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DNA barcoding: An important tool for biodiversity conservation

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ABSTRACT

The conservation of biodiversity has emerged as one of the most crucial scientific and societal issues of the 21st century, due to rapid habitat destruction, climate change, invasive species, pollution, and the unsustainable use of natural resources. The correct identification of species is crucial for effective conservation planning, ecological research, and environmental management. Traditional taxonomic approaches, which mainly depend on morphological features, can be time consuming, needs specialized knowledge, and may find difficult to differentiate between cryptic species or various life stages. In this scenario, DNA barcoding has appeared as an effective molecular tool that greatly improves biodiversity evaluation and conservation efforts. DNA barcoding is the process of identifying species by comparing sequences to reference databases using a brief, standardized section of DNA, most frequently the mitochondrial cytochrome c oxidase I (COI) gene in mammals, rbcL and matK in plants, and ITS in fungi. Even from little or deteriorated samples, this method allows for quick, precise, and economical species identification. Its use has revolutionized the documentation and monitoring of biodiversity. DNA barcoding continues to develop with advances in sequencing technologies and bioinformatics, despite certain constraints, such as insufficient reference libraries and difficulties in particular taxonomic groupings. It is an essential tool for contemporary conservation biology because of its increasing accessibility and dependability.

Keywords: PCR, Identification of Species, Conservation.

INTRODUCTION

The variety of life at the genetic, species, and ecological levels is known as biodiversity, and it is essential to human survival and well-being. For food, health, economic security, cultural identity, and environmental stability, humans rely on biodiversity both directly and indirectly. According to recent international evaluations, human wellbeing and sustainable development are seriously threatened by the fast loss of biodiversity. Food security and nutrition are two of biodiversity's most important contributions. Numerous foods, vital nutrients, and genetic resources for improving crops and livestock are provided by a variety of plant and animal species. Resilience against diseases, pests, and climate change is enhanced by agricultural diversification. More than 75% of the world's food crops depend on pollinators like bees, butterflies, and birds, whose populations depend on healthy ecosystems (FAO, 2019) [1]. Food availability and nutritional diversity are directly threatened by biodiversity loss, particularly in developing nations. Additionally, biodiversity is essential to human health and medicine. Numerous contemporary medications are made from organic substances that can be found in microbes, plants, and animals. For example, biological resources play a major role in the production of antibiotics, anticancer medications, and traditional medicines. By regulating pathogen populations and preserving ecological balance, ecosystem variety also aids in the regulation of disease transmission. As demonstrated by current global health crises, studies show that biodiversity loss can raise the danger of zoonotic infections (WHO, 2020) [2]. Biodiversity is also closely linked to economic development and livelihoods. Millions of people depend on biodiversity-based activities such as agriculture, fisheries, forestry, and ecotourism for income and employment. The Das gupta Review (2021) [3] emphasizes that economic prosperity is inseparable from nature, warning that unsustainable exploitation of biodiversity undermines long term economic stability. Biodiversity includes cultural, spiritual, and psychological benefits in addition to financial ones. Numerous indigenous tribes and cultures have strong relationships to the local biodiversity, which influences customs, beliefs, and knowledge systems.

Accurate species identification and monitoring is a crucial challenge in biodiversity conservation. Cryptic species, phenotypic plasticity, and immature life phases are common problems for traditional taxonomy, which is based on morphological features. In this regard, DNA barcoding has become a potent molecular tool that facilitates conservation decision making, improves biodiversity inventories, and speeds up species identification. The importance of DNA barcoding for biodiversity conservation is explained in this paper, along with its uses, difficulties, and potential future developments.

PRINCIPLES OF DNA BARCODING

DNA barcoding involves sequencing a standardized segment of the genome to identify organisms to species level. For animals, the most widely used barcode marker is a fragment of the mitochondrial cytochrome c oxidase subunit I (COI) gene; for plants, chloroplast regions such as *matK* and *rbcL* are commonly used [4]. Fungi often use the internal transcribed spacer (ITS) region. These barcodes are compared against reference libraries to assign unknown samples to known taxa with high confidence.The DNA barcode approach assumes that genetic divergence between species (interspecific variation) exceeds variation within species (intraspecific variation). This "barcode gap" enables discrimination among taxa. Rapid sequencing technologies, automation, and global databases like the Barcode of Life Data System (BOLD) facilitate widespread adoption of barcoding in conservation science [5]. Species identity is contextualized within a genetic framework through DNA barcoding. It creates a barcode gap that facilitates discrimination by assuming that genetic divergence between species (interspecific variation) is typically greater than variation within the same species (intraspecific variation) [6].

SELECTION OF BARCODE MARKERS

A fundamental principle of DNA barcoding is selecting a suitable gene region that is present in all target taxa, possesses conserved primer binding regions, and shows enough variation to distinguish between different species. Due to its significant interspecific diversity and simplicity of amplification using universal primers, the mitochondrial COI gene has become the standard barcode marker in animals [7]. However, because plant mitochondria have little sequence variation, COI functions poorly for plants. Plant barcodes are instead created by combining nuclear ribosomal internal transcribed spacer (ITS) regions with chloroplast genes like rbcL and matK [8,9]. Evolutionary principles are also reflected in the choice of barcode marker: in many animals, mitochondrial DNA (mtDNA) develops more quickly than nuclear DNA, resulting in more distinct species boundaries [10]. Plants, on the other hand, exhibit sluggish mitochondrial evolution, necessitating the use of other loci that better capture variation.

STANDARDIZATION AND UNIVERSALITY

Standardization is a key component of DNA barcoding. Adopting common methods is necessary to compare sequences across research, labs, and taxonomic groups. Defined primer sets, PCR settings, and sequencing techniques that reduce error and increase comparability are all part of standard barcoding protocols. By establishing a common reference library that can be used to compare unknown samples, standardization makes it easier to include novel sequences into international databases like GenBank and the Barcode of Life Data Systems (BOLD) [7]. Because they contain confirmed reference sequences connected to voucher specimens and metadata, these repositories serve as the foundation for DNA barcoding.

GENETIC DIVERGENCE AND THE "BARCODE GAP"

The barcode gap notion, which states that genetic distances between sequences from different species should be greater than those between sequences from the same species, is a defining principle. Basic distance metrics or clustering algorithms can be used to consistently define species when there is a noticeable gap [11]. According to this principle, species eventually diverge due to accumulating mutations brought about by speciation. Its universality, however, differs among taxa. Divergence may be restricted in young or quickly evolving lineages, which would reduce the barcode gap and make species classification more difficult. The barcode gap is still essential to many analytical procedures in molecular taxonomy, despite these difficulties.

TAXONOMIC VALIDATION AND VOUCHER SPECIMENS

DNA barcoding is most reliable when genetic data are linked to physical voucher specimens that have been morphologically verified by taxonomic experts. This linkage ensures that barcodes are assigned to correctly identified species and enables reevaluation as taxonomy evolves [9]. Voucher specimens provide a physical reference for future study, allowing researchers to revisit identifications, validate unusual or ambiguous barcodes, and incorporate taxonomic revisions. This principle emphasizes that barcoding augments not replaces traditional taxonomy. Another core principle is the use of well curated reference libraries. A barcode is only as informative as the database against which it is compared. Consequently, quality control both in sequencing and in taxonomic annotation is essential. Repositories such as BOLD implement rigorous standards for sequence submission, including minimum sequence length, absence of stop codons, and verified species names [5]. Ensuring high-quality reference data reduces misidentification and improves analytical confidence.

REFERENCE LIBRARIES AND DATA QUALITY

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APPLICATION OF DNA BARCODING IN BIODIVERSITY CONSERVATION

Accurate Species Identification

The conservation of biodiversity depends on accurate identification. Using a little tissue sample, DNA barcoding makes it possible to quickly and accurately identify species at any stage of life. This is especially helpful for taxa with similar morphologies or inadequate descriptions. According to recent research, DNA barcoding can effectively resolve taxonomic uncertainties and enhance biodiversity inventories, particularly in megadiverse and understudied areas.

Detection of Cryptic and Endangered Species

Because of their cryptic form, many endangered species are still unknown. DNA barcoding helps uncover hidden diversity, leading to reassessment of conservation status and improved protection strategies. Cryptic lineages within vulnerable taxa have been identified using molecular identification, highlighting the necessity for conservation strategies specific to genetically different populations [11]. This contributes directly to more accurate IUCN Red List assessments.

Biodiversity Monitoring Using eDNA and Metabarcoding

Environmental DNA (eDNA) and DNA metabarcoding are two of the most revolutionary uses of DNA barcoding in conservation. Without physically capturing organisms, these methods enable the identification of species from samples of water, soil, or air. eDNA metabarcoding, which provides a non-invasive, affordable technique for long-term ecosystem surveillance, is being utilized more and more to monitor soil fauna, aquatic ecosystems, and forest biodiversity [14].

Early Detection of Invasive Species

Native biodiversity is seriously threatened by invasive species. Even at larval or fragmented stages, DNA barcoding makes it easier to identify invasive organisms early on. Early detection makes it possible to take prompt management measures, which lessens financial losses and ecological harm. Barcoding based surveillance has been incorporated into invasive species risk assessment frameworks in recent conservation initiatives.

Wildlife Forensics and Illegal Trade Control

By identifying species from processed or degraded biological materials like meat, wood, medicinal plant products, and animal derivatives, DNA barcoding plays a critical role in wildlife forensics. This application helps prevent illegal trade and overexploitation of endangered species by supporting the implementation of international agreements like CITES and animal protection regulations.

Conservation Planning and Policy Support

DNA barcode data supports conservation planning, habitat prioritization, and ecosystem management by contributing to national and international biodiversity databases like BOLD and GenBank. Policymakers increasingly rely on molecular biodiversity data to design protected areas, monitor restoration success, and assess the impacts of climate change on species distributions [15].

Integrative Taxonomy for Conservation

Modern conservation biology emphasizes integrative taxonomy, which combines morphological, ecological, and molecular data. DNA barcoding strengthens this approach by providing genetic evidence that complements traditional taxonomy, resulting in more robust species delimitation and improved conservation decision making.

CONSERVATION APPLICATIONS ACROSS ECOSYSTEMS

Freshwater Ecosystems

Rivers, lakes, and wetlands are examples of freshwater ecosystems that are among the most endangered in the world. In these systems, barcoding-based monitoring has proven to be quite helpful. Traditional fish and macroinvertebrate identification frequently calls for a high level of taxonomic knowledge. As markers of ecosystem health, barcoding speeds up evaluations of species composition and water quality.

Marine Ecosystems

Although there is a lot of marine biodiversity, it is not well recorded. Plankton, benthic invertebrates, and coral reef fish have all benefited from DNA barcoding. One study found regional changes associated with pollution and climate change using the metabarcoding of plankton populations along oceanic gradients [16]. By matching processed seafood to species-specific barcodes, barcoding also helps identify illegal, unreported, and unregulated (IUU) fishing, bolstering enforcement of fishing quotas and marine protected areas [17].

Terrestrial and Forest Ecosystems

Understanding species interactions and ecological dynamics in forests is improved by barcoding soil fauna and insect herbivores. High insect diversity was found by metabarcoding canopy fogging samples, highlighting the need of intact forests for conservation measures [18]. Additionally, barcoding aids in tracking illicit wildlife trafficking. In order to identify exploited species, sequences from seized animal parts can be compared to validated barcodes, which helps guide policy and enforcement decisions [19].

LIMITATIONS AND CHALLENGES

Despite its contributions, DNA barcoding faces several challenges. Many species remain sequenced, especially tropical insects and deep-sea organisms. Closely related species sometimes share barcodes, complicating identifications. No single universal barcode exists for all life forms. Developing countries may lack sequencing facilities or trained personnel. Genetic divergence does not always correlate with species boundaries. Despite these issues, barcoding continues to improve as databases expand and sequencing becomes more affordable. DNA barcoding, which offers a dependable, scalable, and uniform technique for species identification, has completely transformed biodiversity conservation. Taxonomy, ecological monitoring, animal forensics, invasive species control, habitat restoration, and environmental policy are just a few of its uses. The advent of global barcode libraries, portable sequencing technology, and eDNA metabarcoding has sped up the finding of biodiversity and saved many endangered species. Despite ongoing difficulties, DNA barcoding is becoming an essential tool for preserving life on Earth in the face of swift environmental change.

FUTURE PROSPECTS IN CONSERVATION

Higher resolution than single gene barcodes is provided by advances in genomics, such as whole genome sequencing and genome skimming. Understanding evolutionary relationships and delineating species are improved when barcoding is combined with genomic data. Machine learning tools can improve sequence classification, detect errors, and automate biodiversity assessments, reducing expert dependency and accelerating analysis [20]. Global barcoding efforts like the International Barcode of Life (iBOL) and BIOSCAN aim to barcode millions of species. Expanded sampling in biodiversity hotspots, especially underrepresented regions, will enhance global conservation planning [21].

CONCLUSION

DNA barcoding has become an indispensable tool in biodiversity conservation. Its applications range from accurate species identification and cryptic species detection to ecosystem monitoring, invasive species management, and wildlife forensics. With advancements in eDNA metabarcoding, and genomic technologies, DNA barcoding will continue to play a central role in addressing global biodiversity loss and guiding sustainable conservation strategies.

Conflict of interest

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