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Review Article

Advances in Molecular and Genomic Tools for Sustainable Fisheries Management, A Comprehensive Review

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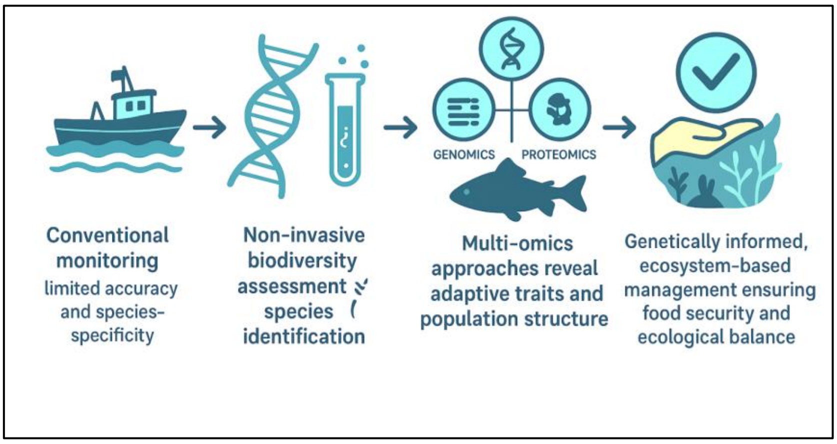
Abstract



Graphical Abstract

Sustainable management of fisheries plays a key role in ensuring food security, ecological stability, and socioeconomic sustainability of the world. The conventional methods of monitoring and evaluation are not always sufficient because of the inability to achieve high accuracy, time, and species-specificity. The recent development of molecular and genomic technology has revolutionized the ability to measure, monitor, and preserve aquatic biodiversity in a more precise manner than ever before. Genomics, transcriptomics, and proteomics have become the central activities in the dissection of the genetic architecture of fish populations, which has made it possible to identify adaptive traits, as well as population structures, that are important in the management of stocks. The DNA barcoding and environmental DNA (eDNA) methods have transformed the concept of species identification and biodiversity monitoring that enabling non-invasive detection of rare, cryptic, or endangered species. The application of population genetics and genomic selection can again assist in defining the management unit and informing breeding programs that will improve resilience and productivity. Having all these molecular advancements leads to the creation of ecosystem-based management that incorporates genetic information into policy frameworks that enhance conservation, traceability, and sustainability. Fisheries genomics continues to be extended with the integration of the multi-omics platform with the advanced bioinformatics and artificial intelligence that allows predictive and adaptive management strategies to respond to environmental change. All molecular and genomic technologies are a revolutionary direction of sustainable, information-driven fisheries management, which combines the preservation of the ecological environment with human nutritional requirements.

Keywords: Molecular ecology, genomics, DNA barcoding, environmental DNA, population genetics, sustainable fisheries, biodiversity conservation.

INTRODUCTION

Fisheries are important in the world's food security, sustaining livelihoods, and ecological integrity. Fish and water resources play a significant role in providing protein in the world, especially in developing countries, where they constitute a major source of food and livelihood (Dugan *et al.*, 2006). In addition to their nutritional value, fisheries also support the economies of millions of coastal and inland communities, as well as maintaining complex ecological processes that control aquatic ecosystems. Nevertheless, global fisheries have become more and more threatened by overexploitation, degradation of habitats, unreported and illegal fishing, as well as rising effects of climate change (Okafor-Yarwood *et al.*, 2019). Old methods of fisheries management, mostly based on catch data, morphological identification, and restricted ecological surveys, tend to give incomplete or slow information on population changes, species diversity, and the health of the ecosystem. These traditional approaches, though useful, are often insensitive and unable to resolve complex biological and environmental processes that control aquatic biodiversity (Reid *et al.*, 2019).

The development of molecular and genomic technologies has transformed the paradigm of fisheries science, providing instruments that allow for managing it more precisely, efficiently, and predictably (Shahi *et al.*, 2024). Molecular studies, based on the analysis of DNA and RNA, give a specific detail of the identity of the species, genetic variation, and evolutionary connections, which can hardly be observed by other methods. The nature of the genetic information has been analyzed in large volumes based on genomics and next-generation sequencing (NGS) platforms that have made it possible to discover additional molecular markers related to the differentiation of populations, their adaptation, and their resilience (Chatterjee *et al.*, 2025). Such developments facilitate the discovery of specific fish stocks, aid in the definition of management units, and shape strategies aimed at avoiding the occurrence of genetic homogenization and population loss (Holl *et al.*, 2022).

DNA barcoding, as a technique founded on short standardized genetic segments, has become an effective instrument in precise species identification, particularly in instances where morphological elements are indistinct or deteriorated (Antil *et al.*, 2023). It enables fast authentication of the authenticity of seafood, which will fight mislabeling and boost transparency in the global supply chains. Environmental DNA (eDNA) analysis further extends these applications, as it is used to identify genetic material released into aquatic environments, and as a result, non-invasive biodiversity studies can be done (Rees *et al.*, 2013). eDNA-based surveillance is a non-invasive technology that can be used to test the organismal composition of whole communities without any physical sample, providing real-time information about species abundance and distribution. It is also used in particular in surveying rare or endangered species, and in surveilling invasive taxa before they reach an ecological niche dominance (Duenas *et al.*, 2018).

Similar developments of transcriptomics and proteomics have enhanced knowledge about the molecular pathways of physiological adaptation, stress response, and reproductive biology in fish (Martyniuk *et al.*, 2012). Making use of transcriptomic profiling it is a type of gene expression that can indicate the process of ecological disturbance or habitat degradation, and which associates the gene expression in relation to the environmental fluctuations. These findings are further given throughout proteomic analyses to help in explaining the functional responses at the protein level, which fills the gap between genotype and phenotype. A combination of these omics methods leads to a better description of the biology of fish and the work of the ecosystem (Li *et al.*, 2025).

Population genetics and landscape genomics are critical when determining the genetic connectivity, gene flow, and demographic history of fish populations (Knutsen *et al.*, 2022). Such knowledge is necessary in the definition of conservation units and in the achievement of effective restocking or breeding programs. Meanwhile, genomic selection has transformed the field of aquaculture by making it possible to identify and cultivate those individuals that possess the desired characteristics of disease resistance, thermal tolerance, and growth efficiency. This not only optimizes productivity but also reduces environmental effects by optimizing resource use and minimizing the use of chemical interventions (Nikolopoulou *et al.*, 2012).

Molecular data is even more useful in the field of fisheries management through the combination of bioinformatics and computational modeling (Nambiar *et al.*, 2025). The interpretation of large-scale datasets of genomic data is supported by advanced algorithms and artificial intelligence to generate raw molecular data into usable ecological information. Genomic-based predictive models can be used to predict how a population will respond to a change in the environment so that adaptive management actions are not only proactive but also evidence-based. Molecular and genomic advances have enhanced traceability and transparency in the seafood sector in terms of policy (Leal *et al.*, 2015). Genetic tracking will make sure that they are able to adhere to the sustainability certifications and also implement measures against the illegal, unreported, and unregulated fishing. The integration of molecular means and ecosystem management principles enables decision-makers to combine the objectives of conservation with the interests of economics and social priorities to ensure the long-term sustainability of fisheries resources (Stephenson *et al.*, 2018).

Molecular and genomic tools are a gateway between scientific innovations and environmental stewardship in the larger sense of sustainability. They allow a shift in management towards data-based predictive regimes that are capable of predicting and preventing environmental risks (Seele *et al.,* 2017). With the increasing stressors of human impacts and climate change on the global fisheries, the synthesis of the multi-omics technologies, high-resolution sequencing, and computational analytics offers an invigorating platform on which the sustainability and stability of the aquatic-based ecosystems can be ensured. The further development of these tools along with the interdisciplinary cooperation, is going to characterize the future of fisheries management, and molecular science will be put in line with the ideals of conservation and sustainable development (Phillipson *et al.,* 2013).

This review aims to synthesize the latest advancements in molecular and genomic technologies and their transformative applications in sustainable fisheries management. It seeks to critically evaluate how innovations such as genomics, transcriptomics, proteomics, DNA barcoding, eDNA monitoring, and population genetics contribute to biodiversity conservation, stock assessment, and ecosystem-based governance. Furthermore, the review highlights emerging interdisciplinary trends and outlines future research directions that will enhance the integration of molecular data into adaptive, sustainable, and policy-relevant fisheries management frameworks.

2. Technological Innovation and Genomic Revolution in Modern Fisheries Management

This framework highlights the transformative role of emerging molecular and genomic technologies in reshaping fisheries science into a predictive, data-intensive discipline. Through the integration of high-throughput sequencing, bioinformatics, and artificial intelligence, fisheries research now enables accurate biodiversity assessment, population monitoring, and adaptive trait analysis, promoting transparent, traceable, and sustainable resource management (Alam *et al.,* 2024).

2.1. Evolution of Molecular Approaches in Fisheries Science

Fisheries genetics has progressed from morphology- and enzyme-based diagnostics to advanced molecular characterization. Early phenotypic and biochemical analyses provided limited insights into population variability, whereas the introduction of mitochondrial and nuclear markers revolutionized taxonomic and evolutionary investigations. Milestones such as microsatellite discovery, DNA barcoding, and early genome mapping established the foundation for current genomic fisheries research (Hauser *et al.,* 2008). The convergence of sequencing innovation, computational modeling, and molecular ecology now positions genomics at the core of evidence-based fisheries management.

2.2. High-Throughput Genomic Platforms and Analytical Advances

Next-generation and third-generation sequencing systems have accelerated genomic exploration across aquatic organisms, enabling deep insights into complex genome architectures. Techniques including SNP genotyping, RAD-seq, and whole-genome resequencing provide unprecedented resolution for identifying population structure, gene flow, and adaptive differentiation (Holliday *et al.,* 2018). Integration of AI and machine learning facilitates rapid interpretation of massive datasets, enabling predictive modeling and genotype–environment association analyses that strengthen decision-making in stock conservation and aquaculture enhancement.

2.3. Functional Genomics and Adaptive Mechanisms in Aquatic Species

Functional omics approaches have revealed molecular networks driving environmental adaptation, physiological performance, and resilience in aquatic taxa. Transcriptome and proteome profiling elucidate gene regulation under salinity, temperature, and oxygen stress, while epigenetic modifications such as methylation dynamics modulate plasticity in fluctuating habitats (Dildar *et al.,* 2025). Discovery of functional genetic markers linked to growth, fertility, and stress tolerance supports precision breeding and conservation strategies that align with changing climate scenarios.

2.4. Applications in Stock Identification and Traceability

Genomic markers serve as reliable tools for stock discrimination, population assignment, and lineage tracking. These approaches enhance fisheries management by defining biological boundaries, informing quota design, and maintaining ecosystem integrity. DNA-based authentication ensures transparent supply chains, deters seafood mislabeling, and safeguards consumer confidence, aligning fisheries governance with international sustainability certifications and trade regulations (Gleadall *et al.,* 2024).

2.5. Technological Frontiers and Future Perspectives

Emerging tools such as portable sequencers, nanogenomic sensors, and lab-on-chip diagnostics are paving the way for real-time, in-field genetic surveillance. Coupled with bioinformatics-driven predictive systems, these technologies can forecast ecological shifts, assess habitat health, and support adaptive policy frameworks. Addressing challenges related to ethical data use, equitable capacity development, and open genomic repositories will be crucial to fully realizing the global benefits of the genomic revolution in fisheries (Blasiak *et al.,* 2020).

3. Ecological Genomics for Resilient and Adaptive Fisheries

This framework underscores how ecological genomics unites molecular diversity with ecosystem resilience, enabling the prediction and management of species adaptation in rapidly changing aquatic environments. By decoding genetic responses to environmental variability, ecological genomics bridges the gap between molecular biology and ecosystem science, guiding adaptive fisheries strategies under climate-induced pressures (Lancaster *et al.*, 2022).

3.1. Ecological Foundations of Fisheries Genomics

Fisheries genomics has evolved from isolated population genetics toward an integrative discipline linking molecular variation to ecological performance and habitat stability. Understanding how genetic diversity supports resilience is fundamental to predicting species persistence under environmental stress. Conceptual models of adaptive fisheries management now emphasize genomic diversity as a functional component of ecosystem robustness (Baltazar-Soares *et al.*, 2018). Ecological genomics thus serves as a bridge connecting genetic architecture, species interactions, and ecosystem functionality, facilitating informed conservation and sustainable resource utilization.

3.2. Genomic Signatures of Environmental Adaptation

Genomic signatures provide molecular evidence of how aquatic species adjust to fluctuating environmental conditions. Genetic determinants of thermal tolerance, osmoregulatory efficiency, and hypoxia resistance reveal adaptive processes driven by selection across heterogeneous habitats. Landscape genomics integrates spatial and environmental data to map adaptive loci and gene–environment associations, while environmental DNA (eDNA) enables non-invasive monitoring of community composition and biodiversity dynamics (Adams *et al.,* 2019). Functional gene networks identified through transcriptomic and comparative genomic analyses elucidate mechanisms of local adaptation and population differentiation essential for resilience forecasting.

3.3. Molecular Indicators of Ecosystem Health and Stress

Molecular biomarkers derived from transcriptomic and proteomic profiling have become powerful indicators of ecological status and anthropogenic stress. Expression patterns of stress-responsive genes, antioxidant enzymes, and heat-shock proteins reflect physiological responses to pollutants, temperature shifts, and nutrient fluctuations. eDNA-based biomonitoring expands these insights by capturing multispecies signals from environmental samples, offering a rapid and sensitive means of assessing species distribution and habitat quality. Multi-species genomic surveillance systems further enhance ecosystem diagnostics by integrating community-level molecular data into predictive ecological assessments (Gupta *et al.*, 2020).

3.4. Integrating Genomic Data into Ecosystem-Based Management (EBM)

Incorporating adaptive genetic information into ecosystem-based management frameworks strengthens fisheries governance by embedding evolutionary and ecological processes into decision-making. Genetic connectivity models inform ecosystem linkages and migration corridors, supporting habitat protection and sustainable exploitation. Cross-scale integration of ecological metrics and genomic datasets enables holistic management approaches that align population-level adaptation with ecosystem function, ensuring long-term sustainability amid environmental uncertainty (XU *et al.*, 2025).

3.5. Future Outlook, Toward Predictive and Climate-Responsive Fisheries Genomics

The convergence of ecological modeling, climate science, and genomics heralds a new era of predictive fisheries management. Genomic forecasting tools can anticipate species responses to temperature rise, ocean acidification, and habitat transformation, aiding proactive conservation and adaptive policy design. Coupling ecological simulations with genomic data enhances the capacity to model adaptive potential and ecosystem connectivity under climate variability. However, advancing this integration demands harmonized data infrastructures, standardized bioinformatics pipelines, and interdisciplinary frameworks to translate molecular insights into ecosystem-scale resilience strategies (Waldvogel *et al.*, 2020).

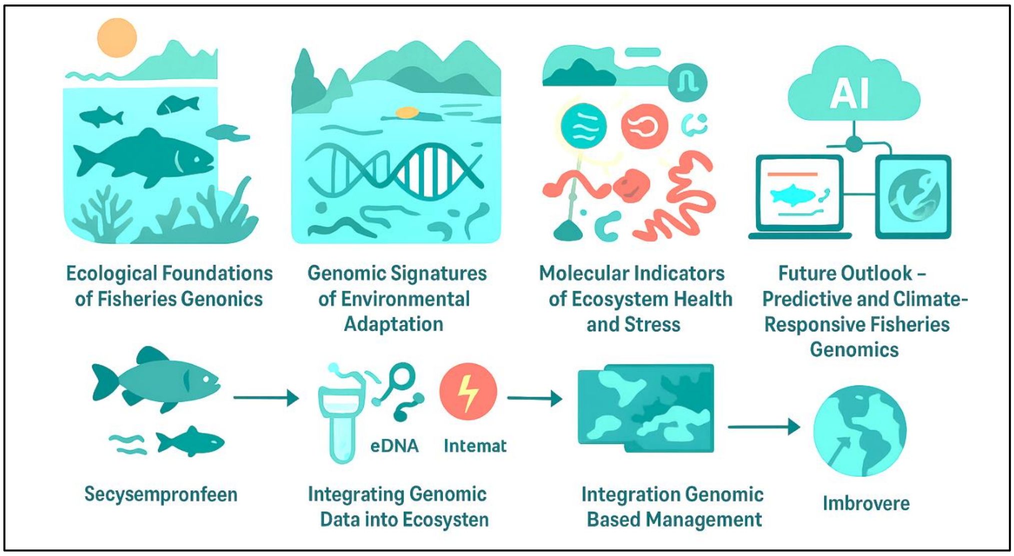


Fig. 1: Decoding ecosystem resilience through ecological genomics linking genetic adaptation with environmental sustainability in fisheries. From genes to ecosystems: integrating molecular insights for adaptive and climate-resilient fisheries management

4. Conservation Genetics and Biodiversity Preservation in Fisheries

This framework emphasizes the integration of molecular genetics into fisheries conservation to safeguard biodiversity, maintain evolutionary potential, and promote long-term ecological balance. By linking genetic data with management strategies, conservation genomics provides a foundation for sustaining fish populations amid global pressures such as overexploitation, habitat degradation, and climate change (Bernos et al.,2020).

4.1. Genetic Dimensions of Fisheries Sustainability

Genetic diversity underpins the adaptive capacity, stability, and productivity of fish populations. Maintaining allelic variation ensures resilience against environmental fluctuations and disease outbreaks, securing the evolutionary potential required for future adaptability. However, anthropogenic stressors such as overfishing, pollution, habitat fragmentation, and interspecific hybridization erode genetic integrity, leading to population bottlenecks and reduced fitness. Conservation genomics offers a comprehensive approach to monitor, restore, and preserve genetic variability, reinforcing the biological basis of sustainable fisheries management (Pearse *et al.,* 2016).

4.2. Molecular Tools for Population and Stock Structure Analysis

Molecular techniques have revolutionized the assessment of population structure and stock delineation in aquatic systems. Mitochondrial DNA sequencing and microsatellite profiling provide insights into historical demography and maternal lineages, while genome-wide single-nucleotide polymorphism (SNP) analyses offer high-resolution differentiation of management units (You *et al.,* 2018). Integrating demographic parameters with genomic data enables precise evaluation of population connectivity, effective population size, and recruitment dynamics key elements in designing science-based conservation strategies and harvest regulations.

4.3. Monitoring Genetic Connectivity and Gene Flow

Understanding genetic connectivity is essential for preserving evolutionary processes and maintaining population viability. Genomic markers facilitate the mapping of migratory pathways, revealing metapopulation structures and gene flow across environmental gradients. Such information aids in delineating biologically meaningful conservation boundaries and optimizing the design of marine protected areas (MPAs) (Kirkman *et al.,* 2013). By aligning molecular evidence with spatial ecology, managers can enhance enforcement strategies and ensure that MPAs support both biodiversity conservation and fisheries replenishment.

4.4. Molecular Approaches to Endangered and Invasive Species Management

Genomic approaches are increasingly pivotal in restoring depleted populations and mitigating biological invasions. Genetic rescue and assisted gene flow can counteract inbreeding depression and restore adaptive potential in threatened species. Environmental DNA (eDNA) surveillance allows early detection of invasive organisms, enabling rapid response before ecological disruption occurs. Furthermore, genomic characterization supports reintroduction and recovery programs by identifying source populations with optimal genetic compatibility and adaptive traits, improving survival and establishment success (He *et al.,* 2016).

4.5. Policy and Ethical Dimensions of Conservation Genomics

The translation of genomic knowledge into fisheries governance demands coherent policy integration, ethical oversight, and equitable data management. Incorporating molecular evidence into international frameworks such as the Convention on Biological Diversity and regional fisheries agreements ensures that conservation measures reflect genetic sustainability. Emerging issues surrounding data sovereignty, benefit-sharing, and intellectual property rights necessitate transparent genomic governance (Bagley *et al.*, 2022). Moving forward, developing inclusive genomic databases, capacity-building initiatives, and standardized protocols will be vital for promoting fairness and long-term stewardship of aquatic genetic resources.

Table 1: Integrated overview of conservation genetics and biodiversity preservation in fisheries, highlighting molecular tools, their conservation applications, and policy implications for achieving long-term genetic sustainability and ecosystem resilience. This framework links genomic insights with management strategies to ensure adaptive capacity, population viability, and ethical stewardship of aquatic genetic resources

Section / Concept	Scientific Description	Key Genetic or Molecular Tools	Applications in Fisheries Conservation	Broader Ecological or Policy Implications
Genetic Dimensions of Fisheries Sustainability	Genetic diversity forms the foundation of population adaptability and resilience. High allelic richness ensures species can withstand environmental stressors, pathogens, and climate-induced shifts. Loss of genetic variation reduces evolutionary potential, leading to lower recruitment and population collapse.	Microsatellite markers, SNP genotyping, mitochondrial DNA analysis, RAD sequencing	Assessment of genetic variability, monitoring of inbreeding levels, identification of bottlenecked populations, and restoration planning	Supports ecosystem resilience, informs adaptive management strategies, and ensures sustainable exploitation of genetic resources
Molecular Tools for Population and Stock Structure Analysis	Molecular markers enable fine-scale differentiation among populations and reveal hidden structuring critical for defining management units. Genomic resolution enhances understanding of gene flow and recruitment dynamics.	Mitochondrial COI sequencing, microsatellites, genome-wide SNP arrays, ddRADseq, whole-genome resequencing	Delineation of stocks, reconstruction of historical demography, and detection of hybridization or introgression events	Enables science-based harvest quotas, improves traceability in fisheries, and prevents genetic homogenization
Monitoring Genetic Connectivity and Gene Flow	Gene flow maintains population cohesion and adaptive potential across geographic barriers. Understanding connectivity identifies sources and sinks within metapopulations and highlights the impact of anthropogenic fragmentation.	SNP genotyping, population assignment tests, landscape genomics, isolation-by-distance models	Mapping migratory corridors, identifying connectivity hotspots, and evaluating MPA effectiveness	Informs spatial management, enhances MPA design, and supports biodiversity corridors across ecological gradients
Molecular Approaches to Endangered and Invasive Species Management	Conservation genomics enables identification of genetically compatible populations for reintroduction, while eDNA facilitates non-invasive detection of invasive taxa. Genetic rescue techniques improve adaptive capacity of endangered populations.	Environmental DNA (eDNA), genomic sequencing, transcriptomic profiling, CRISPR-based diagnostics	Early detection of invasive species, genetic restoration of endangered populations, and assessment of adaptive gene flow	Strengthens proactive conservation measures, supports biosecurity protocols, and improves restoration success rates
Policy and Ethical Dimensions of	Integrating genetic data into fisheries policy ensures sustainability at the molecular level. Equitable	Open-access genomic databases, bioinformatics platforms, digital	Integration into international biodiversity treaties, development of	Promotes transparency, ensures equitable resource use, and

Section / Concept	Scientific Description	Key Genetic or Molecular Tools	Applications in Fisheries Conservation	Broader Ecological or Policy Implications
Conservation Genomics	genomic governance promotes fair data sharing and conservation accountability. Ethical frameworks are necessary for biobanking, data sovereignty, and benefit-sharing.	sequence information (DSI) systems	regional genomic observatories, and standardization of data management	aligns conservation goals with global sustainability agendas

5. Data-Driven Fisheries, Integrating Multi-Omics, Bioinformatics, and Artificial Intelligence

This framework represents a paradigm shift from conventional observation-based fisheries toward a data-driven, integrative, and predictive discipline. By merging molecular biology, computational science, and artificial intelligence, modern fisheries management is evolving into a digital ecosystem capable of processing complex biological, environmental, and socioeconomic data in real time. Such transformation empowers evidence-based decision-making, precision resource management, and long-term sustainability (Ogundeko-Olugbami *et al.,* 2025).

5.1. From Data Scarcity to Data Abundance in Fisheries Science

Fisheries research has transitioned from limited sampling and fragmented records to an era of massive data accumulation enabled by genomic sequencing, digital sensors, and global databases. The digital revolution in aquatic genomics allows researchers to decode entire genomes, transcriptomes, and metagenomes at unprecedented resolution. Integrating molecular insights with ecological, climatic, and socioeconomic information establishes a multidimensional understanding of fisheries systems. Big data infrastructures and distributed analytics frameworks now enable continuous monitoring, providing accurate, transparent, and timely assessments of fish stocks, ecosystem health, and market dynamics (Wang *et al.,* 2024).

5.2. Multi-Omics Integration for System-Level Understanding

Multi-omics integration has become central to understanding the complexity of aquatic life and its environmental interactions. Combining genomics, transcriptomics, proteomics, and metabolomics offers a holistic view of physiological function, adaptive mechanisms, and environmental stress responses. Network biology approaches reveal regulatory and metabolic pathways driving growth, reproduction, and resilience in aquatic species (Williams *et al.,* 2011). Coupling omics data with environmental parameters through dynamic modeling enhances the capacity to predict ecosystem responses and design adaptive management strategies grounded in molecular evidence.

5.3. Bioinformatics Pipelines and Computational Innovations

Rapid advances in computational biology have revolutionized the processing, storage, and interpretation of vast genomic datasets. Modern bioinformatics pipelines facilitate genome assembly, gene annotation, variant detection, and population structure analyses across diverse species. Cloud-based platforms allow collaborative management of global fisheries datasets, ensuring accessibility and scalability. Artificial intelligence and machine learning algorithms further enable predictive modeling of population trends, habitat suitability, and genetic adaptation under environmental variability, transforming raw data into actionable insights for policy and conservation (Ullah *et al.,* 2025).

5.4. Digital Fisheries Management Systems and Decision Support Tools

The integration of molecular and ecological data into digital decision-making systems marks a major leap toward precision fisheries management. Geographic information systems (GIS) and remote sensing technologies now incorporate genomic and environmental indicators to map population distributions, migration routes, and ecosystem risks. Real-time dashboards and predictive analytics platforms translate molecular signals into early-warning tools for stock depletion, disease outbreaks, and environmental anomalies. These innovations promote adaptive and proactive management, improving both ecological resilience and economic stability in fisheries sectors (Woods *et al.,* 2022).

5.5. The Future of Data-Driven Fisheries Governance

Sustainable digital fisheries governance requires interoperability, open-access data policies, and adherence to FAIR (Findable, Accessible, Interoperable, Reusable) principles. Building robust cyberinfrastructures will enhance global collaboration, linking genomic repositories, monitoring systems, and predictive models. However, the growing digitalization of fisheries data introduces new ethical and privacy challenges related to data ownership, sovereignty, and equitable access. Future governance must ensure transparency, inclusivity, and responsible innovation to realize the full potential of data-driven, AI-enabled fisheries management (Iyiola *et al.,* 2025).

6. Integrative Sustainability Models, Linking Genomic Science, Policy, and Socioeconomic Impact

This framework embodies the convergence of genomic innovation, sustainability science, and policy to reimagine fisheries as dynamic systems where molecular knowledge informs governance, social equity, and economic resilience. By aligning genomic discoveries with sustainability principles, integrative models enable a shift from resource exploitation toward adaptive, evidence-based stewardship of aquatic biodiversity.

6.1. Reframing Sustainability through Genomic Innovation

Fisheries sustainability is being reconceptualized through the lens of molecular science, where genetic diversity is recognized as a cornerstone of ecological stability and food security. The genomic era allows the assessment of evolutionary potential and adaptive capacity within exploited populations, providing metrics for resilience under environmental stress. Systems thinking in fisheries genomics integrates biological, ecological, and socioeconomic dimensions, creating feedback loops that link genetic health to ecosystem productivity and human wellbeing (Goodson *et al.*, 2015). This multidimensional approach reframes sustainability from static management to dynamic, genomically informed adaptation.

6.2. Translational Genomics for Management and Policy

The transition from laboratory research to governance applications marks a pivotal step in implementing genomic insights within fisheries management. Molecular evidence now supports certification, labeling, and trade regulations by verifying species authenticity and traceability, ensuring compliance with sustainability standards. Genomic datasets inform policy decisions related to stock assessments, conservation prioritization, and trade monitoring, strengthening the scientific foundation of international fisheries agreements. This translation of molecular knowledge into actionable governance enables precision management aligned with ecological integrity and economic transparency (Bernos *et al.*, 2020).

6.3. Socioeconomic and Ethical Dimensions of Genomic Fisheries

Integrating genomics into fisheries must consider the socioeconomic realities of diverse communities. For small-scale and artisanal fisheries, access to genomic technologies can enhance management but also risk exclusion without equitable frameworks. Ensuring technology transfer, capacity building, and participatory innovation are essential for fair benefit-sharing. Ethical stewardship grounded in biodiversity justice recognizes the rights of indigenous and coastal populations as custodians of aquatic genetic resources (Parsons *et al.,* 2021). Responsible data governance and inclusive policy design safeguard both cultural heritage and biological diversity in the genomic age.

6.4. Cross-Sectoral Integration, Ecology, Technology, and Economy

Sustainable fisheries now intersect with broader blue economy initiatives that unify conservation, biotechnology, and circular bioeconomy concepts. Integrating aquaculture genomics with wild fish management supports genetic balance between cultivated and natural stocks. Applying genomic insights to waste valorization, biomaterial production, and ecosystem restoration advances sustainable innovation across aquatic sectors (Carmona Marques *et al.,* 2025). This cross-sectoral integration strengthens economic viability while reducing environmental impact, positioning genomic science as a driver of blue biotechnology and resource circularity.

6.5. Pathways Toward Future-Ready Sustainable Fisheries

The future of sustainable fisheries lies in establishing interdisciplinary genomic policy networks that connect scientists, managers, and stakeholders under shared sustainability goals. Translational research must prioritize adaptive management tools, climate-resilient genetic monitoring systems, and globally harmonized standards for genomic data exchange. Developing sustainability metrics that integrate genomic, ecological, and socioeconomic indicators will guide international frameworks toward accountable, resilient, and future-ready fisheries systems (Ramanathan *et al.,* 2021).

CONCLUSION

The integration of molecular and genomic tools has revolutionized the landscape of fisheries management by providing precise, data-driven insights into species identification, population dynamics, and ecosystem health. Techniques such as DNA barcoding, eDNA monitoring, and next-generation sequencing have enabled rapid, non-invasive, and comprehensive assessments of aquatic biodiversity, supporting evidence-based decision-making. Genomic approaches further facilitate the identification of adaptive traits, stock differentiation, and resilience potential, essential for sustaining fish populations under environmental stressors and climate change. Collectively, these innovations are transforming fisheries from conventional exploitation models toward precision-based, conservation-oriented management. The continued fusion of genomics, bioinformatics, and environmental monitoring will be pivotal in developing predictive frameworks, promoting traceability, and achieving long-term ecological and economic sustainability in global fisheries.

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