as insect location, data size, concentrated insects on images, and similarity in species appearance pose obstacles to AI implementation.



(**Source:** https://onlinelibrary.wiley.com/doi/10.1111/ele.14239)

Fig 2: Illustration of self-supervised AI learning model.

AI-driven approaches are transforming insect-related data collection and processing, offering high accuracy and efficiency in species identification and pest management. However, further research is needed to expand the number of monitored species, improve detection accuracy, and address challenges related to diverse insect life stages and behaviours. As the field evolves, integrating AI with other technologies like environmental DNA analysis, remote sensing, and genome editing holds promise for advancing entomological research and conservation efforts [23].

G. Challenges and Limitations of AI in Entomology

AI applications in entomology face several challenges and limitations, despite their potential to revolutionize the field. The primary challenge is the scarcity and quality of data available for training AI models in entomology. Unlike other fields with abundant data, entomology often deals with rare species or limited sample sizes, making it difficult to develop robust AI systems [21]. This data limitation can lead to biases and inaccuracies in AI-driven insect identification and classification. Additionally, the vast diversity of insect species and their morphological variations pose significant challenges for AI algorithms to accurately distinguish between closely related species. While AI shows promise in detecting plant diseases, which could indirectly benefit entomology by identifying insect-borne plant pathogens, there are still obstacles in implementing these technologies in resource-constrained environments [21]. This limitation could hinder the adoption of AI tools in field entomology, particularly in remote or underdeveloped areas where insect-related research is often conducted. While AI has the potential to enhance entomological research and applications, significant hurdles remain. These include data scarcity, model interpretability, and deployment challenges in resource-limited settings [21]. Overcoming these limitations will require collaborative efforts between entomologists and AI specialists to develop tailored solutions that address the unique challenges of the field. As seen in other disciplines, successful integration of AI in entomology will likely depend on harnessing diverse knowledge rather than mere interdisciplinary team composition [1].

H. Future Needs and Directions of AI in Entomology

AI methods have shown significant potential in revolutionizing various aspects of entomological research, offering improved accuracy, speed, and efficiency across multiple subfields. In behavioural biology, AI-based tracking systems have enhanced the classification of insect behaviours and movement patterns [8]. For species identification, deep learning neural network models have demonstrated superior performance compared to traditional morphological methods [8]. The application of AI in entomology has extended to critical areas such as climate change research, pest management, and disease vector control. AI-driven tools have improved habitat modelling, allowing for more accurate predictions of insect distribution and abundance in response to environmental changes [8]. In agriculture, smart traps and monitoring systems powered by AI can detect and identify pest species in real-time, enabling targeted control measures [8]. Similarly, AI-based predictive models have enhanced disease vector control by identifying areas at risk of disease transmission [8]. Despite these advancements, future research in AI for entomology should focus on developing more sophisticated tools to address complex ecological questions. Integration of AI methods into entomological research needs to be further explored to unlock its full potential [8]. Additionally, as with other AI applications, addressing challenges such as data quality, ethical concerns, and regulatory frameworks will be crucial for responsible implementation [15]. The convergence of AI with other emerging technologies, such as nanotechnology, may also open new avenues for entomological research, particularly in areas like environmental monitoring and materials discovery [15].

Conclusion

The field of entomology is undergoing a significant transformation with the integration of artificial intelligence (AI) and advanced technologies. This review has highlighted the crucial role of entomology in understanding and preserving biodiversity, while also exploring the evolving landscape of research methodologies in this field. Traditional entomological methods, while still valuable, are being complemented and sometimes surpassed by AI-driven approaches. These new technologies offer enhanced capabilities in automated species identification, behavioural tracking, disease vector analysis, and data collection and processing. AI-powered tools have demonstrated remarkable accuracy in insect classification, real-time monitoring, and predictive modelling for pest management and disease control. However, the implementation of AI in entomology is not without challenges. Issues such as data scarcity, model interpretability, and deployment in resource-limited settings need to be addressed. The vast diversity of insect species and their morphological variations also pose significant hurdles for AI algorithms. Looking ahead, the future of AI in entomology lies in developing more sophisticated tools to address complex ecological questions. The integration of AI with other emerging technologies, such as environmental DNA analysis and nanotechnology, holds promise for advancing entomological research and conservation efforts. To fully realize the potential of AI in this field, collaborative efforts between entomologists and AI specialists will be crucial. AI presents exciting opportunities for enhancing entomological research and applications, it is essential to approach its integration thoughtfully. Balancing the benefits of new technologies with the foundational principles of entomology will be key to advancing our understanding of insects and their critical role in global ecosystems.

Author Contributions

Chude Meghraj V: Conceptualization, original draft preparation. Narayan Lal Choudhary: Writing - review and editing, validation.

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The authors declare no conflict of interest in relation to this work.

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