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Perspective

A stakeholder empowerment framework to advance eDNA biodiversity monitoring in Africa: Perspectives from Namibia

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https://doi.org/10.1016/j.oneear.2025.101244

SUMMARY

Environmental DNA (eDNA) technologies hold considerable promise for biodiversity and ecosystem monitoring across Africa, where rapid human population growth and associated environmental pressures pose mounting conservation and management challenges. International research collaborations can enhance the capacity for eDNA implementation and promote its integration into regional decision-making. Here, we propose a stakeholder-driven framework for applying eDNA technologies in Africa, integrating local priorities, cultural contexts, infrastructure development, and capacity-building efforts. This framework is illustrated by a project in the Kavango-Zambezi Transfrontier Conservation Area that leverages eDNA technology to support conservation management. The framework was implemented in collaboration with Namibian organizations, identifying key eDNA application needs and priorities and fostering partnerships to launch pilot projects aiming to demonstrate eDNA's potential, train local students, and enhance laboratory capacity. Our experience underscores the importance of stakeholder empowerment, emphasizing its role in unlocking the full potential of eDNA technology for conservation and sustainable environmental management in Africa.

INTRODUCTION

Africa will house the world's fastest-growing human population in the 21st century,[1] placing increasing pressure on its rich biodiversity.[2] Robust biodiversity assessments and monitoring are needed to effectively address this challenge and meet the targets set by the Kunming-Montreal Global Biodiversity Framework.[3] However, current efforts in most of Africa are hindered by a lack of scientific and technological knowledge, financial resources, and infrastructure.[4] Thus, to understand and address the threats to the region's biodiversity, it is crucial to rapidly bridge the gap between monitoring needs and the practical ability to undertake such monitoring. This will require a strong upscaling of the current capacity to survey biological taxa, which could benefit from the wealth of contemporary technologies to enhance the efficiency and cost effectiveness of monitoring programs.[5] Researchers from scientifically advanced countries may help deploy such technologies and promote their application in Africa and elsewhere, provided that the culture, needs, and priorities of local stakeholders are properly understood and respected.

Molecular biomonitoring, particularly the use of environmental DNA (eDNA) extracted from water, soil, or air, is one of the newer approaches that might be used on a large scale in Africa to speed up ecosystem assessment and regular monitoring of biodiversity.[6,7] eDNA methods are fast and powerful for producing inventories of indicator, invasive, or threatened taxa, enabling assessments of biodiversity and ecological quality.[8,9] However, there is currently a lack of experience with eDNA-based methods in Africa.[10] Therefore, implementation should be made through equitable and inclusive approaches, engaging local stakeholders in collaborative processes that assess the value of eDNA monitoring and its uptake, as recommended by work in other settings, such as Europe.[9] First, it is important to identify the key stakeholders in the region who could benefit from eDNA technology and assess their ability to inform conservation decisions and sustainable development. Then, to achieve optimal results, engagement should take place throughout the development process. This includes developing high-quality infrastructure, training professionals, establishing research collaborations, and creating a supportive policy environment that facilitates the adoption of eDNA technologies.

To address these challenges, we propose a framework for the implementation of eDNA technologies for biodiversity monitoring in Africa.

THE FRAMEWORK

The proposed framework consists of three phases: stakeholder engagement; field pilot testing, and the establishment of eDNA infrastructure in the target region.

Stakeholder engagement

To enhance the capacity of African countries in implementing eDNA monitoring as a biodiversity assessment and monitoring tool, stakeholders need to understand its potential, applications, and limitations to effectively address practical management challenges. To achieve this overall goal, this phase includes the following steps.

(1) Assess the capacity of local scientific partners in using and understanding eDNA and identify local conservationists and land managers interested in its long-term application.
(2) Engage conservation partners seeking to integrate eDNA into resource management and conservation efforts.
(3) Identify key conservation challenges where eDNA can enhance monitoring and provide valuable data for decision-making.
(4) Co-design pilot studies with partners to assess the effectiveness of eDNA in the target region.
(5) Address financial constraints and explore sustainable strategies for long-term infrastructure maintenance.

To complete these steps, we propose a mixed approach combining desk-based research, focus group discussions with stakeholders, and field visits. This will help identify partners interested in testing eDNA technology and co-design pilot studies to evaluate its effectiveness in addressing conservation and resource management questions. These partners should include representatives from government, academia, the private sector, and non-governmental organizations (NGOs), ensuring diverse perspectives and interests across marine, freshwater, and terrestrial ecosystems in the target region. The primary objective is to engage a wide range of stakeholders and potential eDNA users, including those involved in conservation, natural resource management, and environmental impact assessment.

Focus group meetings should begin with a presentation on the state of the art in eDNA, highlighting its potential applications across different contexts while also acknowledging its limitations and potential shortcomings. This should be followed by a discussion of each partner's specific portfolio of activities and interests, identifying opportunities where eDNA could help address knowledge gaps and monitoring needs. Partner feedback and suggestions should be integrated into the design of pilot eDNA studies, with discussions on their potential involvement and interest in continued collaboration during subsequent implementation phases.

Field pilot testing

Pilot studies are a fundamental part of the process of demonstrating the feasibility and benefits of eDNA-based methods, such as their non-invasiveness, cost effectiveness, and broad applicability.[11–13] In addition, pilot studies can facilitate the identification of a wide range of environmental, infrastructural, cultural, and administrative challenges. They can help to optimize sampling protocols for different objectives, regions, and environments, taking into account national, regional, and environmental differences. Many regions may lack the necessary laboratory facilities and trained personnel for eDNA analysis.[10,14] Pilot studies can identify the infrastructure needs of the region and provide initial training for local scientists and technicians. In addition, pilot studies can demonstrate the value of eDNA methods to local communities and decision-makers, thereby fostering the acceptance and cooperation that are essential for the success of biodiversity monitoring programs.[7]

Besides showcasing its potential benefits, pilot studies can be used to create awareness among stakeholders about the challenges, limitations, and potential shortcomings of current eDNA technology and the strong impacts of methodological options on the reliability of results.[15,16] Pilots can show the limitations of eDNA in providing direct evidence on behavior, population size, or interactions and that inferring population biomass from eDNA is problematic.[11–13] Also, pilots can be used to highlight detection errors (i.e., false positives and negatives) and compare them to those of other surveying methods,[7,16] as well as the potential mismatch between the temporal and spatial production and detection of eDNA due to variations in its persistence and transport.[13,16] Pilots should thus be designed to minimize and quantify potential errors such as imperfect detection, involving, for instance, biological and technical replication; multiple decontamination steps, including blanks; and the assessment of sources of variability and error at all stages of protocol implementation.[17] In this way, pilots can contribute to developing optimized and standardized protocols, which provide results that are consistent and acceptable to regulatory authorities.

Finally, as the use of genetic material is subject to legal and ethical regulations, these pilots can help identify the most appropriate frameworks in which to operate and establish best practices for eDNA research and monitoring.

Building on the discussions with stakeholders in the previous phase, the pilots should be designed to advance both fundamental research and conservation and management efforts in the target region. To achieve this, we recommended that pilot studies adopt the following structured approach.

(1) Select diverse and representative topics, study sites, and taxa in different ecological zones to test the implementation potential of eDNA methods.
(2) Develop and refine sampling and analytical protocols tailored to local conditions, considering factors such as climate, biodiversity, and available resources.
(3) Provide training for local researchers and technicians in eDNA sampling, laboratory techniques, and data analysis to build local expertise and ensure sustainable monitoring programs.
(4) Involve local communities, government agencies, and conservation organizations from the beginning to ensure the relevance and acceptance of the pilot study outcomes.
(5) Promote the integration of eDNA data with existing biodiversity databases and ensure open access to data to support broader conservation efforts.

It is recommended that these studies be carefully selected and designed to address key limitations and methodological challenges while enhancing biodiversity monitoring and strengthening its role in supporting conservation and management decision-making. In particular, such studies can be especially valuable where eDNA has the potential to complement existing legally binding monitoring frameworks, providing additional evidence to support policy development and regulatory integration. To maximize their impact, pilot studies should be conducted in close collaboration with local stakeholders, fostering a regional understanding of eDNA's capabilities and generating insights to improve conservation outcomes. Actively involving local communities in these efforts can help assess eDNA's potential to empower and engage them in the management of their ecosystems and natural resources, thereby promoting long-term environmental stewardship. To facilitate the uptake of results, these studies should be conducted in collaboration with experienced national and international researchers and involve students at various levels from local academic institutions.

Establishment of an eDNA infrastructure

Africa faces significant conservation and resource management challenges that require targeted infrastructure and capacity-building initiatives. A key priority is the development of molecular laboratory facilities, as many regions lack the infrastructure for eDNA extraction and analysis. Establishing state-of-the-art laboratories with cutting-edge technologies will enable local processing and analysis of eDNA samples, reducing reliance on external facilities and strengthening research sovereignty. While outsourcing to more scientifically developed countries may seem practical, it is not the preferred approach due to risks such as sample degradation, delays, and inequities in data access and ownership. Local facilities allow for faster and more efficient biodiversity monitoring while ensuring compliance with the Nagoya Protocol, thereby promoting fair access to genetic resources and facilitating equitable benefit sharing. By eliminating the need to export samples for analysis, this approach prevents potential misappropriation of genetic resources and ensures that the benefits of research remain within the countries of origin. It also helps protect data on threatened or commercially valuable species, preventing exploitation, overharvesting, and unauthorized access without community consent. Overall, strengthening local infrastructure enhances research autonomy and empowers African institutions to contribute more effectively to global biodiversity conservation efforts.

The eDNA extraction stage is critically important, necessitating a high-standard clean laboratory equipped with a positive air pressure system. It also requires multiple independent decontamination steps and controls, along with a stringent protocol to minimize contamination risks.[18] A potential alternative to the establishment of a standard physical laboratory is the installation of portable eDNA laboratories in containers already available on the market. The performance of the new labs should be assessed as much as possible through independent validation tests involving established eDNA laboratories. Such validations should ensure the protection of national knowledge and genetic resources, taking into account national sample export permits and other legal guidelines, including the Nagoya Protocol.[19]

Another challenge is the shortage of expertise and the need for skilled personnel in eDNA sampling, laboratory techniques, bioinformatics, and data interpretation. This challenge can be addressed through comprehensive, specialized training programs for local scientists, technicians, and conservationists. These programs should focus on building local expertise and ensuring the sustainable application of eDNA technologies.

Enhancing the availability of molecular reference libraries for African taxa is another crucial step toward the development of an eDNA infrastructure, as this is essential for the identification of sequences retrieved from eDNA samples. Achieving this requires a targeted effort to build regional libraries by sequencing African species, leveraging local natural history infrastructures such as museums,[20] and fostering collaborations among local and foreign researchers.

In addition, there is a need for optimized and standardized field protocols tailored to the diverse ecological conditions of Africa. These protocols should ensure the reliability and reproducibility of eDNA data. Finally, it is recommended that effective data management systems and open access databases be established to store, analyze, and share eDNA data. Such a framework would facilitate collaboration and informed decision-making in the region and should support the development of national reporting standards for eDNA-based assessments.

This third phase of the framework involves the implementation of an eDNA infrastructure and targeted capacity-building initiatives. We recommended that this phase should be implemented with the following structure.

(1) Develop initiatives toward the production of molecular reference libraries for African taxa, prioritizing species of conservation (e.g., endangered species) or socio-economic importance (e.g., disease vectors and crop pests).
(2) Develop and deliver training programs in collaboration with academic institutions and research organizations. These programs should cover all aspects of eDNA methods, from sample collection and laboratory processing to bioinformatics, data analysis, and interpretation. Quality control of the results should be ensured through independent validation tests involving international eDNA labs.

(3) Establish and disseminate standardized protocols for eDNA sampling and analysis tailored to African environmental conditions. These will improve the reliability and comparability of eDNA data across different regions.
(4) Establish national or regional databases and data-sharing platforms to ensure data ownership and accessibility while enabling contributions to international repositories where appropriate.[19] These infrastructures should be designed to facilitate the integration, storage, and dissemination of eDNA data, promoting collaboration among researchers and conservationists. Whenever possible, data repositories should be open access to allow reuse and support informed conservation decision-making. Safeguards must be in place to protect sensitive information, such as the locations of threatened or commercially valuable species, ensuring responsible data management and ethical use.
(5) Establish a sustainable long-term funding strategy by integrating support from governments, international organizations, and private sector partners. This strategy should prioritize investments in laboratory and computational infrastructures for eDNA analyses, including the acquisition of state-of-the-art equipment and computing resources. Additionally, it should ensure reliable equipment maintenance and establish secure, efficient supply chains for reagents and consumables. Key components of this strategy could include public-private partnerships, regional funding initiatives, and capacity-building programs to enhance local expertise. By fostering financial stability and technical self-sufficiency, this approach will help ensure the continuous operation of eDNA facilities, even in resource-limited settings.

Securing consistent and continued funding from national and international institutions is essential for the successful implementation of eDNA technologies. This support will enable the establishment of essential physical infrastructure and facilitate concerted capacity-building efforts, including training professionals, fostering research collaborations, and developing a supportive policy framework. However, to ensure long-term viability, laboratory facilities should progressively transition toward self-sufficiency, both technically and financially. This can be achieved by offering DNA-based services to the broader community, including applications in conservation and biological research, such as ecological quality monitoring and the detection of illegal wildlife poaching and trade. Additionally, eDNA technologies can support medical and veterinary needs, such as the surveillance of human and animal pathogens. These initiatives will play a vital role in sustaining and expanding eDNA infrastructure, ensuring the continuous development of technical expertise and financial resources needed to keep pace with the rapid advancement of new techniques and technologies.

APPLICATION OF THE FRAMEWORK: eDNA IMPLEMENTATION IN NAMIBIA

This framework is illustrated through the results of a project aimed at building the capacity of local institutions in the Kavango-Zambezi Transfrontier Conservation Area (KAZA-TFCA)[21] to use eDNA for long-term, adaptive management of wildlife and natural resources. Titled ''Improving Conservation Decision-Making in Africa with Environmental DNA Technology,'' the project was implemented through partnerships between local organizations and international collaborators, including the World Wildlife Fund, the eDNA company SPYGEN (France), and the BIOPOLIS-CIBIO Research Center for Biodiversity and Genetic Resources (Portugal), with funding provided by the JRS Biodiversity Foundation.[22]

The project was conducted in Namibia, where stakeholders from diverse sectors and organizations were engaged to explore the potential applications of eDNA technology for conservation and natural resource management. The response was overwhelmingly positive, with stakeholders expressing strong interest in further discussions during our visit. The stakeholders engaged included representatives from government, academia, the private sector, and NGOs, covering a wide range of ecosystems and conservation challenges, including Etosha, Zambezi, Nyae Nyae, and coastal areas. Collectively, their expertise spanned marine, freshwater, and terrestrial ecosystems, reflecting a broad range of activities and interests across the country.

Stakeholder engagement was conducted through focus group discussions,[23] facilitating direct, in-depth dialogue and knowledge exchange. This approach was chosen for its ability to provide rich, in-depth data, foster interaction and engagement, and remain flexible and culturally adaptive to participants' expectations. Additionally, it proved to be a cost-effective and time-efficient method for reaching multiple stakeholders within a limited time frame.

Meetings with stakeholders took place between October 31st and November 21st, 2022, involving 30 organizations and 101 participants. While each meeting was held with a single stakeholder organization, multiple participants selected by the respective focal organization were involved. During these discussions, we carefully listened to feedback and suggestions from our partners, incorporating their insights into the project's development. With stakeholders expressing interest in piloting eDNA technologies, we collaboratively designed the pilot studies for the second phase of the project and explored their potential involvement in the subsequent phases 2 and 3 of the initiative.

IDENTIFICATION OF eDNA APPLICATIONS

Information from the focus group discussions revealed that the use of eDNA technology in the region remains limited, with only a few projects identified (Figure 1). Notable examples include RhODIS,[24] a rhino biobank used to trace the sources of illegal wildlife trade; Nat Geo Okavango Wilderness,[25] an initiative that has been using eDNA analysis since 2019 to establish baseline biodiversity data in the Okavango system; and Debmarine Namibia,[26] a pioneering project that has been piloting eDNA sampling of sediment and water since 2021 to assess environmental impacts associated with offshore diamond mining.

Despite the limited experience with eDNA monitoring, the discussions facilitated the identification of eight key topics where eDNA could be strategically applied in Namibia and perhaps

Figure 1. Focus group meetings with stakeholders
(A) Debmarine.
(B) GCF (Giraffe Conservation Foundation).
(C) Nyae Nyae Conservancy.
(D) KIFI (Kamutjonga Inland Fisheries Institute).

neighboring countries to support and enhance conservation decision-making (Figure 2). These topics were selected based on three key criteria: (1) relevance to conservation decision-making, based on the potential to generate actionable insights for biodiversity conservation, ecological assessments, and environmental management; (2) stakeholder interest, considering the level of engagement and demand for eDNA applications among conservationists, policymakers, and resource managers; and (3) long-term sustainability, considering the ability to maintaining eDNA-based monitoring efforts through local capacity-building, funding mechanisms, and integration with existing conservation frameworks. Overall, we selected topics that were highly relevant to multiple stakeholders and demonstrated strong potential for long-term sustainability beyond the duration of the project. The eight selected topics span a diverse range of applications, including general biodiversity monitoring, wildlife and fisheries management, environmental impact assessment, and human health surveillance, among others.

The topics identified are as follows.

T1. General biodiversity baselines and monitoring.

Concept: developing national programs for cost-effective biodiversity assessment and monitoring is crucial for establishing biodiversity baselines and tracking environmental change. These programs help identify biodiversity hotspots, assess key drivers of species diversity, and assess and predict impacts from climate change, land-use changes, and invasive species. They also support systematic conservation planning and wildlife credit initiatives. Namibian stakeholders recognized the value of integrating eDNA into a national biodiversity monitoring program, highlighting its potential to enhance understanding of global change impacts on species and ecosystems. Such a program could also inform conservation and management strategies aimed at mitigating these impacts.

Key challenges: (1) expanding DNA reference databases for all taxonomic groups and ecological realms; (2) optimizing eDNA sampling of terrestrial fauna in semi-arid landscapes lacking permanent water using alternative eDNA sources (e.g., temporary water bodies, carrion flies, soil, dust, and air); and (3) assessing plant diversity from alternative environmental samples (e.g., beehive honey, pollen, pollinators, soil, dust, and air).

T2. Effective detection of rare, cryptic, and flagship species.

Concept: understanding the distribution patterns of rare, cryptic, and flagship species is crucial for effective conservation. Many of these species are elusive, making conventional detection methods (e.g., camera traps and aerial surveys) ineffective, particularly in vast, inaccessible landscapes. Namibian stakeholders recognized eDNA surveys as a scalable, cost-effective, and user-friendly approach for detecting the occurrence of species of conservation concern. This perspective was reinforced during focus group discussions by recent eDNA surveys in the Kunene River, which uncovered a previously unknown remnant population of common hippos (*Hippopotamus amphibius*) (M.L.-L. and V.P., unpublished data).

Key challenges: (1) expanding the DNA reference database for threatened species, particularly birds, and (2) optimizing eDNA sampling of terrestrial fauna in semi-arid landscapes without permanent water (see T1).

T3. Management of waterholes in semi-arid landscapes.

Concept: water availability in Namibia and other African semi-arid regions has shifted dramatically over the past century. Once reliant on springs, many of which are now dry, tens of thousands of permanent water points now support people, livestock, and wildlife in conservancies and on farms.[27] Yet, their impact on wildlife distribution, pathogen transmission, and ecosystem interactions remains poorly understood.[28–30] Namibian stakeholders expressed interest in exploring the ecological role of waterholes in shaping biodiversity, land use, aridity, vegetation, soils, and water quality. Integrating eDNA with remote sensing, animal tracking devices, camera traps, and water sensors could offer a comprehensive understanding of these habitats, informing biodiversity management and disease mitigation strategies.[31,32]

Key challenges: (1) expanding DNA reference databases for mammals, birds, pathogens, and other micro-organisms, (2) optimizing eDNA protocols for detecting pathogens and

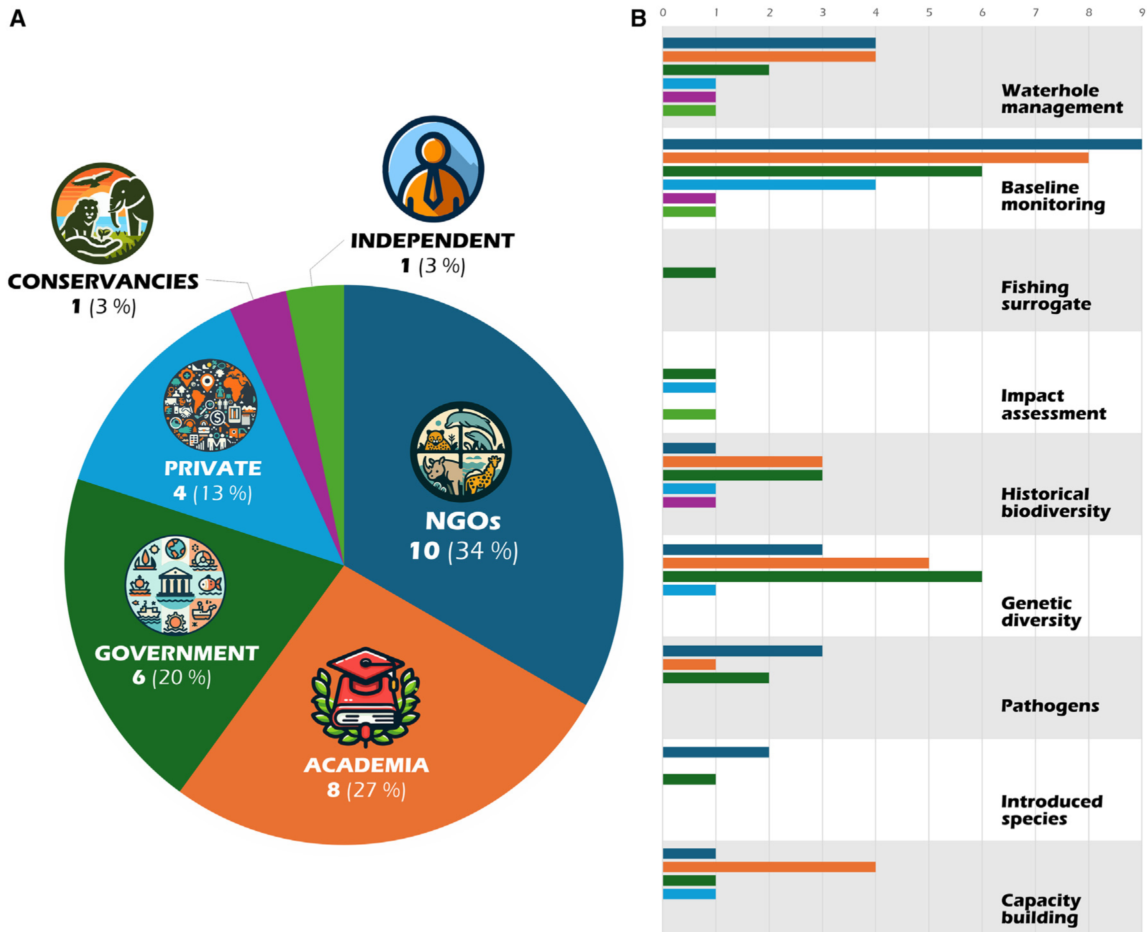

Figure 2. Stakeholders consulted and their main interests
(A) Number and percentage of consulted stakeholders per group during the project.
(B) Interest of stakeholders per group in the identified topics. The x axis shows the number of stakeholders interested in each topic.

micro-organisms from waterholes, and (3) optimizing eDNA protocols for detecting vertebrate species from waterholes.

T4. Fish stock assessment and early detection of invasive species.

Concept: effective fish stock assessment and early detection of invasive species are essential for sustainable fisheries management. However, conventional assessment methods are often costly and inefficient, particularly in resource-limited regions of Africa. Namibian stakeholders recognized the need to replace or complement current inland fish stock assessments, reliant on lethal techniques like rotenone poisoning or gillnetting, with more cost-effective, non-lethal approaches. Therefore, they expressed interest in the use of eDNA for detecting commercially important fish species and invasive species[33,34] and for testing quantitative eDNA methods, such as qPCR and digital droplet PCR (ddPCR), to estimate fish biomass.[35,36] These techniques could support conservation planning, fisheries management, and commercial fisheries while enhancing the detection of invasive species that can cause significant damage to native ecosystems (e.g., aquatic plants[37] and red crayfish[38]).

Key challenges: (1) expanding DNA reference databases for fish and invasive species, (2) optimizing eDNA protocols for detecting fish and invasive species, and (3) testing methods such as qPCR or ddPCR to reliably estimate fish biomass based on eDNA copy numbers and read counts.

T5. Monitoring of pathogens and their impact on humans and wildlife.

Concept: eDNA is an established tool for detecting pathogens, with applications in tracking diseases such as sylvatic anthrax (*Bacillus cereus* biovar *anthracis*) and tuberculosis (*Mycobacterium tuberculosis*).[39–41] In Namibia, stakeholders highlighted its potential for monitoring pathogen threats such as anthrax, rabies, schistosomiasis, foot-and-mouth disease, tuberculosis, and canine distemper. Similarly, eDNA was considered a valuable tool for tracking harmful algal blooms,[37,41] which pose risks to ecosystems and public health. This concern was underscored by a recent cyanobacterial poisoning incident that killed 350 elephants in Botswana's Okavango Delta.[42] Implementing eDNA-based surveillance could enable rapid detection and timely interventions to mitigate these threats.

Key challenges: (1) expanding eDNA reference databases for pathogens and microorganisms and (2) optimizing eDNA protocols for detecting pathogens and micro-organisms from water and soil samples.

T6. Strategic environmental assessment and environmental impact assessment.

Concept: eDNA offers a cost-effective way to assess human impacts on marine, freshwater, and terrestrial ecosystems due to activities such as urbanization, deforestation, or mining.[43,44] It also facilitates monitoring of the effectiveness of mitigation and compensation measures such as dam removal.[45] Namibian stakeholders identified eDNA as a valuable tool for establishing biodiversity baselines to support strategic environmental assessment and Kwando basin planning. They further identified its potential as a standardized tool for regulatory reporting on diamond mining impacts by monitoring marine biodiversity's natural variability, impacts, and recovery. Implementing standardized eDNA approaches could greatly enhance the quality and cost effectiveness of impact assessments for planning and licensing economic activities.

Key challenges: (1) expanding DNA reference databases for terrestrial and marine species of conservation concern; (2) standardizing eDNA approaches to meet regulatory requirements; (3) developing innovative eDNA techniques for challenging environments, such as deep-sea monitoring; and (4) creating eDNA-based indicators for impact assessments, including proxies for threatened species abundance.

T7. Monitoring genetic diversity and connectivity in a changing climate.

Concept: preserving genetic diversity and ensuring connectivity among wildlife populations is a key challenge in global biodiversity conservation.[46,47] Advances in eDNA technology have provided a non-invasive and cost-effective approach to assessing intraspecific genetic diversity and divergence patterns.[48,49] These insights enable researchers to infer landscape permeability and identify movement corridors across various temporal and spatial scales.[48,50] Namibian stakeholders recognized the value of eDNA to understand the degree of connectivity among wildlife populations and how this affects their genetic diversity and potential differentiation. Notably, they highlighted the potential of integrating eDNA sampling with advanced landscape genomics to evaluate the effectiveness of wildlife corridors previously identified in the KAZA region. This approach could provide critical insights into how well these corridors facilitate species movement among protected areas, supporting more effective conservation planning and management.[16] Additionally, eDNA's ability to reveal spatial patterns of genetic diversity and divergence across multiple species holds promise for combating illegal wildlife trade by enabling the identification and tracking of seized animals and animal parts.[51]

Key challenges: (1) enhancing reference DNA databases to capture the genetic diversity of target wildlife species, (2) identifying suitable DNA markers from environmental samples that provide sufficient variability for accurate inferences on genetic diversity, and (3) developing and optimizing sampling and analytic protocols to effectively infer landscape connectivity from eDNA data.

T8. Reconstruction of past biological communities.

Concept: Africa lacks reliable ecological baseline data, leading to shifting baseline syndrome. Analyzing eDNA from sediment core samples in permanent or temporary water bodies can help reconstruct past biological communities, providing insights into historical species composition, abundance, and genetic diversity.[52] This information enhances baseline accuracy and informs reintroduction and translocation strategies, providing insights into the suitability of different sites for species reintroduction and their potential impact on local ecosystems.[53] After reviewing case studies from North America[54,55] and Japan,[56] stakeholders acknowledged eDNA as a valuable tool for reconstructing past ecosystems, thus supporting informed decision-making in Namibia's ecological management and restoration efforts.

Key challenges: (1) expanding DNA reference databases for all taxonomic groups and ecological realms, (2) identifying suitable aquatic ecosystems for extracting sediment cores that reliably capture past environmental conditions, and (3) developing and optimizing sampling and analytic protocols tailored to arid and semi-arid environments to reconstruct past biological communities from eDNA in sediment cores.

SELECTION OF PILOT STUDIES

Based on the eight key topics previously identified, we, together with the stakeholders, selected five pilot studies focusing on pathogen detection and monitoring, inland fisheries management, marine fish and mammal surveys, wildlife monitoring in semi-arid landscapes, and flowering plant biodiversity assessment using honey samples (Table 1). These pilots were selected given their conservation relevance, stakeholder interest, and potential long-term sustainability. Each pilot study will be conducted by an international research team in collaboration with graduate and post-graduate students from Namibian universities, ensuring knowledge transfer and local capacity building. Additionally, they will actively involve local stakeholders to strengthen regional expertise and generate practical insights for improving conservation and biodiversity management in Namibia and the broader KAZA region (Table 1). Overall, these pilots provide a representative set of practical applications in biodiversity conservation, natural resource management, and health, with the potential for advancing eDNA research, fostering collaboration, and delivering tangible impacts in Namibia.

CONCLUSIONS

Here, we propose integrating the knowledge, culture, needs, and priorities of local stakeholders into a framework for implementing eDNA technologies to support biodiversity conservation in Africa. We demonstrated this approach through an ongoing project in Namibia, highlighting how stakeholder engagement expands the scope of eDNA applications beyond conventional priorities. While initial capacity-building efforts

Table 1. Pilot studies selected with Namibian stakeholders to promote the application and showcase the potential of eDNA assessments and monitoring in the country

Title	Aim	Relevance	Approach	Potential partners
Detection and monitoring of pathogens	optimize eDNA methodologies for early detection and surveillance of mammalian viruses in waterholes	provides a cost-effective tool for detecting and controlling viral disease outbreaks in Namibia	develop a targeted sequence capture panel for detecting known and related viruses, tested both *in silico* and *in situ* at sites with a history of viral disease outbreaks	ETN, NUST, ORC, UNAM
Inland fisheries	evaluate eDNA-based monitoring of inland fish stocks	support fisheries management while replacing lethal sampling methods (gillnets and rotenone poisoning)	conduct eDNA surveys alongside the annual fisheries assessment on the Kwando River; fieldwork commenced in November 2023; analyses are ongoing	KIFI, UNAM
Marine fish and mammal surveys	develop and optimize protocols for marine eDNA monitoring	provides critical data on marine mammals of conservation concern, fish stock assessments, and biodiversity inventories	conduct eDNA sampling along transects, collecting water at various depths using deep-water pumps and filtration systems	DEBM, MEFT, MFMR, NDP
Wildlife monitoring in semi-arid landscapes	develop and optimize protocols for detecting terrestrial vertebrates using eDNA from water and alternative sources.	enhances species distribution data to support wildlife management within protected areas	optimize eDNA processing pipelines for eDNA collected from water (waterholes and streams) and alternative sources (soil, dust, and air), and compare species detectability with conventional monitoring methods (camera traps, live traps, and aerial surveys)	EEI, ENP, MEFT, NNC, NNF, OPGR, ORC, UNAM
Monitoring flowering plants from honey	develop and test eDNA-based protocols for monitoring plant biodiversity from honey	provides a cost-effective approach for monitoring the diversity and phenology of flowering plants	extract and metabarcoding of plant DNA from honey samples, collected across different habitat types and levels of human disturbance, comparing results with conventional sampling	MEFT, NBA, NUST

DEBM, Debmarine; EEI, Etosha Ecological Institute; ENP, Etosha Natural Park; KIFI, Kamutjonga Inland Fisheries Institute; MEFT, Ministry of Environment, Forestry and Tourism; MFMR, Ministry of Fisheries and Marine Resources; NBA, Namibian Beekeeping Association; NDP, Namibian Dolphin Project; NNC, Nyae Nyae Conservancy; NNF, Namibia Nature Foundation; NUST, Namibia University of Science and Technology; OPGR, Ongava Private Game Reserve; ORC, Ongava Research Center; UNAM, University of Namibia.

might have focused on large mammal monitoring or zoonotic disease surveillance, stakeholder discussions revealed additional valuable applications, such as certifying Namibia's nascent honey industry by identifying flowering plant sources and developing less destructive fish stock assessment methods for inland fisheries. These insights underscore the importance of stakeholder-driven innovation in shaping effective and context-specific eDNA applications.

This initiative also highlights the transformative potential of equitable North-South partnerships, emphasizing the importance of inclusivity and long-term collaboration in scientific capacity building. By implementing a structured stakeholder engagement framework, as outlined in this study, we can strengthen Africa's ability to effectively adopt and apply emerging monitoring technologies. Understanding local conservation priorities allows for tailored capacity-building efforts, fostering sustained integration of eDNA technology across the region.

Beyond conservation, this approach has broader implications for policy development and environmental governance. Strengthening regional expertise in eDNA monitoring can support regulatory frameworks for sustainable resource management, inform national and transboundary conservation policies, and contribute to biodiversity reporting under international agreements such as the Convention on Biological Diversity (CBD) and the Sustainable Development Goals (SDGs).

Future efforts should focus on scaling up stakeholder engagement across diverse ecosystems and testing eDNA applications in a wider range of African contexts. Additionally, fostering regional collaboration among research institutions, policymakers, and local communities will be critical for ensuring the long-term success of eDNA as a cost-effective and scalable tool for biodiversity monitoring.

By integrating scientific innovation with local knowledge systems, this initiative not only enhances conservation practices but also contributes to sustainable development and resilience in the face of environmental change. As eDNA technology continues to evolve, stakeholder-driven approaches will be instrumental in shaping its implementation for maximum ecological and societal benefit across Africa.

ACKNOWLEDGMENTS

This work was funded by the JRS Biodiversity Foundation under project "Improving Conservation Decision-making in Africa with Environmental DNA Technology" and by the FEDER program of the European Union under project "TROPIBIO - Research Toward the Conservation, Restoration and Sustainable Use of Tropical Biodiversity and Ecosystems" (REF: NORTE-01-0145-FEDER-000046).

AUTHOR CONTRIBUTIONS

M.L.-L. and P.B. conceptualized the paper and led the writing of most of the sections. M.L.-L., A.L., V.P., and M.W. co-organized and attended all the focus group meetings, and the remaining authors were present at some of the meetings and provided iterative feedback on the paper, as well as contributed to the review and editing process.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT and DeepL to correct grammar and spelling. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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