Early Detection and Enhanced Surveillance of Invasive Species Using eDNA-Based Strategies

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ABSTRACT

Invasive species pose a serious ecological and economic threat to various natural and manmade ecosystems, often remaining unrecognized until their effects become severe and irreversible. Conventional monitoring techniques such as frequent netting, trapping, visual surveys, and morphological identification are time-consuming, labour-intensive and costlier approaches. They are often inefficient in identifying species at low abundance or early developmental stages. Environmental DNA (eDNA)-based techniques offer a sensitive, non-invasive, and cost-effective alternative for the early detection and improved surveillance of invasive species. This technique detects species without direct observation or capture by collecting and analysing DNA that organisms release into their environments (such as water, soil or sediment). Environmental DNA combined with advanced molecular techniques like high-throughput sequencing and quantitative PCR enables precise species identification and real-time detection in challenging environments, combined with advanced molecular techniques like high-throughput sequencing and quantitative PCR. This article highlights using an eDNA-based approach for effectively monitoring and detecting invasive species at an earlier stage.

INTRODUCTION

Invasive species are non-native organisms, including microbes, animals, plants, insects, fungi, which are intentionally or unintentionally introduced into new habitats. Upon introduction, they disrupt native biodiversity by competing with indigenous species for food, space, light and other resources (Simberloff *et al*., 2013; Pimentel *et al*., 2005). These non-native species lead to the extinction of flora and fauna by altering habitats, disrupting food webs and causing ecological imbalances. Invasive species can have serious economic impacts in addition to ecological threats by influencing infrastructure, fisheries, aquaculture, agriculture, and human health (Pimentel *et al*., 2005).

Ecological threat from invasive species

African catfish *(Clarias gariepinus)*, an invasive species, disturbs native populations through competition and predation in Vembanad Lake waters (Krishnakumar *et al*., 2011). Amazon sailfin catfish *(Pterygoplichthys spp.)* degrade riverbanks and compete with native benthic species (Hussan *et al*., 2025). Native crustaceans are displaced by the redclaw crayfish *(Cherax quadricarinatus)* (Victor *et al*., 2024). Aquatic plants, such as *Salvinia molesta* and water hyacinth *(Eichhornia crassipes),* develop dense mats that block sunlight and deplete oxygen (Diop *et al*., 2006) and *Hydrilla verticillata* which outgrows native flora (Kennedy *et al*., 2009). Zebra mussels *(Dreissena polymorpha)* from Eastern Europe have spread worldwide and are impacting the ecosystem by outcompeting native filter feeders and clogging water intake systems (Strayer *et al*, 2007). Toxins released from the microscopic species include golden algae *(Prymnesium parvum),* causing massive fish kills (Roelke *et al*., 2016).

Environmental DNA

Environmental DNA (eDNA) is genetic material that is released by organisms into their environment through gametes, skin cells, mucus, faeces, urine, or decaying tissue. This genetic material shed by the organisms can remain in water, soil, or sediments. It can be sampled and analyzed to detect species within an ecosystem without the need for physical capture or visual examination. Aquatic organisms constantly release DNA into the water, making it an invaluable tool for monitoring species and tracking biodiversity (Thomsen & Willerslev, 2015). Traditional survey methods include netting, trapping or visual identification, which are time-consuming, labour-intensive and ineffective for detecting rare, cryptic or early-stage species. In contrast, eDNA techniques are sensitive, non-invasive, economical, and enable large aquatic biodiversity monitoring with relatively limited habitat disturbance (Rees *et al*., 2014; Deiner *et al*., 2017).

Workflow

Environmental DNA methodology starts with collecting environmental samples, including water, soil or sediments. Collected samples are then filtered or preserved to capture the free-floating DNA fragments released by organisms through their skin, feces, or secretions. The captured DNA is subsequently isolated using molecular methods and purified for downstream analysis (Goldberg *et al*., 2015). The isolated DNA is then amplified using the Polymerase chain reaction (PCR), followed by library preparation and High-throughput sequencing using platforms like Illumina, Ion Torrent, etc. The obtained sequences are analysed and compared against reference databases, using advanced bioinformatics tools to accurately identify the organisms present (Thomsen & Willerslev, 2015; Deiner *et al.*, 2017). This strategy provides a highly sensitive and efficient method for biodiversity assessment, invasive species detection and ecological monitoring.

Workflow

⬇

Environmental sample collection

⬇

DNA Extraction

⬇

PCR Amplification

⬇

Library Preparation

⬇

High-throughput sequencing

⬇

Bioinformatics analysis

Application of eDNA in Invasive Species Surveillance

Environmental DNA (eDNA) has emerged as a useful tool for invasive species surveillance across various aquatic ecosystems. eDNA makes it possible to identify non-native species in freshwater systems, such as rivers, lakes, ponds, and hatcheries, before they become visibly established, which helps to guide timely management (Jerde *et al.*, 2011). Additionally, it is being used to monitor ballast water discharge in ports, where invasive species are introduced through international shipping routes. Identifying invasive or non-native species in ballast water helps prevent their entry and establishment in local ecosystems (Sangeetha *et al.*, 2025; Zaiko *et al.*, 2018). By identifying harmful species early, eDNA-based surveillance aids biosecurity measures in wetlands and coastal areas, which are rich in biodiversity but susceptible to invasion. This approach helps identify invasive or disease-causing organisms early in the aquaculture site and lowers the outbreaks and financial losses (Abbott *et al.*, 2021). Overall, eDNA enhances the accuracy and surveillance efficiency across a wide range of aquatic environments.

Case studies

The following non-native species were identified through the eDNA approach from various ecosystems. The Round goby *(Neogobius melanostomus)* (Clark *et al.*, 2022) and the golden mussel *(Limnoperna fortunei)* were found early in the Great Lakes (Guo *et al.*, 2024) and in farm ponds, respectively (Ito *et al.*, 2021). A freshwater diatom called *Didymosphenia geminata*, which affects eastern North American streams and they were detected from freshwater systems at low densities (Keller *et al.*, 2017). The invasive Asian carps *(Hypophthalmichthys spp.)* were observed and quantified from the river systems (Klymus *et al.*, 2015), while zebra mussels *(Dreissena polymorpha)* were successfully identified in American lakes (Miller *et al et al.*, 2024). Chinese mitten crabs *(Eriocheir sinensis)* have been identified in European water bodies (Chevrinais *et al.*, 2023), whereas American bullfrogs *(Lithobates catesbeianus)* were found in wetland environments in Japan (Everts *et al.*, 2022).

Challenges

eDNA-based detection has several drawbacks and difficulties despite its potential. One major concern is the risk of false positives, which can be caused by external contamination or residual DNA from non-target organisms carried by water currents or human activity (Goldberg *et al.*, 2016). Furthermore, comparing data and ensuring reproducibility is challenging due to a lack of standardized laboratory techniques (Darling & Mahon, 2011). In some cases, validation of results often requires traditional methods, adding cost and time. These challenges underscore the need for careful sample handling, robust protocols, and integrated approaches for reliable invasive species monitoring (Goldberg *et al*., 2016).

CONCLUSION

Future developments in invasive species surveillance are expected to be revolutionized by the incorporation of environmental DNA (eDNA), artificial intelligence (AI), and real-time biosensors, which will allow for faster automated detection and response systems (Cordier *et al*., 2019). In order to monitor ecosystems more effectively without depending on centralized labs, field personnel may be encouraged by developing portable eDNA kits for on-site analysis (Yamanaka & Minamoto, 2016). In conclusion, eDNA provides a proactive, sensitive, and efficient method of identifying aquatic invasive species before they become established and begin to cause harm. Harnessing its full potential in addressing the risks posed by invasive species requires widespread support and investment in training, standardisation, and integration with existing monitoring systems. eDNA must be integrated into national surveillance programs as an essential strategy for early detection and rapid mitigation of biological invasions in order to provide the maximum impact.

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