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Environmental DNA, Water Quality, and Plankton Community Dynamics in the Niger Delta: A Critical Review of Molecular Approaches for Biodiversity Monitoring and Ecosystem Management

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ABSTRACT

The Niger Delta is home to a variety of freshwater, estuarine and coastal ecosystems that provide fisheries, biodiversity and other critical ecosystem services. But the area has been significantly changed by increasing anthropogenic impacts such as petroleum activities, industrial effluents, agricultural pollutants, urbanization and climate change. These disturbances have been associated with a loss of biodiversity and altered plankton community structure which affects the functioning of the ecosystem and its monitoring. This review critically assesses the interrelationships between water quality, biodiversity, plankton dynamics and environmental DNA (eDNA) based monitoring in the Niger Delta. Specific attention is paid to the impacts of physicochemical conditions on plankton communities, and the utility of molecular tools for the assessment of plankton biodiversity. There is evidence that environmental degradation causes a shift in community composition and degradation of the eDNA detection.Environmental degradation has been shown to have complex ecological and physicochemical effects on aquatic community composition and on eDNA detection. Although the use of eDNA in the region holds great promise, there are certain limitations in their application such as limited validation studies, limited reference databases, and methodological inconsistencies. The combination of traditional ecological surveys and eDNA can provide a comprehensive approach to the conservation of biodiversity and monitoring pollution and the management of aquatic ecosystems in the Niger Delta in a sustainable way.

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INTRODUCTION

Global Biodiversity Decline and the Need for Advanced Aquatic Monitoring

Pollution, modification of aquatic habitats, biological invasion, overexploitation, and environmental change caused by climate change are causing significant ecological changes in aquatic ecosystems, causing loss of biodiversity in freshwater, estuarine and marine environments (Wilson, 2024; Ogwu et al., 2025). The changes are especially notable since aquatic biodiversity provides ecosystem services such as nutrient cycling, primary production, carbon sequestration, fisheries productivity, and food web stability (Borics et al., 2021; Henson et al., 2021).

Biodiversity monitoring has been found to have some important gaps as anthropogenic pressures increase in complexity. The traditional methods of net sampling, microscopy, morphological identification, and culture-dependent analyzes are still fundamental in aquatic ecology, but they are not always suitable for detecting rapid changes in the aquatic ecosystem, are unable to detect cryptic species, and underestimate biodiversity (Deiner et al., 2021; Miya, 2022; Du et al., 2024). These restrictions are exacerbated in ecosystems with high species diversity and environmental heterogeneity and temporal variability, which makes surveying difficult (Valdivia Carrillo et al., 2021; Zhou et al., 2022).

The molecular ecology has revolutionized in recent years, and new techniques have emerged that surmount many of these limitations. Environmental DNA (eDNA) enables biodiversity assessment based on DNA that enters environmental matrices without the need for direct capture of organisms (Pawlowski et al., 2020; Power et al., 2023; Akpomughe et al., 2023). The growing use of such an approach is a sign of a broader movement towards ecosystem scale monitoring frameworks that incorporate biodiversity patterns with environmental processes and ecosystem functioning (Blackman et al., 2024; Liang et al., 2025). However, the ecological interpretation of environmental DNA is still largely dependent on the environmental context and it is important to consider how the quality of the environment and the dynamics of the ecosystems affect the molecular signals.

Understanding the Aquatic Ecosystems of Africa and Emerging Challenges in Monitoring Them

Even though the field of environmental DNA (eDNA) has grown significantly around the world, its use is not equally distributed geographically. Most methodological developments and validation studies are from Europe, North America, East Asia and Australia, and aquatic ecosystems are underrepresented in Africa (von der Heyden, 2023). This imbalance is concerning because many of the African inland and coastal systems are suffering from higher levels of human activities and have an outstanding biodiversity (Ude et al., 2022).

There are more reasons behind the fact that molecular monitoring has not been widely used in Africa. Limited long-term funding, inconsistent funding, inadequate laboratory infrastructure, incomplete barcode reference libraries and limited capacity for bioinformatics continue to hinder implementation and ecological interpretation (von der Heyden, 2023). However, biodiversity assessments are often conducted using more traditional methods which may not adequately reflect ecological responses to environmental stressors, especially under rapidly changing ecosystems (Ude et al., 2022).

Another issue is the scarcity of research on transferability of evidence from temperate environments. Local environmental conditions significantly affect the production, transport and degradation of eDNA, however, few studies have been conducted in tropical aquatic environments (Joseph et al., 2022; von der Heyden, 2023). Essential uncertainties therefore remain, as to the performance of molecular monitoring tools in African environments.

Ecological and Socio Economic Significance of the Niger Delta Region

The Niger Delta region is important for the following reasons: The Niger Delta region has the following ecological and socio-economic significance:

The Niger Delta is an African coastal system with the largest interconnected rivers, estuaries, tidal creeks, wetlands, mangrove forests, and nearshore marine habitats (Anyanwu et al., 2023). The hydrological interactions between these environments create high ecological connectivity and gradients in salinity, nutrient availability, sediment transport and biological productivity, which support biodiversity and rich aquatic communities (Feng and Chen, 2023; Mariani et al., 2022; Harvey et al., 2023).

The ecological significance of the area is not just in terms of species richness. The deltaic ecosystems provide valuable nursery, nutrient transformation and fisheries production areas, connecting terrestrial, freshwater and marine ecological processes (Prakash and Ganie, 2024; Aragón Flores et al., 2026). These functions underpin large fisheries industries, transportation, agriculture and other livelihood activities supporting millions of people in southern Nigeria (Ude et al. 2022).

In the same way the Niger delta is a very special place in the field of global environmental studies, as its ecological value is linked to heavy industrialization. While providing significant economic returns, petroleum exploitation has also led to chronic environmental problems that have remained to affect the condition of the ecosystems and the trajectories of biodiversity across the region (Ogolo et al., 2022). The Niger Delta is an area of exceptional ecological value and chronic environmental stress, making it a valuable natural laboratory for assessing the potential of biodiversity monitoring systems to assist in ecosystem management in highly-disturbed tropical coastal environments.

Environmental Pressures on Niger Delta Aquatic Ecosystem

Niger Delta is one of the most environmentally degraded coastal areas of Africa, yet it is ecologically important for the region. The activities of petroleum exploration, industrial discharge, urbanization, agricultural run-off, dredging, and mangrove degradation have all contributed to deterioration in water quality and ecosystem functioning in freshwater, estuarine, and coastal habitats (Ogolo et al., 2022; Anyanwu et al., 2023; Fenibo et al., 2024).

Contamination from oil is the biggest environmental issue. Hydrocarbons, heavy metals and related pollutants have been reported to be present at high levels in water, sediments and biota in the region, suggesting chronic exposure to multiple stressors (Raimi et al., 2022; Anyanwu et al., 2023). Beyond its toxicity, the ecological effects of hydrocarbon contamination involve changes to microbial processes and community composition, ecosystem resilience, and the disruption of trophic interactions (Okafor et al., 2022; Fenibo et al., 2024).

But blaming the degradation of the environment on petroleum activities alone is a simplistic approach to the environmental changes in the Niger Delta. The increasing mixing of nutrient enrichment, untreated wastewater, agricultural chemicals, plastic pollution, and hydrological modification with petroleum derived stressors is causing cumulative impacts that are hard to detect with traditional monitoring methods (Sharma et al., 2024; Singh, 2024). Thus, the degradation of the ecosystems in the region can be considered as a result of several interacting factors instead of a single dominant factor.

Water Quality, Plankton Dynamics and Ecological Indicators in Aquatic Ecosystems

Ponds, lakes, and streams are affected by the introduction of these species. These species impact ponds, lakes and streams. Aquatic ecosystems strongly depend on water quality, as the processes of community assembly, ecological interactions, and species distribution are influenced by physicochemical conditions (Nguyen and Huynh, 2023; Chang et al., 2024). If the dissolved oxygen (DO), nutrient levels, salinity, turbidity, temperature and contaminant load change, ecological responses can occur well before the onset of ecosystem degradation becomes visible (Iwegbue et al., 2023; Fubara et al., 2022).

Plankton communities are among the most sensitive indicators of environmental changes among the biological ones. The phytoplankton control primary production, the zooplankton mediate energy transfer to higher trophic levels, and the microbial plankton mediate nutrient recycling and biogeochemical transformations important for ecosystem functioning (Borics et al., 2021; Choi et al., 2023; Kunal and Ganie, 2024). Plankton are sensitive to environmental change because they are rapidly replaced as well as exposed to water column conditions, and therefore can serve as a sensitive measure of ecosystem condition (Chandel et al., 2024).

With the accumulation of evidence from contaminated aquatic ecosystems, nutrient enrichment, exposure to contaminants, and hydrological alteration have been shown to restructure plankton communities, decrease ecological stability, and change ecosystem functioning (Amorim and do Nascimento Moura, 2021; Geng et al., 2022; Li et al., 2025). However, plankton response is still not well incorporated into the monitoring programs for biodiversity in most of the Niger Delta, which hampers their use in ecosystem assessment and management.

Environmental DNA as a Transformative Monitoring Tool

The use of environmental DNA as a transformative monitoring tool has been discussed.There is a discussion of environmental DNA as a transformative monitoring tool.

The detection of aquatic biodiversity using eDNA has emerged as one of the most important advances in aquatic biodiversity monitoring in recent years, as it allows species detection from the presence of DNA in the water, sediments, and other environmental matrices (Pawlowski et al., 2020; Mauvisseau et al., 2022). Environmental DNA can identify organisms that are rare, cryptic, elusive, and/or at low abundance, unlike traditional surveys which rely on capturing organisms or sighting them in the water (Bessey et al., 2020; Chen et al., 2024).

These applications are not limited to species inventories, but also include community level biodiversity assessment, invasive species detection, microbial ecology, restoration monitoring, and ecosystem health assessment (Miya, 2022; Hou et al., 2025; Liang et al., 2025). However, eDNA should not be considered as a panacea for the assessment of biodiversity. The success of detection can be affected by DNA production, transport and degradation, sampling design, laboratory practices, and the extent of reference database coverage (Joseph et al., 2022; Kumar et al., 2022; McKnight et al., 2024).

In aquatic tropical environments, the effects of high temperatures, microbial activity, fluctuating salinity and various pollutant mixtures can lead to changes in DNA persistence and the efficiency of detection (Joseph et al., 2022; von der Heyden, 2023). It is therefore crucial to understand these interactions if environmental DNA is to be reliably used in Niger Delta ecosystems.

Problem Statement and Rationale for the Review

The problem is to describe the nature of the problem and to identify the objectives of the review.

While significant information relevant to water quality degradation, water quality pollution, biodiversity loss, and plankton ecology has been obtained from the study of the Niger Delta, these themes have mostly developed as islands of research investigation without significant conceptual integration (Anyanwu et al., 2023; Fenibo et al., 2024; Ohimain et al., 2024). Concurrently, the use of eDNA has earned greater significance in global biodiversity assessment, and there is still limited usage of this technology in Nigerian aquatic ecosystems (Nneji et al., 2025; von der Heyden, 2023).

This disconnection is a large knowledge gap. Water quality impacts on biological communities as well as on the signals of these communities derived from environmental DNA, and plankton communities are highly sensitive to changes in the environment and are an important nexus between ecosystem functioning and biodiversity dynamics. However, there are relatively few studies that have explored the interaction between these processes in the extremely disturbed waters of the Niger Delta.

This review, therefore, consolidates the existing information on the water quality dynamics, the ecology of plankton communities and the use of environmental DNA (eDNA) in biodiversity assessment in the Niger Delta. Mechanisms connecting environmental stressors to biodiversity change are emphasized, as are the effects of environmental conditions on molecular detectability, and the potential of integrated monitoring frameworks to facilitate ecosystem management, conservation planning, and environmental policy development in tropical coastal ecosystems

Water Quality

Water Quality, Biodiversity and Plankton Dynamics in the Niger Delta

The Niger Delta is a region plagued by environmental issues.The Niger Delta is an area of ecological problems.

The Niger Delta is an ecologically dynamic region, characterized as a mosaic of marine and marine-influenced environments including rivers, distributaries, estuaries, tidal creeks, mangrove forests, freshwater swamps, and coastal waters, which is one of the most biologically productive in West Africa (Anyanwu et al., 2023; Ude et al., 2022). The Niger Delta is highly dynamic as in most river deltas, the ecological gradients are not that predictable, but rather are strongly variable in space, especially due to seasonal river discharge, tidal exchange, sediment transport, salinity intrusion, and anthropogenic disturbances and modifications over relatively short distances (Feng and Chen, 2023; Harvey et al., 2023).

This hydrological complexity is not only important for habitat diversity, it also has ecological additional value. ETZs are biogeochemical hotspots, where the mixing of freshwater and marine processes affects nutrient cycling, decomposition of organic matter, and biological productivity (Mariani et al., 2022; Prakash and Ganie, 2024). Such habitats tend to have high species diversity due to the presence of freshwater-brackish-sea adapted species, all together. Yet, this ecological complexity makes it more sensitive to environmental disturbances as changes in a single habitat can ripple through the system, affecting other interconnected habitats and trophic levels (Aragón Flores et al., 2026).

The Niger Delta has traditionally been thought of as a rich ecosystem in terms of biodiversity but the extent of this biodiversity is not evenly distributed among taxonomic groups. Much research has been conducted on fish assemblages and economically important species while diversity of microorganisms, planktonic communities, protists and many aquatic invertebrates are comparatively under studied (Ude et al., 2022; Nneji et al., 2025). This imbalance makes it difficult to assess the extent of biodiversity change within the region as ecosystem level responses can be a product of bottom-up events, which are less well documented.

A recurring limitation within the literature is the tendency to assess ecosystem condition using isolated biological indicators without considering broader ecological interactions. Such approaches provide valuable local information but frequently fail to capture the interconnected processes linking water quality, microbial dynamics, plankton succession, fish production, and ecosystem resilience. Consequently, a more integrated perspective is required to understand how environmental stressors influence ecological functioning across multiple biological scales.

Current State of Water Quality in the Niger Delta

The current state of the water quality in the Niger Delta is discussed in this section.

The quality of water samples collected from various locations in the Niger Delta has shown significant spatial and temporal variations, as a result of the combined effect of natural hydrological processes and anthropogenic disturbance (Anyanwu et al., 2023; Iwegbue et al., 2023). Many studies have reported localised degradation linked to industrial, urban development, petroleum production and agricultural run-off, while a number of aquatic systems still have physicochemical features which are all favourable for ecological functioning (Fenibo et al., 2024; Raimi et al., 2022).

The region has the most variable physical parameters recorded, such as temperature and turbidity. Suspended particulate levels can vary significantly from one season to another due to variations in rainfall, river discharge and sediment transport (Fubara et al., 2022; Anyanwu et al., 2023). Higher turbidity doesn't just impact water clarity; it can also impact water quality by changing light penetration, affecting primary production, changing habitat quality, and influencing movement of pollutants throughout the aquatic food web (Chang et al., 2024).

The chemical indicators tell a similar story. In zones where pollution from organic matter and petroleum hydrocarbons occurs, dissolved oxygen levels often become low, indicating enhanced biological oxygen demand and ecosystem metabolism changes (Iwegbue et al., 2023; Fenibo et al., 2024). Enrichment due to domestic wastewater and agriculture inputs have also been documented in various aquatic systems, but the ecological effects are quite different at different locations depending upon the hydrological connectivity and dilution capacity (Sharma et al., 2024; Singh, 2024).

Heavy metals and hydrocarbons from petroleum products have been of special interest. Contaminants that can bioaccumulate in biological tissues and interfere with ecological processes have been studied both in aquatic and sedimentary environments (Ogolo et al. 2022; Raimi et al. 2022). But contamination patterns do not usually have a consistent distribution throughout the region. Concentrations above ecological thresholds were observed in some investigations while comparatively low concentrations were reported in others, despite their similar exposure histories (Anyanwu et al., 2023; Iwegbue et al., 2023). These discrepancies are partially due to methodological differences between studies, but also reflect the likelihood of significant differences in the process of transport, dilution and ecosystem recovery effects of contaminants.

A key finding from recent studies is that traditional water quality indicators are not necessarily directly related to biological conditions. Apparent acceptable physicochemical characteristics can lead to changes in community composition, an impairment in functional diversity, or changes in microbial assemblages that are not detected by routine monitoring (Tee et al., 2021; Li et al., 2025). This difference demonstrates the basic problem of using only physicochemical parameters to assess the health of an ecosystem.

Major Drivers of Water Quality Deterioration in the Niger Delta

The major drivers of water quality deterioration are outlined below.The following are the major drivers of water quality deterioration.

Petroleum exploration is the most prevalent environmental stressor that affects the water quality trajectory in most parts of the Niger Delta (Ogolo et al., 2022; Fenibo et al., 2024). Collectively, oil spills, pipeline failures, operational discharges and artisanal refining activities all contribute to the introduction of hydrocarbons to aquatic environments and their impacts on water chemistry, sediment quality and biological communities (Raimi et al., 2022; Okafor et al., 2022). The effect of these inputs is not limited to the point of pollution; residual contamination can occur and if present, can last long after the point of pollution has been cleaned up. However, the blame for the degradation of the ecosystem is assigned exclusively to petroleum activities in the Niger Delta which is an oversimplification of the environmental realities of the Niger Delta. Given the rapid urbanisation, the amount of untreated domestic wastewater has grown, and the industrialization has led to a greater influx of chemical contaminants into receiving water bodies (Singh, 2024; Sharma et al., 2024). Intensification of agriculture also adds nutrients, pesticides, and sediments that are able to affect ecological processes and cause eutrophication.

Another driver of environmental change is gas flaring, which often is overlooked. The emissions from the atmosphere due to flaring may affect precipitation chemistry, affect acidification processes and lead to the presence of contaminants in the atmosphere which in turn may be deposited in aquatic systems (Ogolo et al., 2022). The ecological impacts of gas flaring can be direct but there is limited knowledge of the effects on aquatic life, and there is a growing recognition that the cumulative effects may be more significant than previously reported.

Rising concern is also being raised about plastic pollution. The microplastic particles can bind with chemical pollutants, change eating habits, and also impact the feeding behavior of aquatic organisms at various trophic levels (Sharma et al., 2024). However, while the risks of plastic pollution have been acknowledged worldwide, few studies have considered the interactions between plastic pollution and other stressors in the Niger Delta ecosystems. This is an important empirical deficit, as it is expected that under environmental conditions, several stressors will interact with each other.

Ecological Consequences of Water Quality Impairment for Biodiversity and Ecosystem Functioning

In the event of a spill, the ecological consequences for biodiversity and ecosystem functioning will be assessed.

The ecological impacts of impaired water quality are typically not manifested in ecosystem loss, but rather as shifts in the diversity, community structure and ecosystem function (Li et al., 2025; Chang et al., 2024). In many aquatic systems, the first response to stress is a change in species composition with an abundance increase in taxa that tolerate the stress and a decrease of sensitive taxa. While there may not be a large change in species richness, these changes can significantly affect ecological processes.

The pollution related ecological changes are not limited to a single trophic level, but rather have impacts at several levels, as evidenced in the Niger Delta (Anyanwu et al., 2023; Fenibo et al., 2024). Differences in microbial communities can cause changes in nutrient cycling, differences in phytoplankton species can cause changes in primary productivity and differences in zooplankton species can cause changes in energy transfer to higher trophic levels. These cascading effects finally affect fish populations and their productivity and sustainability in fisheries.

Noticeably, biodiversity loss shouldn't be treated as an exclusively taxonomic event. To assess ecosystem resilience, functional diversity can be a better indicator of the diversity of ecological roles played within the biological communities (Borics et al., 2021; Choi et al., 2023). The loss of important functional groups can lower ecosystem stability despite a relatively constant diversity of species. Unfortunately, functional responses to environmental stress are less documented in most of the Niger Delta region and hence understanding of the consequences at ecosystem level is limited.

Many of the published studies are weak due to the lack of long-term studies. Although useful snapshots of environmental conditions, these investigations are sometimes unable to reveal long-term ecological trends or to differentiate short-term fluctuations from long-term ecosystem change. In order to determine whether the observed patterns in biodiversity are temporary responses or the result of an ecologic change, monitoring along a continuum is still necessary.

Plankton Communities as Indicators of Environmental Change

Plankton are valuable indicators of aquatic ecosystem health as they are central to aquatic food webs and sensitive to changes in environment conditions (Amorim and do Nascimento Moura, 2021; Chandel et al., 2024). Their ecological importance is not only as bio-indicators, as they contribute to regulation of primary production, nutrient transformations and transformation of organic matter, as well as transfer of energy in aquatic ecosystems (Borics et al, 2021).

Nutrient enrichment, salinity change, exposure to pollutants, and hydrological changes are common factors that can cause changes in phytoplankton communities that are measurable (Geng et al., 2022; Choi et al., 2023). Environmental stress has been associated with replacement of diverse phytoplankton communities by opportunistic taxa, which has been interpreted as a sign of reduced ecological stability, in several studies (Amorim and do Nascimento Moura, 2021; Fai et al., 2023). But responses are not always consistent across communities, as the hydrology found in different areas can shape the recovery potential of communities and their trajectories.

Zooplankton assemblages complement the ecological information because they are integrating environmental conditions through various trophic pathways (Chandel et al., 2024). Variations in zooplankton diversity can be interpreted as both bottom-up (due to changes in the phytoplankton structure) and top down (due to predation and habitat changes) effects. Thus, broader ecosystem processes need to be taken into account when interpreting the responses of zooplankton to pollution exposure.

Although microbial plankton are an integral part of ecosystem functioning, its contribution and understanding of microbial plankton biodiversity in Niger Delta is considered inept.Microbial plankton might be the most ignored part of the Niger Delta biodiversity but it plays a fundamental role in the functioning of the ecosystem (Tee et al., 2021). Microbial communities are found to change their composition in response to environmental changes long before the changes occur in the higher trophic levels in other aquatic ecosystems (Kunal and Ganie, 2024; Hou et al., 2025). This is a sign that microbial diversity can provide significant potential as an early warning of ecological degradation.

Although plankton is becoming a recognized ecological indicator, there are still many gaps in knowledge about the long-term dynamics of plankton in the Niger Delta. Many existing studies are located in limited areas, are only done during a specific season, or only deal with certain taxonomic groups. Therefore, there is a lack of comprehensive knowledge about plankton succession, resilience and response to combined stressors. To overcome these limitations, integrated monitoring frameworks that simultaneously monitor water quality conditions, community structure, and molecular biodiversity signals in a variety of aquatic environments will be needed.

Environmental DNA AND Molecular Approaches for Aquatic Biodiversity Assessment

Sources, Production and Persistence of Environmental DNA

Environmental DNA (eDNA) is genetic material shed, excreted, produced in mucus, decomposing and being shed from tissues during reproduction, along with other biological processes, and is detectable in the environment without direct capture or observation of the species (Pawlowski et al., 2020; Power et al., 2023). The methodology has revolutionized aquatic biodiversity research as the molecular signature of organisms at different trophic levels and in different habitats may all be present in one single environmental sample (Deiner et al., 2021; Blackman et al., 2024).

The ecological interpretation of environmental DNA signals is far more complicated than the mere detection of a species, however. The presence of environmental DNA is not only the result of the presence of viable particles, but also a result of biological abundance, rates of DNA production, transport and degradation processes (Mauvisseau et al., 2022; Kumar et al., 2022). This means that the probability of detection differs among species and environmental conditions and that there is a need to consider ecological context when interpreting molecular results.

This is especially important in tropical aquatic ecosystems where high temperatures, high levels of microbial activity and variable hydrological conditions could cause increased degradation of DNA compared to those of temperate ecosystems from which many methodological frameworks were developed (Joseph et al., 2022; von der Heyden, 2023). Although the use of environmental DNA is increasing worldwide, few studies to date have tried to validate environmental DNA methods in tropical African systems, and there is uncertainty about the performance of these methods under Niger Delta conditions.

Environmental Drivers of eDNA Detection

DNA persistence and species detectability are both highly dependent on environmental conditions. Among those known factors, temperature is generally considered to be one of the most important, as temperature will affect the longevity of DNA in aquatic environments, due to increased enzymatic activity and microbial degradation at higher temperatures (Kumar et al., 2022; McKnight et al., 2024). Similar effects have been reported with ultraviolet radiation (UV) which can damage DNA molecules and decrease the detection efficiencies (Joseph et al., 2022).

In addition, salinity, pH, turbidity and suspended sediments can also impact the dynamics of eDNA, though effects have been reported across different ecosystems and taxa (Mauvisseau et al., 2022; Kumar et al., 2022). Recent studies have suggested that suspended particles can also have protective effects against DNA degradation via adsorption, while other studies have noted that suspended particles can lead to decreased detection efficiency due to filters issues and/or PCR inhibition (Joseph et al., 2022; McKnight et al., 2024). The conflicting results imply that environmental DNA behaviour is context dependent, and not necessarily subject to universal rules of ecology.

The Niger Delta is a region with high salinity, sediment, nutrient and hydrocarbon gradient variations, and therefore, a primary research need remains to understand these environmental controls. To date, there has been a limited number of studies evaluating the effects of local water quality on the persistence and detection of environmental DNA in freshwater, estuarine and coastal water.

Sampling and Analytical Approaches

The majority of environmental DNA aquatic studies are based on water sampling as it is considered a non invasive, and logistically viable, means of assessing biodiversity (Deiner et al., 2021; Miya, 2022). Sediment origin DNA has also been discussed due to the fact that sediments may preserve DNA for much longer periods, thus that may be a source for historical and contemporary information about biodiversity patterns (Mauvisseau et al., 2022).

Sampling, filtration, preservation, DNA extraction, and laboratory processing can make significant methodological choices that impact the estimates of biodiversity (McKnight et al., 2024). Thus, what is observed as differences between studies may be due to methodologic variations rather than actual ecological differences. This is one of the most recurrent problems in eco-DNA studies and is still hampering inter-regional and inter-monitoring programme comparisons.

The lack of common protocols is a significant issue for tropical systems which have environmental conditions that vary considerably from those present in most of the areas where protocols have been developed. Consequently, temperate methods may not always yield the best results in the Niger Delta.

Technologies for Monitoring Biodiversity at Molecular Level

There are several molecular techniques used for assessment of aquatic biodiversity. In general, the use of conventional PCR is useful for the presence confirmation of species but is not very useful for abundance determination or for assessing complex communities (Pawlowski et al., 2020). Useful for monitoring economically important, endangered, or invasive taxa, quantitative PCR is more sensitive, providing detection of targeted species (Chen et al., 2024).

Digital PCR is also even more precise because it allows for absolute quantification of target DNA molecules, but is more expensive and is not widely used at the present time (McKnight et al., 2024). Unlike DNA metabarcoding, which enables the identification of several taxa from the same environmental sample, has emerged as the preferred method for assessing biodiversity at the community level (Deiner et al., 2021; Du et al., 2024).

The following genes are used as markers: 16S rRNA for bacteria, 18S rRNA for eukaryotic microorganisms, COI for animals, ITS for fungi, and rbcL for photosynthetic taxa (Pawlowski et al., 2020; Du et al., 2024). Not all biodiversity assessments are made with a single barcode region and the choice of marker affects the taxonomic level that is resolved and the ecological interpretation that can be drawn from the barcode.

The next step in shotgun metagenomics methodology is that it does not suffer from the biases of PCR amplification, and can measure taxonomic and functional diversity at the same time (Hou et al., 2025). The environmental RNA approach could offer further ecological information because it focuses on metabolically active organisms, but there are significant methodological challenges to overcome (Liang et al., 2025).

These technologies come with varying degrees of complexity and cost, but there is a growing consensus that methodologic integration may generate more reliable ecological information as compared to depending on any one molecular technology. The real challenge is not just to choose the best technique in all circumstances, but to find the right mix of tools to meet monitoring goals.

Opportunities and Remaining Limitations

Compared to traditional biodiversity surveys, environmental DNA has several advantages: it is more sensitive, requires fewer specimens, can reveal cryptic species and can survey large geographic areas with fewer samples. (Bessey et al., 2020; Miya, 2022). These strengths are appealing in areas like Niger Delta where access to the environment may be challenging and there is limited knowledge of the diversity.

However, the use of eDNA cannot replace traditional ecological monitoring. Species detection does not always give abundance or demographic structure information, reproductive success, or ecology interaction information (Deiner et al., 2021; McKnight et al., 2024). Moreover, the incomplete nature of reference databases remains a limitation for taxonomic assignment, especially for those in Africa, of many fishes, plankton taxa and microorganisms (von der Heyden, 2023; Nneji et al., 2025).

The least understood knowledge gap is the lack of integration of molecular and ecological datasets. The literature on environmental DNA is dominated by the issue of species detection, while ecosystem management needs to address the link between biodiversity patterns and water quality, functioning of ecosystems, and environmental change. It is an important bridge to the implementation of molecular monitoring in the Niger Delta basin and sets the conceptual framework for the relationship between environmental DNA and dynamics of plankton and assessment of ecosystem health.

Use of Environmental DNA in Biodiversity Monitoring and Pollution Assessment

Since then, eDNA has evolved from a species detection technique into a comprehensive approach for biodiversity monitoring, environmental surveillance, and environmental management (Deiner et al., 2021; Blackman et al., 2024). Applications have been mainly concentrated on improving the detection of biological communities that are hard to monitor with traditional sampling methods, especially in ecosystems with a high biodiversity, complex hydrology, and limited access (Miya, 2022; Chen et al., 2024).

Fish monitoring of biodiversity is still the most established use of eDNA. Key studies have shown that environmental DNA metabarcoding is often more effective than surveys based on captures at detecting more taxa, especially for uncommon, cryptic, migratory and low abundance species (Bessey et al., 2020; Zhou et al., 2022). The advantages are particularly applicable to the Niger Delta region, which has a large network of creeks, seasonal flooding and a heterogeneous habitats.These benefits are particularly relevant to the Niger Delta region where the large network of creeks, seasonality and habitat heterogeneity make conventional sampling difficult. Better detection, however, does not necessarily mean better understanding of the ecology. Molecular methods generally yield less information about population size, age structure, reproductive status and species interactions and are best used in combination with ecological surveys (Deiner et al., 2021; McKnight et al., 2024).

In addition to fishes, the analysis of environmental DNA has greatly aided in the ability to assess the biodiversity of plankton and microbes. While traditional microscopic identification has limitations in taxonomic expertise, morphological variability and the challenge of identifying cryptic taxa, especially microorganisms and early developmental stages, these challenges are increasingly being addressed through molecular approaches (Du et al., 2024; Hou et al., 2025). The results of metabarcoding approaches are also much higher than previous estimates, suggesting that more complexity in aquatic ecosystems may be found than previously considered (Liang et al., 2025; Hou et al., 2025). However, the interpretation is still subject to the limitations of the database which are not complete for many taxa in Africa (von der Heyden, 2023).

Environmental DNA has also proven useful in the detection of invasive, endangered, and conservation priority species. Environmental DNA may detect species before populations reach a density where they can be detected using traditional methods because genetic material can be found at very low concentrations (Chen et al., 2024; Power et al., 2023). The sensitivity implies that viable management interventions are likely to be more effective if ecological change is detected early, which has important consequences for biodiversity conservation.

An emerging research field is the analysis of "Environmental DNA" as a tool to assess the environmental response to pollution. Research in polluted water bodies continues to show that changes in microbial and planktonic community can be used to indicate hydrocarbon pollution, nutrient enrichment, and other environmental changes, which may be sensitive indicators (Lanzen et al., 2021; Li et al., 2025).

These methods are not species specific, but consider community level responses which may be more representative of ecosystem condition. Such uses are especially applicable to the Niger Delta region, where pollution frequently takes the form of a complex of petroleum pollution, nutrient pollution, and habitat disturbance rather than a single stressor.

However, the use of environmental DNA is still relatively underdeveloped in the Niger Delta compared to Europe, North America and some parts of Asia (Nneji et al., 2025; von der Heyden, 2023). Therefore much of what is currently known is inferred from studies in other environmental conditions. This is an important empirical question because tropical ecosystems could vary significantly in the dynamics of DNA production, transport, degradation, and detection. However, it is still important to develop region specific evidence prior to the integration of environmental DNA into regular programmes of biodiversity monitoring and environmental assessment across the Niger Delta.

The overall importance of environmental DNA is not just in being able to identify more species, but to have a scalable framework for relating biodiversity assessment and management of the ecosystem. Its greatest potential for the Niger Delta may thus lie in its use in conjunction with water quality monitoring and plankton ecology, where molecular signals can be attributed to a wider environmental context than just a species presence.

The Use of Environmental DNA and Plankton Community Dynamics to Link Water Quality

Although the environmental processes that govern water quality, environmental DNA and plankton communities are the same, the relationship between these three components is seldom addressed in a holistic ecological context. Water quality impacts biological communities by affecting their composition and functioning, and also affects production, persistence, transport, and detection of environmental DNA (Joseph et al., 2022; Kumar et al., 2022). Therefore, it is not possible to independently interpret molecular signals without taking into account the environmental conditions.

One of the clear examples of this interaction is the contamination of hydrocarbons. Petroleum pollutants affect microbial metabolism and change the microbial community composition, which in turn affects the functioning of trophic pathways (Lanzen et al., 2021; Fenibo et al., 2024). They affect the sources and the longevity of environmental DNA in aquatic systems. Concurrently, hydrocarbons and related organic compounds can hinder molecular analyses, impacting detection efficiency and biodiversity estimates (McKnight et al., 2024; Kumar et al., 2022). The data from eDNA collected from polluted environments will thus be influenced by both ecological change and methodological limitations.

Nutrient enrichment leads to a more complicated response. Nutrient enrichment could also lead to higher levels of phytoplankton productivity and microbial growth, which may result in enhanced biological signals in the environmental DNA datasets in the initial stages (Geng et al., 2022; Sharma et al., 2024). Rather, extended eutrophication tends to cause a decrease in community stability, changes in species composition and dominance by opportunistic species, which eventually results in simplified ecological networks (Amorim and do Nascimento Moura, 2021; Li et al., 2025). These shifts can be detected using molecular methods, but this detection is useful only in the context of water quality conditions and ecological processes.

Another significant but poorly-researched factor in the Niger Delta is salinity gradients. Estuarine zones feature complex mixing of freshwater and marine environments that result in dynamic biological gradients over short spatial gradients (Mariani et al., 2022; Harvey et al., 2023). Salinity affects the structure of the ecosystem, plankton succession, microbial processes and DNA degradation, all at once (Joseph et al., 2022; Mauvisseau et al., 2022). These interactions need to be taken into consideration to ensure that the conclusions on patterns of biodiversity are accurate if they are not.

The planktonic communities play a special role in this context as they are sensitive to environmental disturbance and influence ecosystem productivity and nutrient cycling (Borics et al., 2021; Chandel et al., 2024). Phytoplankton, zooplankton and microbial composition changes often occur before ecosystems start to degrade, making them important indicators of ecosystem health and well-being (Fai et al., 2023; Hou et al., 2025). However, traditional plankton measurements still have a number of issues in terms of taxonomy and uneven sampling. Many of these limitations can be mitigated with the use of environmental DNA, which can simultaneously encompass a wider breadth of biodiversity from multiple taxonomic groups (Du et al., 2024; Liang et al., 2025).

One of the weaknesses of the ongoing research is that various studies of water quality, plankton and biodiversity are carried out in isolation. This disjointed approach hinders the understanding of the mechanisms involved in the environmental change-ecological response connection. Consequently, management decisions are often made without considering an ecosystem assessment.

It is then unlikely that the strongest use of environmental DNA in the Niger Delta is going to be species detection. More value is obtained by the use of molecular biodiversity metrics together with physicochemical indicators and plankton based assessments and to provide a more comprehensive measure of the health of the ecosystem. This would enable biodiversity changes to be understood in the context of the environment and enhance the ability of monitoring programmes to identify ecological degradation, assess the effectiveness of the restoration and contribute to evidence based environment management.

Environmental Pressure
↓
Water Quality Change
↓
Environmental DNA Persistence and Detectability
↓
Plankton Community Response
↓
Biodiversity Change
↓
Ecosystem Functioning
↓
Management and Conservation Decisions

Figure 1: Conceptual Framework

This framework highlights a central argument of the review: environmental DNA should not be viewed merely as a molecular tool for species detection but as part of an integrated ecological monitoring system linking environmental conditions, biodiversity dynamics, and ecosystem management. Such a perspective is particularly relevant to the Niger Delta, where multiple environmental stressors operate simultaneously and where conventional monitoring approaches often fail to capture the full complexity of ecological change.

Biodiversity Monitoring and Ecosystem Management in the Niger Delta

Good ecological information to support decision making is crucial to the effectiveness of ecosystem management. Traditionally, biodiversity monitoring in the Niger Delta has been performed by physicochemical measurements, fisheries surveys, plankton studies, and periodic environmental impact assessments (EIA) (Ude et al., 2022; Anyanwu et al., 2023). These are all useful methods, but they are sometimes lacking in providing a holistic picture of ecosystem health, and may not capture early biological indicators of environmental stress (Fenibo et al., 2024; Nneji et al., 2025).

The difficulty is always that the scale of environmental pressures does not match that of monitoring programmes. Oil spills, alteration of habitat, urbanization and hydrological variability as a result of climate change affect interconnected aquatic systems, but ecological assessments are often conducted at specific locations or at short time scales (Ogolo et al., 2022; Raimi et al., 2022). These constraints limit the ability to detect cumulative impacts and long term ecological trends.

Environmental DNA can be used to improve current monitoring systems, add biodiversity coverage, and minimize the need for intensive field sampling (Deiner et al., 2021; Miya, 2022). Its real value might be to supplement, rather than supplant, traditional methods. Molecular monitoring can enhance the detection of rare species and discover cryptic species, and can offer more comprehensive assessments of biological communities that are missed in common surveys (Chen et al., 2024; Du et al., 2024). These capabilities can be combined with physicochemical and ecological data to contribute to a more holistic assessment of ecosystem health.

The implications of using env-DNA are applicable in multiple management sectors. For fisheries management, molecular tools can be used to enhance the biodiversity inventories and help identify shifts in species composition prior to the appearance in commercial catches of such shifts (Bessey et al., 2020; Zhou et al., 2022). Environmental DNA can be used to monitor and track biodiversity responses to mangrove and wetland habitat degradation and restoration (Power et al., 2023; Blackman et al., 2024). New applications are emerging for the use of molecular indicators at the community level, such as for pollution assessment, where these indicators could be more ecologically sensitive than traditional water quality measures (Lanzen et al., 2021; Li et al., 2025).

With all these benefits, however, there are significant implementation issues. However, ecological interpretation is needed in addition to species detection for effective management of the environment. Uncorrelated molecular data with ecosystem functioning, hydrological processes and environmental variables is little help in making management decisions. The future potential of environmental DNA in the Niger Delta, therefore, will largely rely on how it can be incorporated into existing monitoring programmes as opposed to as a single technology in its own right.

Biodiversity monitoring frameworks are therefore in need of a shift from indicator based assessments to ecosystem based surveillance systems, which are able to assess environmental conditions, biological communities and ecological processes at the same time. While environmental DNA offers a key piece of such a program, its effective implementation will require a common set of methods, more reference libraries and better connections between molecular ecology and environmental governance. The requirements are largely not met in the Niger Delta and are a key constraint to evidence based ecosystem management.

Challenges, Knowledge Gaps and Future Directions

Although environmental DNA science developed at a rapid pace, there are some scientific and institutional challenges that remain to be surmounted to improve the use of eDNA in the Niger Delta. The first is that there is limited region-specific research. The majority of existing knowledge of environmental DNA performance comes from temperate environments, but environmental conditions in tropical estuaries vary significantly in terms of temperature, microbial activity, hydrological fluctuations and pollutant exposure (Joseph et al., 2022; von der Heyden, 2023). Thus, transfers of assumption from temperate systems may not always be applicable to the Niger Delta.

The second restriction is the partial nature of the reference databases. However, many West African fishes, plankton taxa, microorganisms and aquatic invertebrates are poorly represented in available repositories, thus requiring validated barcode sequences for accurate taxonomic assignment (Nneji et al., 2025; von der Heyden, 2023). This limitation lowers the taxonomic level of the resolution as well as can cause an underestimation of regional biodiversity. The problem is especially pertinent when considering the plankton, where there is significant documentation of diversity on the species level, and ecological sampling in many instances relies on species level identifications.

Methodological uncertainty is another challenge. Sampling design, filtration methods, preservation techniques, marker selection, sequencing platforms, and bioinformatic pipelines (Du et al., 2024; McKnight et al., 2024) can all impact eDNA detection. Comparisons between studies are thus hindered by variation between different studies and locations and different time periods. One of the major constraints to regular implementation and long-term monitoring is the lack of standardised protocols for tropical ecosystems.

A lack of molecular and ecological data integration is perhaps the most significant scientific challenge. The current studies mainly focus on the detection of biodiversity or environmental assessment, with few studies investigating the interaction between water quality, plankton dynamics, ecosystem functioning, and molecular signals along the environmental gradient (Li et al., 2025; Liang et al., 2025). This separation can hinder interpretation of environmental DNA data sets for ecological purposes and can reduce its utility for management applications.

Moving towards the development of process based monitoring frameworks should be the focus of future research efforts, not inventories of species. Regional barcode libraries, validation of tropical sampling protocols, long-term monitoring programmes that correlate environmental DNA signals with hydrological variability, pollution gradients and plankton succession are among the priorities. New technologies, like portable sequencing platforms, automated water samplers, machine learning algorithms, and remote sensing, can provide additional benefits for biodiversity surveillance by enhancing data collection and ecological forecasting (Blackman et al., 2024; Hou et al., 2025).

Whether environmental DNA could detect biodiversity is not a central research question anymore, but rather how molecular information can be used to provide confidence indicators of ecosystem condition and ecosystem change. The answer to this question will make the difference between environmental DNA being a promising research tool and a tool in ecosystem management in the Niger Delta.

Proposed Framework for Molecular Biodiversity Monitoring in the Niger Delta

Monitoring is currently fragmented in the Niger Delta with water quality assessment, biosurvey and ecological evaluation being conducted as independent monitoring activities. Although these methods can give useful information, they only give a partial picture of ecosystem condition as environmental change, biodiversity response, and ecosystem functioning are closely coupled (Anyanwu et al., 2023; Fenibo et al., 2024). A monitoring framework that effectively combines environmental pressures, ecological responses, and molecular indicators should therefore be based on a single assessment system. The framework outlined here does not see environmental DNA as a tool of monitoring, but as a connecting thread. The first step involves identifying the key environmental stressors, such as petroleum contamination, nutrient enrichment, habitat destruction, urban expansion, and hydrologic variability (Ogolo et al., 2022; Sharma et al., 2024). These pressures further impact water quality parameters including dissolved oxygen, nutrient availability, salinity, suspended sediments, and concentrations of contaminants, which affect patterns of biodiversity and ecosystem functioning (Chang et al., 2024; Li et al., 2025). The next layer of information comes from the environmental DNA (eDNA) of water, sediments, and biofilms, which allows for the inclusion of data from several taxonomic groups at once (Deiner et al., 2021; Pawlowski et al., 2020). Molecular datasets, in combination with metabarcoding, quantitative PCR, or metagenomic methods, can provide insights into shifts in fish assemblage, plankton community, microbial diversity, and more that can be hard to identify using traditional survey techniques (Du et al., 2024; Hou et al., 2025). One of the unique aspects of the framework is the incorporation of the biodiversity data with the indicators at the ecosystem level. Molecular data is not necessarily used to detect species, but is used in conjunction with water quality and plankton based indicators to assess ecosystem condition. This practice acknowledges the importance of understanding biodiversity change in the context of the environmental processes that shape ecological responses.The last step is adaptive management. Biodiversity assessments produced by monitoring as part of an integrated approach can be used for fisheries management, restoration programmes, pollution mitigation, environmental impact assessments and conservation planning. Continual monitoring cycles also enable the evaluation and adaptation of management response to changing environmental conditions.

Environmental Pressures
Oil pollution
Industrial discharge
Urbanization
Climate variability
↓
Water Quality Assessment
Physicochemical parameters
Nutrients
Heavy metals
Hydrocarbons
↓
Environmental DNA Sampling
Water
Sediment
Biofilms
↓
Molecular Analysis
qPCR
Metabarcoding
Metagenomics
↓
Biodiversity Assessment
Fish communities
Plankton communities
Microbial diversity
Aquatic invertebrates
↓
Ecosystem Health Evaluation
↓
Adaptive Ecosystem Management

Figure 2: Proposed Integrated Monitoring Framework

The principal strength of this framework lies in its ability to connect environmental change with biological responses across multiple levels of ecological organization. By integrating molecular, physicochemical, and ecological indicators, it provides a pathway toward ecosystem based monitoring capable of supporting evidence driven management in the Niger Delta. More importantly, it shifts environmental DNA from a species detection technology to a decision support tool for biodiversity conservation and ecosystem governance

CONCLUSION

The Niger Delta is one of the most ecologically important aquatic systems in Africa but at the same time one of the most environmentally fragile ecosystems in Africa. Over the decades, petroleum extraction, growing urbanization, industrial effluents, habitat loss and climate change effects have brought changes in water quality conditions and exacerbated stress on aquatic biodiversity. While these stresses are well documented, monitoring of biodiversity in the region is still largely based on traditional methods that are often not taxonomically comprehensive and have low sensitivity to detect early ecological change.

This review is showing that eDNA has great potential to enhance the biodiversity assessment in the Niger Delta as it is a non-invasive, efficient, and high-resolution technique for detecting communities of organisms from many taxonomic groups. The use of eDNA is not only to inventory species, though. The findings presented here suggest that molecular signals are strongly associated with environmental factors such as water quality dynamics, pollution gradients and plankton community structure. Therefore, environmental DNA analyses for biodiversity patterns can not be regarded without taking into account the ecological processes that create them.

One of the key findings from this review is that future biodiversity monitoring in the Niger Delta region should not be based on the idea of replacing traditional ecological surveys with molecular methods, but rather a combination of both approaches within the framework of a comprehensive ecosystem based approach. Water quality indicators are not mutually exclusive of plankton dynamics and environmental DNA and all are good sources of ecological information. These indicators, taken together, provide a more complete picture of the condition of an ecosystem than any one monitoring program can provide alone.

Although there has been significant technological advancement, there is still considerable challenges that need to be addressed. However, the use in operation is still limited due to scarce local studies, poor integration of molecular with ecological data, and data inconsistencies. There is a need to coordinate investments in regional barcode libraries, standardise tropical protocols, build bioinformatics capacity and establish long-term monitoring programmes that connect biodiversity responses with environmental change to overcome these limitations.

In conclusion, it is necessary to consider environmental DNA in the context of an overall shift toward ecological surveillance. Future monitoring frameworks can advance water quality monitoring to a more mechanistic understanding of ecosystem health by incorporating molecular assessment of biodiversity combined with water quality monitoring and plankton ecology. This would offer greater scientific basis for the management of fisheries, habitat restoration, pollution abatement and conservation planning in the Niger Delta. It provides a general model for monitoring biodiversity in tropical coastal ecosystems that are experiencing greater pressure than can be met by traditional monitoring systems.

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