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eDNA and Metabarcoding: A New Frontier in Insect Biodiversity and Pest Surveillance

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Accurate monitoring of insect populations is essential for effective pest management, biodiversity conservation, and ecological studies. However, conventional survey methods are often labor-intensive, time-consuming, and dependent on taxonomic expertise, limiting their efficiency in detecting early-stage or cryptic insect populations. In this context, environmental DNA (eDNA) and metabarcoding have emerged as innovative molecular tools for insect monitoring. eDNA refers to genetic material released by organisms into their environment, while metabarcoding combines DNA barcoding with high-throughput sequencing to enable simultaneous identification of multiple species from mixed samples. This article provides an overview of the principles, workflow, and applications of eDNA metabarcoding in insect surveys. It highlights the advantages of these approaches, including high sensitivity, non-invasive sampling, and the ability to detect multiple species simultaneously, while also addressing limitations such as DNA degradation, database dependency, and technical complexity. Overall, eDNA and metabarcoding offer a powerful and scalable approach for early pest detection and biodiversity assessment, with significant potential to enhance Integrated Pest Management (IPM) and support sustainable agricultural practices.

Keywords: DNA barcoding, High-throughput sequencing, Biodiversity assessment, Pest monitoring, IPM, Molecular ecology, Early pest detection

Introduction

Insects play a vital role in both agricultural systems and natural ecosystems, functioning as pests, pollinators, decomposers, and biological control agents (Jankielsohn, 2018). Accurate monitoring of insect populations is therefore essential for effective pest management, biodiversity conservation, and ecological research. In agriculture, timely detection of pest species is a key component of Integrated Pest Management (IPM), helping to minimize crop losses and reduce excessive pesticide use. However, conventional insect survey methods, such as visual inspection, sweep netting, and trapping, are often labour-intensive, time-consuming, and highly dependent on taxonomic expertise. These limitations can result in delayed or inaccurate assessments, particularly when dealing with cryptic, rare, or early-stage insect populations.

In recent years, advances in molecular biology have introduced innovative approaches for biodiversity assessment, among which environmental DNA (eDNA) and metabarcoding have gained significant attention. Environmental DNA refers to genetic material shed by organisms into their surroundings, including soil, water, air, or plant surfaces, while metabarcoding combines DNA barcoding with high-throughput sequencing to identify multiple species from mixed samples. Together, these techniques provide a powerful, non-

invasive, and highly sensitive method for detecting insect diversity without the need for direct specimen collection (Roger *et al.*, 2022).

This article aims to provide an overview of eDNA and metabarcoding approaches in insect surveys, highlighting their principles, applications, advantages, and challenges, as well as their potential role in advancing sustainable pest monitoring systems.

What is eDNA?

Environmental DNA refers to genetic material that organisms release into their surroundings through natural processes such as shedding of cuticle, scales, hairs, faeces, saliva, or decomposing body parts. Instead of collecting and identifying whole organisms, scientist can detect their presence by extracting and analysing this DNA from environmental samples like soil, water, air, or plant surfaces.

Environmental DNA becomes important as it gives independence to researchers from capturing living insects. It is further found useful in studying cryptic, rare or low-density populations. In crop systems, eDNA can be used to detect pest insects (e.g., aphids, borers) at early stages, supporting timely management decisions and improving the efficiency of Integrated Pest Management (IPM) programs (Lunghi *et al.*, 2022).

What is Metabarcoding?

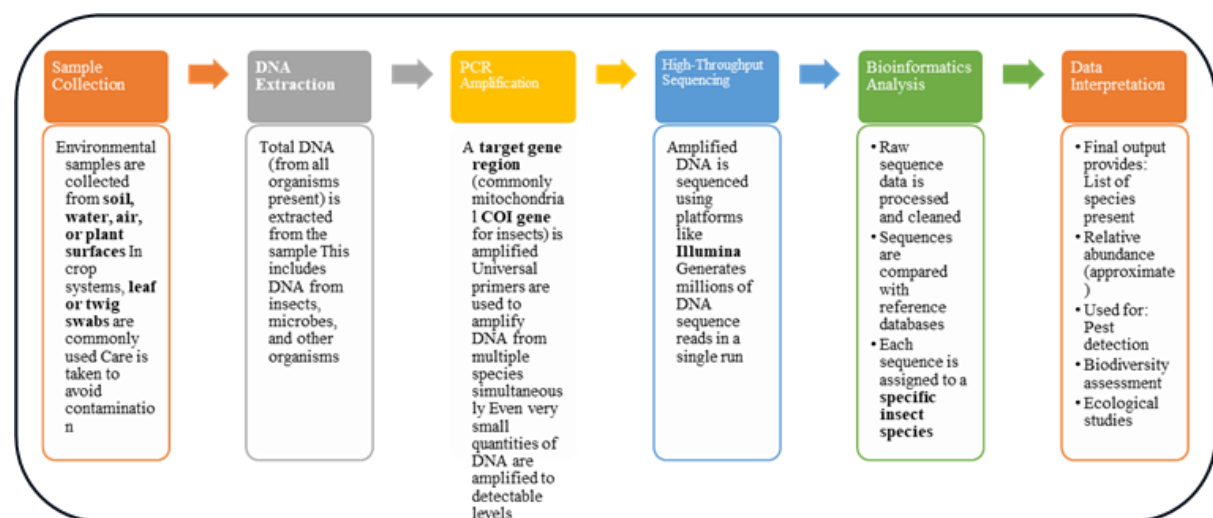
Metabarcoding is a molecular technique that allows the simultaneous identification of multiple species from a mixed environmental sample using DNA sequencing (Piper *et al.*, 2019). It combines two key concepts:

- DNA barcoding (using a standard gene, commonly the mitochondrial COI gene in insects)
- High-throughput sequencing (HTS) to analyze many DNA fragments at once.

Key Features

- Detects multiple insect species in a single sample
- Does not require individual insect collection (Identifies both pests and beneficial insects)
- Works with mixed DNA (eDNA samples)
- Highly useful for biodiversity and pest surveys

Work flow of eDNA metabarcoding



DNA Barcoding vs Metabarcoding

Aspect	DNA Barcoding	Metabarcoding
Sample type	Single organism	Mixed environmental sample (eDNA)
Output	One species at a time	Multiple species simultaneously
Application	Species identification	Community-level analysis
Throughput	Low	High (massively parallel)

Time efficiency	Slower (one-by-one analysis)	Faster (bulk processing)
Cost efficiency	Higher per sample	Lower per species (bulk analysis)
Taxonomic scope	Limited (single species)	Broad (entire community)
Data complexity	Simple	Complex (requires bioinformatics)
Requirement of specimen	Required	Not required
Sensitivity	Moderate	High (detects rare/cryptic species)
Quantification ability	Accurate for single specimen	Semi-quantitative (relative abundance)
Technical requirement	Basic molecular tools	Advanced sequencing + bioinformatics
Error sources	Misidentification, contamination	PCR bias, sequencing errors
Field applicability	Limited	High (especially with eDNA samples)

**Metabarcoding extends traditional DNA barcoding by enabling high-throughput, community-level biodiversity assessment from mixed environmental samples, making it more suitable for large-scale insect surveys.*

Advantages and Limitations

While eDNA and metabarcoding offer highly sensitive and scalable tools for insect monitoring, their effectiveness depends on careful sampling, robust databases, and appropriate data interpretation.

Advantages	Limitations
Non-invasive and non-destructive sampling (no need to capture insects)	DNA degradation due to environmental factors (UV, temperature, microbes)
High sensitivity—detects low-density and early-stage populations	Cannot reliably estimate absolute population abundance
Simultaneous detection of multiple species (community-level analysis)	PCR bias may favor some species over others
Effective for cryptic, rare, or morphologically similar species	Requires comprehensive and curated reference databases
Reduces dependence on taxonomic expertise	Risk of contamination leading to false positives
Time-efficient and suitable for large-scale surveys	Requires specialized laboratory and sequencing facilities
Applicable across diverse environments (soil, water, plant surfaces)	Interpretation of results requires advanced bioinformatics skills
Enables early pest detection and supports IPM decisions	Cannot distinguish between live and dead organisms
Can be integrated with AI and digital agriculture tools	High initial cost and technical complexity

Conclusion

Environmental DNA (eDNA) and metabarcoding represent a significant advancement in insect monitoring by offering a rapid, sensitive, and non-invasive approach to biodiversity assessment and pest detection. Unlike conventional methods that rely on direct observation or specimen collection, these molecular techniques enable the detection of insect presence at very early stages through DNA traces in the environment. Their ability to simultaneously identify multiple species from a single sample makes them particularly valuable for large-scale surveys, ecological studies, and precision pest management. Despite these advantages, challenges such as DNA degradation, dependence on reference databases, and limitations in

quantifying population abundance must be addressed for wider application. Continued improvements in sequencing technologies, database development, and analytical tools are expected to enhance their reliability and accessibility. Overall, eDNA and metabarcoding hold immense potential to complement traditional and AI-based monitoring systems, paving the way for more efficient, data-driven, and sustainable insect pest management strategies in modern agriculture.

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