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A Scientific Journal of Kenya Marine and Fisheries Research Institute

KMFRI

Editorial

Editorial: Kenya Aquatica Journal Vol 10(1) – A Showcase of KMFRI's Pioneering Research in Freshwater Ecosystems

The latest edition of Kenya Aquatica Journal, Vol 10(1) showcases pioneering research by KMFRI scientists on Kenya's freshwater ecosystems. This edition, supported by KMFRI and WIOMSA, covers ecological, socio-economic, and environmental challenges, providing valuable insights into sustainable management practices.

One notable study investigates disease surveillance and antimicrobial resistance in fish from lacustrine caged farms, emphasizing responsible antibiotic use to maintain fish health. Another study explores the impact of organochlorine pesticides on macroinvertebrates in Lake ecosystems, advocating for Rhagovelia spp. as a bioindicator for pesticide monitoring across food webs.

Research on Lake Baringo's small-scale fishery assesses the catch and effort composition, stressing the need for regulatory enforcement to avoid overfishing and advocating for capacity building among stakeholders for sustainable management. Additionally, a study on wild fish kills in Lake Victoria focuses on eutrophication and pollution, recommending integrated watershed management to protect the lake's fisheries and local livelihoods.

A comprehensive study on Lake Elementaita – one of Kanya's flamingos' sanctuaries, combines water quality, fisheries studies, and community surveys, calling for integrated watershed management, conservation, and sustainable agriculture. Research on fisheries co-management in Lake Baringo highlights the importance of local community involvement and sustained achievements in ecosystem management, despite challenges in law enforcement.

An article on the socio-economic dynamics of Lake Victoria proposes establishing a regulatory framework incorporating citizen science to manage the lake's resources for long-term sustainability. Addressing plastic pollution in Lake Turkana, a study recommends waste management solutions, public awareness, and better enforcement of regulations to tackle the issue.

The journal also features research on antimicrobial resistance (AMR), with a review exploring Kenya's aquatic biodiversity for potential novel antimicrobial agents. A genetic research study evaluates freshwater fish populations, identifying gaps and proposing future directions for conservation and management.

Lastly, the journal presents an evaluation of fish market dynamics in Lake Naivasha, recommending infrastructure development like fish markets and hatcheries to support the region's fishery sector.

This edition of Kenya Aquatica Journal provides crucial insights into Kenya's freshwater ecosystems, covering a wide range of research on sustainable management, environmental challenges, and the socio-economic factors influencing aquatic resources. The research highlights KMFRI's ongoing contributions to understanding and addressing these issues, fostering a deeper understanding of Kenya's aquatic biodiversity.

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About
Kenya Aquatica

Kenya Aquatica is the Scientific Journal of the Kenya Marine and Fisheries Research Institute (KMFRI). The aim of the Journal is to provide an avenue for KMFRI researchers and partners to disseminate knowledge generated from research conducted in the aquatic environment of Kenya and resources therein and adjacent to it. This is in line with KMFRI's mandate to undertake research in "marine and freshwater fisheries, aquaculture, environmental and ecological studies, and marine research including chemical and physical oceanography", in order to provide sci entific data and information for sustainable development of the Blue Economy.

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Featured front cover picture: Researcher sampling surface plankton in the Kerio River inlet to Lake Turkana. (Photo credit: Mr. John Malala)

Featured back cover picture: Chair of KMFRI Board of Management Amb. Dr. Wenwa Akinyi Odinga Oranga (seated middle), on her right, Ag. KMFRI CEO Dr. James Mwaluma, flanked by KMFRI Heads of Sections: Front (L-R) Dr. Victoria Tarus, Ms Caroline Mukiira, Dr. Jacob Ochiewo, Dr. Irene Githaiga, Mr. Abraham Kagwima. Back (L—R) Mr. Paul Waluba, Ms Jane Kiguta, Dr. Gladys Okemwa, Dr. Eric Okuku, Dr. Joseph Kamau, Mr. Isaac Kojo, Ms Joan Karanja, Mr. Milton Apollo. (Photo credit KMFRI)
Research Vessel MV Mtafiti in the background

Genetic research: Global and Kenyan contextual comprehensive review of freshwater fish populations

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Abstract

Capture fisheries and aquaculture provide more than 15% of the animal protein intake for humans, highlighting their vital role in reducing poverty and promoting sustainable global development by aligning with the 2030 Agenda for Sustainable Development. Genetic studies play a crucial role in tracking evolutionary changes and assessing the genetic health of endangered fish populations. As of August 2022, the National Center for Biotechnology Information (NCBI) database contained a total of 865 fish genomes. With over 15,000 known species of freshwater fish, scientists are continuously investigating genetic variation to enhance biodiversity understanding, stock management, and conservation strategies for endangered species. Freshwater fish populations often evolve in isolation, influenced by geographic barriers and environmental factors like temperature, pH, and food availability, which can result in significant genetic differentiation. Genetic research in Kenya has focused on various aspects, such as genetic divergence and adaptation, species conservation, and population genetics. This review examines the current status of genetic research in freshwater fishes, evaluates the necessary infrastructure to support further studies, summarizes the areas already explored, identifies existing gaps, and proposes directions for future genetic research both globally and within the Kenyan context.

Keywords: freshwater fish genetics, environmental stressors, population genetics, next-generation sequencing

Introduction

Fish populations in freshwater ecosystems play a critical role in maintaining ecological balance through nutrient cycling and serving as integral components of aquatic food webs (Villéger *et al.,* 2017). They also influence the overall health and stability of aquatic habitats by helping regulate populations of other organisms (Lapointe *et al.,* 2014). Adaptations to these environments are reflected in both physiological and behavioral mechanisms that enhance survival in freshwater habitats (Blewett *et al.,* 2022). Furthermore, a significant proportion of freshwater fishes are endemic to specific ecosystems, making them especially vulnerable to environmental changes and anthropogenic pressures (Masoumi *et al.,* 2024). The combined threats of habitat degradation, pollution, and the introduction of invasive species, has made conservation efforts imperative (De Santis *et al.,* 2023).

Genetic studies not only help track evolutionary changes but also allow for the identification of cryptic species, the detection of inbreeding, and the assessment of genetic health in endangered populations (Theissinger *et al.,* 2023). Genetic techniques have been utilized to estimate effective population sizes, determine species and evolutionary significant units (ESUs), and assess molecular variation in endangered aquatic species of the desert Southwest, providing critical conservation insights (Willi *et al.,* 2022).

Recent research has revealed significant genetic divergence in species like *Sarcocheilichthys parvus*, with genetic isolation resulting in the development of distinct lineages and sub-lineages shaped by landscape evolution (Li *et al.,* 2023). Additionally, paleo-drainage connections, which historically linked water courses, have played a key role in shaping the genetic structure and population dynamics of these fish (Bruyn *et al.,* 2013). In the case of *Oreochromis mossambicus*, a species facing threats due to human activities such as overfishing and water management practices, genetic research has shown that population differentiation and reduced genetic diversity are key challenges for its survival (Mashaphu *et al.,* 2024). Understanding the genetic variability of species like *O. mossambicus* is essential for developing conservation strategies that promote genetic resilience.

In Kenya, freshwater ecosystems such as the Nile Basin, Lake Victoria, Tana River and Lake Turkana support a diverse array of fish species, many of which are crucial for the livelihoods of local communities (Nyingi *et al.,* 2013). However, these ecosystems are facing significant increasing threats, including overfishing, habitat destruction, and pollution (Muthoka *et al.,* 2024).

Genetic research in Kenya has focused on the population structure, species identification, and the impact of human activities on freshwater fish populations (Barasa *et al.,* 2014). For instance, genetic studies of the Lake Victoria haplochromine cichlids have revealed significant genetic differentiation, with species being genetically monophyletic across their geographic ranges (Nakamura *et al.,* 2021).

The genetic tools available today offer valuable insights into species differentiation, population dynamics, and the impact of environmental changes on freshwater fish populations (Gebremedhin *et al.,* 2021). As freshwater ecosystems continue to face increasing threats from human activities, the need for genetic research to inform conservation efforts is more important than ever (Albert *et al.,* 2021). Ensuring the long-term viability of freshwater fish populations requires not only an understanding of their genetic makeup but also the development of strategies that protect genetic diversity and restore natural habitats (Mashaphu *et al.,* 2024).

This review highlights the importance of genetic research in understanding the evolution, population dynamics, and adaptation of freshwater fish populations worldwide, with an emphasis on conserving genetic diversity for effective conservation. In Kenya, genetic studies have shed light on species differentiation, the impact of human activities, and the necessity of sustainable management practices to preserve freshwater biodiversity in key ecosystems like Lake Victoria and Lake Turkana.

Discussion

Overview of genetic research on freshwater fish populations

Genetic research on freshwater fish globally has provided crucial insights into species evolution, adaptation to various environmental stressors, and the dynamics of genetic diversity within fragmented ecosystems (Martinez *et al.,* 2018). Kenya's diverse freshwater ecosystems - ranging from the Great Rift Valley lakes to the rivers and wetlands - offer a unique setting for the study of freshwater fish genetics (Nyingi *et al.*, 2013). Lake Victoria, one of the world's largest freshwater lakes, hosts an extraordinary diversity of fish species, including *Mormyrus kannume*, *Protopterus aethiopicus*, various *Haplochromine* species, *Brycinus* spp., *Rastrineobola argentea* (commonly known as *omena*), *Labeo victorianus*, *Enteromius species*., and *Synodontis victorianus* (Vanina *et al.,* 2019).

Genetic divergence and adaptation of freshwater fishes

Freshwater fish populations often evolve in isolation due to geographic barriers like rivers, lakes, and mountains (van der Sleen and Albert, 2022). Genetic studies, especially those using molecular markers like mitochondrial DNA, microsatellites, and next-generation sequencing, provide insights into how populations diverge over time and adapt to local conditions (Wenne, 2023). For example, studies have shown how populations of the same species living in different watersheds can develop significant genetic differentiation due to variations in environmental factors, such as water temperature, pH, and food availability (Liao *et al.,* 2024).

Kenya's freshwater systems host several endemic fish species, particularly in the Rift Valley lakes like Lake Victoria, Lake Nakuru, and Lake Baringo (Omondi *et al.,* 2018). Genetic studies on these endemic species provide valuable insights into how they evolved in isolated environments and the genetic factors that enable their adaptation to unique conditions (Vidal and García-Marín, 2011). Research on the genetics of the Nile tilapia (*Oreochromis niloticus*) and the various cichlid species in Lake Victoria has shown significant genetic divergence between populations in different lakes and rivers, which are essential for developing conservation strategies (Tibihika *et al.,* 2020) (Fig. 1).

Figure 1. Nile tilapia *(Oreochromis niloticus*) from the upper River Nyando, Kenya (Coordinates: 0°13'17.7"S 35°15'27.5"E) (Source: Author)**.**

Figure 2. Endangered cyprinid fish species *Labeo victorianus* from the lower River Nyando, Kenya (Coordinates: 0°10'28.3"S, 34°55'34.9"E) (Source: Author)**.**

Figure 3. *Barbus altinialis* from the upper River Nyando, Kenya (Source: Author)**.**

Genetic research helps in identifying critical populations that need protection and in understanding the impacts of invasive species on native fish populations, like the introduction of the Nile perch (*Lates niloticus*) into Lake Victoria, which has severely disrupted the native fish communities (Nyamweya *et al.,* 2023).

Impact of human activities on freshwater fishes

Human-induced activities, such as dam construction, water pollution, overfishing, and the introduction of invasive species, have profound impacts on freshwater fish genetics (Chen *et al.,* 2023). These activities can lead to genetic bottlenecks, reduced genetic diversity, and the loss of unique genetic traits critical for fish species adaptation (Martinez *et al.,* 2018). In Kenya, genetic studies have been instrumental in assessing the extent of population of isolation and fragmentation, shedding light on how these factors affect genetic diversity and adaptability (Sadler *et al.,* 2023).

Genomic tools for understanding speciation processes in freshwater fish

Next-generation sequencing (NGS) technologies have significantly advanced our understanding of speciation processes in freshwater fish

Figure 4. *Clarias gariepinus* (African catfish) of Lake Victoria Basin, Kenya (Source: Okechi *et al.,* 2004)**.**

(Mehinto *et al.,* 2012). By examining large genetic datasets, researchers can better distinguish between genetic differentiation driven by speciation versus spatial population structure (Hutama *et al.,* 2017). As Kenya's freshwater fisheries support the livelihoods of millions of people, genetic studies are also applied to improve fishery management practices (Obiero *et al.,* 2023). Genetic monitoring helps track fish populations, ensuring sustainable harvests and identifying the impacts of fishing on population structure (Seljestad *et al.,* 2024). Additionally, the genetic diversity of species like *Clarias gariepinus* (African catfish) (Figure 4) and *Cyprinus carpio* (common carp) in Kenyan rivers is crucial in ensuring healthy populations for aquaculture (Emam *et al.,* 2024).

Current status of genetic research in freshwater fishes

Genetic research on freshwater fish populations has advanced significantly globally, driven by advances in molecular techniques and a growing awareness of the importance of genetic diversity for conservation and sustainable management (Martinez *et al.,* 2018). Genetic research in freshwater fish in Kenya is still in its developmental stages compared to more established research fields (Obiero *et al.,* 2023). However, there have been notable efforts in the study of native fish species, population genetics, and the application of genetic tools to aquaculture and conservation (Sanda *et al.,* 2024). The Kenya Marine and Fisheries Research Institute (KMFRI) has made diverse contributions to genetic research on freshwater fish in Kenya, encompassing both basic and applied genetic studies (Obiero *et al.,* 2023).

Biodiversity and freshwater fish species delimitation

Advancements in molecular genetics, particularly DNA barcoding and genomic sequencing, have greatly enhanced our ability to differentiate closely related species and comprehend their genetic divergence (Ali *et al.,* 2020). These methodologies are also instrumental in resolving instances of cryptic speciation, where species that appear morphologically similar are genetically distinct (Fišer *et al.,* 2018). Genetic tools, such as mitochondrial DNA sequencing and microsatellites, have been used to assess genetic diversity within species such as native tilapiine populations and the endemic species in Lake Victoria (Tesfaye *et al.,* 2021).

One of the key areas of genetic research in Kenya has been the identification and classification of freshwater fish species (Barasa *et al.,* 2014). KMFRI has contributed to the identification and classification of native and introduced freshwater fish species in Kenyan water bodies (Obiero *et al.,* 2023). Studies have focused on understanding the genetic diversity within major fish species in Kenyan waters, such as the catfish species and native cichlids (Mwaura *et al.,* 2023). Mitochondrial DNA markers have been frequently used to examine phylogenetic relationships and to identify cryptic species, which are common in Kenyan freshwater fish populations (Schmidt *et al.,* 2017). However, a comprehensive genetic inventory of the entire fish fauna in Kenyan freshwater ecosystems is still lacking (Syanya *et al.,* 2023).

Population genetics and conservation within freshwater fishes

Population genetics focuses on the genetic structure, diversity, and evolutionary processes within fish populations, which are essential for assessing their health, adaptability, and long-term viability (Hohenlohe *et al.,* 2021). The genetic structure of fish populations in Kenya's freshwater systems, such as Lake Victoria, Lake Turkana, and the Tana River, has been an area of active research (Ndiwa *et al.,* 2014). Studies have shown significant genetic differentiation among populations of Nile tilapia, which has implications for their conservation and management (Geletu *et al.,* 2025). Research on the genetic consequences of overfishing and the introduction of non-native species has also provided insights into the impact of human activities on genetic diversity (Pukk *et al.,* 2013). Population genetics studies have revealed the impact of overfishing, habitat degradation, and introduction of non-native species on the genetic diversity of fish populations (Martinez *et al.,* 2018).

Aquaculture genetics and freshwater fisheries management

Studies have explored the genetic improvement of farmed species such as Nile tilapia and the introduction of genetically improved farmed fish strains (Barría *et al.,* 2023). However, research on the genetic impacts of farmed fish escapees and their interaction with wild populations is still limited (San Román *et al.,* 2025). Studies on the genetic improvement of tilapia strains for increased disease resistance, growth rates, and tolerance to environmental stressors have been conducted (Abaho *et al.,* 2025).

Tilapia farming, is a major sector in the economy (Emam *et al.,* 2024) and genetic research in this area has focused on improving the productivity and sustainability of fish farming (Munguti *et al.,* 2022). Scientists have also been involved in evaluating the genetic consequences of farmed fish escaping into wild populations, ensuring that the genetic integrity of wild fish populations is maintained (Diserud *et al.,* 2022).

Ecological and evolutionary studies on freshwater fish populations

Ecologically, freshwater fish play a key role in aquatic ecosystems, influencing trophic dynamics, nutrient cycling, and the structure of biological communities. These studies examine the relationships between fish populations and their habitats, including factors such as water quality, habitat availability, and competition with other species (Mamun and An, 2022).

Genetic research in Kenya has focused on understanding how freshwater fish populations adapt to these environmental stressors (Sanda *et al.,* 2024). For instance, studies have looked into how populations of Nile tilapia in different lakes exhibit genetic adaptations to varying salinity levels and environmental conditions (Ndiwa *et al.,* 2016). KMFRI has examined how freshwater fish populations adapt to varying environmental conditions, such as changes in water quality, temperature, and habitat structure (Oyugi *et al.,* 2014). These studies have focused on understanding the genetic basis of adaptive traits, which is critical for the sustainable management of fisheries in the face of climate change and pollution (Muringai *et al.,* 2022).

Infrastructure needs for genetic research in freshwater fisheries

Laboratory facilities for freshwater fisheries genetic research

The global genetic research is on understanding the genetic structure and diversity within freshwater fish populations (Manel *et al.,* 2020). With the use of molecular markers, such as mitochondrial DNA, microsatellites, and more recently NGS researchers have been able to reveal population dynamics, species differentiation, and the mechanisms of adaptation in freshwater environments (Wenne, 2023). These studies have shed light on how fish populations evolve in isolation due to geographic barriers like rivers, lakes, and mountains (van der Sleen and Albert, 2022).

To advance genetic research on freshwater fishes in Kenya, the development of specialized molecular biology laboratories is essential (Amoussou *et al.,* 2019). Currently, many Kenyan universities and research institutions lack the state-of-the-art facilities required for high-throughput fisheries genetic analysis. Laboratory spaces equipped for DNA extraction, PCR amplification, and DNA sequencing are necessary (Nguinkal *et al.,* 2024).

Freshwater fisheries genetic analysis equipment

Environmental monitoring equipment is fundamental to genetic research, providing critical context for fish genetic data by assessing habitat conditions (Yang *et al.,* 2024). Water quality monitoring systems measure key environmental variables such as temperature, pH, and pollutants, which can influence fish genetics and adaptation (Zhang *et al.,* 2024). Global Positioning System (GPS) devices are also used to map the locations of sampled fish populations, helping researchers correlate genetic data with specific environmental conditions or habitat types (Hebblewhite and Haydon, 2010).

Genetic research on freshwater fish relies on a diverse range of equipment at every stage of the process, from field sampling to advanced sequencing and data analysis (Cermakova *et al.,* 2023). Each tool plays an essential role in generating accurate genetic data, which is increasingly vital as freshwater fish populations face growing threats from habitat destruction, climate change, and overfishing (Bănăduc *et al.,* 2022). Advanced equipment not only informs conservation strategies but also supports sustainable management practices and the preservation of biodiversity in these crucial ecosystems (Niesenbaum, 2019). The journey of genetic research begins in the field, where sampling equipment such as nets, traps, and fishing gear are used to capture freshwater fish from their natural habitats (Yao *et al.,* 2022). Once the fish are collected, biological samples, such as fin clips, scales, or blood, are carefully stored in preservative solutions or frozen to prevent degradation. Proper field sampling is the first step in obtaining reliable data for further analysis (Oosting *et al.,* 2020).

Once the fish samples are collected, DNA extraction is the next critical step. Specialized equipment, such as centrifuges for isolating DNA, microcentrifuge tubes, and pipettes, are used to handle small volumes of genetic material (Formosa *et al.,* 2010). High-quality DNA extraction kits or automated DNA extraction systems are essential for ensuring a high yield of intact fish DNA, which is crucial for successful genetic analysis (Lutz *et al.,* 2023). Polymerase Chain Reaction (PCR) is a technique frequently employed to amplify specific DNA regions, such as mitochondrial DNA or microsatellites. Essential PCR equipment includes thermal cyclers or PCR machines, which regulate the heating and cooling cycles needed for DNA amplification. After amplification, gel electrophoresis systems are used to analyze the PCR products and verify the success of the amplification process (Ghannam and Varacallo, 2018).

NGS has revolutionized genetic research, enabling large-scale, high-throughput fish DNA sequencing at an unprecedented. NGS sequencers, such as those from Pacific Biosciences, Illumina or Oxford Nanopore, are capable of generating millions of DNA reads in a single run, allowing researchers to explore entire genomes or targeted gene regions with great precision (Satam *et al.,* 2023). Alongside these sequencers, bioinformatics tools and software are indispensable for managing the vast amounts of data generated, including aligning sequences, detecting genetic variants, and conducting fish population genetic analyses (Casas and Saborido, 2023). Genotyping and molecular marker analysis also play an important role in studying fish genetic variation. Automated DNA sequencers help determine the nucleotide sequence of specific genetic markers, while fragment analyzers quantify and visualize fish genetic patterns (Dudu *et al.,* 2015). Additionally, SNP genotyping platforms allow for in-depth analysis of genetic variation across thousands of loci, offering detailed insights into fish population genetics and evolutionary processes (Taillebois *et al.,* 2021).

As the amount of data produced by genetic research grows, bioinformatics tools and data storage systems become indispensable

(Saparov and Zech, 2025). High-performance computers and servers are essential for processing large genomic datasets, and secure data storage systems, such as cloud storage or local servers, ensure the integrity and accessibility of genetic data (Shih *et al.,* 2023). Bioinformatics software, such as STRUCTURE or PLINK, facilitates fish population genetic analyses and the visualization of genetic relationships (Solovieva and Sakai, 2023). In some cases, researchers may need to observe specific physical traits or genetic markers in fish tissues (Cuéllar *et al.,* 2016). This requires equipment such as microscopes for examining cellular structures and fluorescence imaging systems for visualizing genetic markers tagged with fluorescent dyes. These tools are particularly useful when studying gene expression or tracking fish genetic changes at the cellular level (Pradhan *et al.,* 2023).

Benchmarking and research capacity on freshwater fish populations

Global benchmarking of fisheries research standards

Benchmarking is essential for aligning fisheries research with international conservation goals, such as the United Nations Sustainable Development Goals (SDGs) and agreements such as the Convention on Biological Diversity (Stratoudakis *et al.,* 2015). It supports the development of internationally recognized frameworks for assessing fisheries sustainability, ensuring that research contributes to the conservation and sustainable use of aquatic resources (Savari *et al.,* 2024).

Kenya's research efforts in freshwater fish genetics are relatively nascent compared to global leaders in the field, such as the United States, Canada, and European countries *(Basiita et al.,* 2018). These countries have well-established research infrastructures and genetic databases for fish species, which Kenya can look to as benchmarks. For example, research institutions such as the Fish Genetics and Breeding Program in Canada have pioneered genetic improvement programs for aquaculture, which can serve as a model for Kenya (Houston *et al.,* 2022).

Fisheries genetic technology capacity in low-resource regions

While there has been substantial fish genetic technology progress in well-resourced regions, many countries in Asia, Africa, and Latin America still face significant capacity gaps. These gaps include limited access to state-of-the-art equipment, underdeveloped research infrastructures, and a lack of trained personnel (Obiero *et al.,* 2019). Capacity-building initiatives, including funding for infrastructure and partnerships with international institutions, are critical to bridging these gaps. While Kenya has made strides in the field of fisheries research, the country faces significant limitations in research infrastructure and resources. Institutions such as the KMFRI and the University of Nairobi have made important contributions to fish genetics research, but there is still a shortage of advanced sequencing facilities and bioinformatics tools (Munguti *et al.,* 2023). Limited funding for research projects further exacerbates this gap. Nevertheless, KMFRI's research output has contributed valuable insights into the genetic diversity of freshwater fish species, and with increased investment, the institute can become a leading force in genetic research for freshwater biodiversity and aquaculture in the region (Aloo *et al.,* 2017).

Fish genetic research - current status and way forward

Genetic research on freshwater fish populations has made significant strides globally, contributing to our understanding of biodiversity, evolution, adaptation, and the impacts of human activities on these vital ecosystems. However, despite the advances, there are still gaps in knowledge and areas where research is limited (De Santis *et al.,* 2023) .

In Kenya, genetic research on freshwater fish populations has made considerable progress, particularly due to the country's rich and diverse aquatic ecosystems, which include lakes, rivers, and wetlands. However, despite these advancements, significant gaps still remain, and more research is needed to fully understand the genetic dynamics of freshwater fish populations in Kenya (Masese *et al.,* 2020).

Completed research areas on freshwater fisheries genetic research

Understanding fish population structure and genetic divergence

Genetic research on freshwater fish has primarily focused on analyzing population structure across various aquatic habitats (Martinez *et al.,* 2018). Researchers have used molecular markers such as mitochondrial DNA, microsatellites, and more recently, NGS, to assess how populations are genetically differentiated across rivers, lakes, and other freshwater systems (Wenne, 2023). Studies have demonstrated that geographic isolation, such as barriers created by dams or natural features, can lead to significant fish genetic divergence (Kobayashi *et al.,* 2024). For instance, research on cichlids in African lakes has shed light on how these populations adapt to different environmental conditions, leading to speciation (Takahashi and Koblmüller, 2011).

Kenya's freshwater ecosystems, particularly in the Rift Valley and Lake Victoria, are home to a number of endemic fish species, many of which face threats from habitat loss, pollution, and overfishing. Genetic research has been conducted to understand the genetic structure and diversity of these species. For example, studies on the genetics of cichlid species in Lake Victoria and other Rift Valley lakes have provided valuable insights into their evolutionary history, population structure, and genetic divergence (Takeda *et al.,* 2013). The tilapiine species has also been extensively studied to understand population genetics and adaptability across different lakes in Kenya (Yongo *et al.,* 2021).

Freshwater fisheries genetic adaptation to environmental stressors

A substantial body of work has explored how freshwater fish populations adapt to environmental stressors such as pollution, temperature changes, and salinity fluctuations (Agarwal *et al.,* 2024). These studies have highlighted the role of genetic variation in enabling fish populations to cope with altered environmental conditions. Examples include genetic adaptations to high levels of pollutants, like heavy metals, and thermal adaptations in species living in warmer waters. This research has been key to understanding the mechanisms of survival in the face of climate change (Hamilton *et al.,* 2017).

Fisheries conservation and management

Genetic research has played a crucial role in conservation efforts for endangered freshwater fish species. Identifying genetically distinct populations and understanding their genetic diversity has helped prioritize conservation efforts (Kim *et al.,* 2023). For instance, studies on the fish genetic health of populations of species such as the Atlantic have provided important data for designing conservation strategies (Sanda *et al.,* 2024). Moreover, the impact of invasive species, like the Nile perch in Lake Victoria, has been studied to understand how they affect the genetic structure of native fish populations (Mwanja *et al.,* 2012).

Genetic research has played a crucial role in the conservation of endangered species, especially those affected by overfishing, invasive species, and environmental degradation (Hedrick and Hurt, 2012). Research has helped identify genetically distinct populations, and genetic diversity studies have been used to design conservation strategies to prevent the loss of fish genetic material through inbreeding (Robledo *et al.,* 2024).

Use of genomic tools for freshwater aquaculture

The application of genetic research in aquaculture has been significant, particularly in the breeding of freshwater fish for sustainable farming. Research on improving traits such as growth rate, disease resistance, and environmental tolerance through genetic selection has been widely conducted (Eknath and Hulata, 2009). This research has helped improve aquaculture productivity and sustainability, benefiting economies and food security globally.

In Kenya, aquaculture, particularly Nile tilapia farming, plays a significant role in food security and economic development (Munguti *et al.,* 2022). Genetic research has been applied to improve fish farming practices by studying the genetic diversity of farmed species. Research has also focused on breeding programs aimed at enhancing disease resistance, growth rates, and tolerance to environmental stressors (Gjedrem *et al.,* 2012). The KMFRI has been actively involved in studies that assess the genetic health of farmed tilapia populations, contributing to the sustainability and productivity of the aquaculture industry (Abwao *et al.,* 2023).

Several studies have been conducted on the population genetics of key fish species such as Nile tilapia, catfish, and native cichlids across Kenya's freshwater systems (Tibihika *et al.,* 2020). These studies have identified genetic differentiation among populations in different lakes and rivers, which is important for managing fish stocks and preventing overfishing. These genetic insights are essential for creating effective management policies to protect fish populations in the face of environmental pressures and human activities (Sadler *et al.,* 2023).

Next-Generation Sequencing (NGS) and Genome-Wide Studies on freshwater fish

The advent of NGS technologies has been transformative for genetic research on freshwater fish. NGS has enabled large-scale, high-throughput sequencing of genomes, allowing researchers to examine entire genomes or specific genetic regions with unprecedented precision (Satam *et al.,* 2023). This has advanced our understanding of species differentiation, gene flow, and evolutionary processes. Several freshwater fish species' complete or partial genomes have been sequenced, providing valuable information for both evolutionary biology and conservation (Yang *et al.,* 2020).

One of the key areas of research in Kenya has been the use of genetic tools for species identification and biodiversity assessment. Molecular markers like mitochondrial DNA and microsatellites have been utilized to assess the genetic diversity of fish populations in Kenya's freshwater ecosystems (Ahmed *et al.,* 2023). These studies have been crucial in identifying cryptic and freshwater fish species and in better understanding the distribution of genetic variation among native and introduced species (Arisuryanti *et al.,* 2019).

Unexplored research areas on fisheries genetic research

Comprehensive global fish genetic databases

While there have been significant studies on specific species, there is still no comprehensive, globally accessible database of genetic information for freshwater fish populations (Brosse *et al.,* 2013). Many freshwater fish species, especially those in under-researched regions, lack detailed genetic data. A global repository could help researchers and conservationists track genetic diversity, identify at-risk populations, and inform conservation management on a larger scale (Obiero *et al.,* 2023).

Despite the progress, there is still a lack of a comprehensive genetic inventory of the entire fish fauna in Kenya's freshwater ecosystems (Hickley *et al.,* 2015). While some species, especially commercially important ones like Nile tilapia, have been extensively studied, many species, particularly those in less-explored regions or with less economic significance, remain understudied (Tibihika *et al.,* 2023). A complete genetic inventory would help assess the overall biodiversity of Kenya's freshwater systems and aid in identifying species that are at risk of extinction due to genetic erosion or environmental factors (Ruppert *et al.,* 2019).

Long-term studies on fisheries genetic effects of climate change

While there have been studies on the immediate genetic impacts of environmental stressors, long-term studies assessing the genetic consequences of climate change on freshwater fish populations remain limited (Huang *et al.,* 2021). Understanding how shifting climates influence genetic diversity, gene flow, and adaptation in freshwater ecosystems over time is crucial, especially as climate change accelerates (Weiskopf *et al.,* 2020).

Climate change is expected to have significant effects on freshwater ecosystems, but there has been limited genetic research on how freshwater fish populations in Kenya are responding to climate change. Research is needed to examine how shifts in water temperature, rainfall patterns, and water quality might affect the genetic diversity and adaptability of freshwater fish (Ficke *et al.,* 2007). Long-term monitoring of genetic changes in fish populations in response to climate change will be essential for predicting future trends and developing effective management strategies (Moltó *et al.,* 2024).

Genetic research on understudied freshwater fish species and ecosystems

Despite progress, many freshwater fish species and ecosystems remain understudied genetically. Research has primarily focused on commercially important species, such as tilapia or salmon, while lesser-known species, especially those in remote or less-accessible regions, are often overlooked (Radinger *et al.,* 2023). Freshwater fish in biodiversity hotspots like the Amazon or Southeast Asia still lack sufficient genetic information, and more studies are needed to understand these species' genetic diversity and evolutionary history (Zieritz *et al.,* 2024).

While certain species, such as Nile tilapia, have received attention in terms of genomic research, many native fish species in Kenya, especially those in remote or under-explored lakes, remain poorly studied. Species like the catfish and endemic cichlids in isolated Rift Valley lakes have not been the subject of in-depth genomic research, and their potential for adaptation to local environmental conditions remains largely unknown (Stauffer *et al.,* 2022). Expanding genomic research to these understudied species could reveal important information for conservation efforts.

Comprehensive Effects of Human-Induced Fragmentation on freshwater fish populations

Although there has been research on the effects of habitat fragmentation on freshwater fish populations, comprehensive studies linking genetic data to the long-term consequences of human-induced fragmentation such as dam construction, water diversion, and pollution are still lacking (Pavlova *et al.,* 2017). The genetic impacts of these human activities need to be studied in more depth to understand their effects on gene flow, population viability, and overall biodiversity (Mimura *et al.,* 2017).

Although genetic research has focused on the effects of invasive species and overfishing, long-term studies on the genetic consequences of other human activities, such as dam construction and water diversion, are still lacking (Wang *et al.,* 2021). These activities have fragmented fish habitats and reduced gene flow, and their impact on the genetic diversity of fish populations needs to be studied in greater detail (Pavlova *et al.,* 2017). Understanding the genetic effects of these human-induced changes will be crucial for the sustainable management and conservation of fish populations in the future (Sonesson *et al.,* 2023).

Impact of fish genetic engineering in aquaculture

While there has been considerable genetic research in aquaculture aimed at improving farmed fish, there is a need for further studies on the ecological and genetic consequences of genetically modified fish in wild populations (Sanda *et al.,* 2024). The escape of genetically modified or selectively bred farmed fish into natural ecosystems could have long-term impacts on genetic diversity and local adaptation. More research is needed to assess the risks of farmed fish escaping into the wild and interbreeding with native populations (Bolstad *et al.,* 2021).

In Kenya, the practice of genetic improvement in aquaculture mainly focuses on selective breeding rather than genetic modification. Research institutions, such as the KMFRI, have engaged in studies on breeding more resilient strains of Nile tilapia (*Oreochromis niloticus*) and African catfish to enhance aquaculture productivity (Munguti *et al.,* 2022). These efforts are aimed at improving growth rates, disease resistance, and stress tolerance, particularly in regions prone to environmental challenges such as fluctuating water temperatures and poor water quality. However, genetic modification (GM) of fish, such as engineering fish to grow faster or tolerate harsher environmental conditions, has not yet been widely implemented in Kenya's aquaculture sector, although the potential for such practices in the future exists (Munguti *et al.,* 2014).

Integrating fish genetic data with ecological and environmental research

Genetic studies often focus on isolated factors, such as genetic markers or environmental stressors, without fully integrating ecological or environmental data. There is a need for more interdisciplinary research that combines genetic data with detailed environmental and ecological studies (Rousseau, 2024). Such research could provide a more comprehensive understanding of how freshwater fish populations adapt to both genetic and environmental challenges, especially in the context of human-induced changes to freshwater habitats.

In Kenya, much of the genetic research is conducted in isolation, without integrating ecological and environmental data. The interaction between genetic factors and ecological pressures is vital for understanding the resilience of fish populations (Terer *et al.,* 2012). For instance, how do environmental stressors like pollution or habitat loss interact with genetic traits to influence fish survival and reproduction? More research is needed that integrates genetic data with detailed ecological studies to provide a holistic understanding of fish population dynamics (Canosa and Bertucci, 2023).

Functional fish genomics and gene expression

While sequencing the genomes of freshwater fish species is an important step, there is less research on functional genomics studying how genes are expressed in different environmental conditions or life stages. Investigating gene expression can provide deeper insights into the physiological processes that underpin adaptation and resilience, particularly in response to environmental stressors like pollution or temperature changes (Nielsen and Pavey, 2010).

Functional genomics, which studies how genes are expressed in different environmental conditions, remains an underexplored area in Kenya. While there has been research on genetic markers and population structure, little is known about how environmental stressors (such as water quality, temperature changes, or pollution) influence gene expression in Kenyan freshwater fish species (Mackler and Lea, 2018). Research on functional genomics could provide valuable insights into how fish adapt to environmental challenges and improve conservation strategies in the face of climate change and habitat degradation (Grummer *et al.,* 2019).

Gene editing clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9 (CRISPR/Cas9)

Gene editing technologies like clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9 (CRISPR/Cas9) offer the possibility of directly modifying the DNA of freshwater fish to introduce or enhance desirable traits, such as enhanced disease resistance or faster growth rates (Yang et *al.,* 2024). The approach could also be used to correct genetic defects in wild populations or restore endangered species. While gene editing in fish is still a developing field, it holds great promise for improving the resilience and health of both wild and farmed populations (Ansori *et al.,* 2023).

Metagenomics and microbiome research

The study of fish microbiomes microorganisms living in or on fish will become increasingly important in understanding how genetics influences fish health, growth, and disease resistance (Kanika *et al.,* 2024). Metagenomics, the study of genetic material recovered directly from environmental samples, will allow researchers to identify beneficial microorganisms that could enhance fish welfare and improve disease resistance, particularly in aquaculture settings (Nogueira and Botelho, 2021).

The way forward on genetic research in the freshwater fish populations

Genetic research is rapidly evolving, particularly with the advent of NGS technologies, bioinformatics tools, and high-throughput systems. To fully leverage these advancements, significant investment in laboratory infrastructure and human capital is required, especially in regions where resources for such research are limited (Koboldt *et al.,* 2013). To move forward in advancing genetic research on freshwater fish populations globally, and specifically in the context of Kenya, there is a critical need to enhance infrastructure and investment in key areas (Munguti *et al.,* 2023).

Investment in laboratory infrastructure for fish genetic studies

The foundation of genetic research lies in having state of the art laboratory facilities equipped to handle complex genetic analyses (Donohue *et al.,* 2021). Globally, well-funded research institutions and sequencing centers have been able to generate vast amounts of genetic data that are shaping our understanding of biodiversity, species adaptation, and evolutionary processes (Hoban *et al.,* 2022). However, in many regions, including Kenya, the lack of adequate infrastructure limits the ability to conduct high quality research (Whalen *et al.,* 2014).

Establishing advanced sequencing laboratories equipped with NGS platforms will allow researchers to sequence the genomes of freshwater fish at a much higher throughput and lower cost than traditional methods (Domrazek and Jurka, 2024). These facilities would not only support local researchers but also provide access to international scientists who may lack access to such resources in their own countries. Bioinformatics infrastructure is equally important, as it provides the computational tools needed to process and analyze the large fish datasets generated by sequencing (Rana *et al.,* 2021). Investment in high-performance computing systems and bioinformatics software will ensure that data is efficiently processed, analyzed, and stored (Sànchez *et al.,* 2015).

In Kenya, this could be addressed by setting up a national genetic research center dedicated to freshwater fish. Such a center would centralize resources, streamline research efforts, and become a hub for knowledge sharing among universities, research institutions, and private sector stakeholders (Bezeng *et al.,* 2025). This would also foster collaborative research projects on both the national and international levels.

Training and capacity building on fish genetics

Investment in infrastructure must go hand in hand with training and capacity building for researchers. To support the growth of genetic research in freshwater fish, particularly in Kenya, local scientists need to be equipped with the knowledge and skills to use advanced genetic technologies (Munguti *et al.,* 2024). This includes training in sequencing, molecular techniques, data analysis, and bioinformatics.

International collaborations, academic partnerships, and exchanges can help build local capacity in Kenya. Furthermore, building expertise in local research institutions will ensure that Kenya can lead its own genetic research programs and contribute to global freshwater fish genetics research (Kombo and Mwangi, 2018). Capacity building should also extend to policy makers, to ensure that they understand the potential of genetic research and can support informed decision-making in the context of conservation and freshwater fisheries management (Kadykalo, 2022).

Funding for research projects on freshwater fishes

While robust infrastructure is crucial, consistent and sustained funding for research is equally important. Governments, international organizations, and private investors need to prioritize freshwater fish genetics research, recognizing its importance in biodiversity conservation, sustainable fisheries, and aquaculture (Nyamweya *et al.,* 2023). In Kenya, government funding, combined with international grants and private sector investment, should be directed towards research that explores how genetic techniques can help restore threatened fish populations, improve aquaculture practices, and ensure the sustainability of freshwater ecosystems (Munguti *et al.,* 2023).

In addition to providing direct funding for research, financial support should also be allocated to long-term monitoring projects that track changes in the genetic diversity of freshwater fish populations in response to environmental pressures, such as climate change, pollution, or the introduction of invasive species (Phiri *et al.,* 2023)

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Strengthening international collaboration on freshwater fisheries genetics

Global challenges like biodiversity loss and the sustainability of freshwater fish populations require coordinated efforts across borders. Strengthening international collaboration is vital to advancing genetic research, as the ecological threats faced by freshwater fish are often not confined by national boundaries (Wang *et al.,* 2024). Kenya, with its rich biodiversity and unique freshwater ecosystems, can play a key role in international research initiatives, especially in the African context (Okello *et al.,* 2024). Collaborative projects, partnerships with international research institutes, and participation in global scientific networks will ensure that Kenya remains at the forefront of genetic research on freshwater species.

Through international collaboration, Kenya can gain access to resources, knowledge, and technology that may not be available locally. Additionally, sharing data and research outcomes can help shape global conservation strategies and policies aimed at preserving freshwater biodiversity (Otieno, 2023). Collaborative efforts would also facilitate joint research programs on transboundary rivers and lakes, where multiple countries share the responsibility of preserving fish populations (Ndimele *et al.,* 2024).

Developing and implementing policies on fisheries genetic research

Regulatory frameworks should be put in place to address the potential risks associated with genetically modified organisms (GMOs) in aquaculture. For example, policies can ensure that genetically modified or selectively bred fish are securely contained within farming environments and do not escape into wild ecosystems, potentially threatening the genetic diversity of native fish populations (Robinson *et al.,* 2024).

Investment in infrastructure must be paired with sound policies that guide genetic research and its applications. Kenya needs to develop and implement policies that promote the responsible use of genetic technologies in aquaculture, conservation, and fisheries management. Policies must ensure that the genetic integrity of native fish populations is safeguarded, especially with regards to genetic modification and selective breeding (Lal *et al.,* 2024).

Conclusion and recommendations

In both global and Kenyan contexts, genetic research in freshwater fish is indispensable for biodiversity conservation, sustainable fisheries management, aquaculture improvement, and environmental monitoring. As freshwater ecosystems face increasing pressures from human activities and climate change, genetic tools provide critical insights into how fish populations evolve, adapt, and interact with their environments. For Kenya, in particular, leveraging genetic research can help protect the rich freshwater biodiversity in the Great Rift Valley lakes and rivers, improve the sustainability of aquaculture, and ensure that conservation efforts are based on scientifically sound data. Continued investment in genetic research will be essential to address these challenges and secure the future of freshwater fish populations worldwide.

Table 1. Key focus areas of genetic research on some freshwater fish species worldwide

Fish Species	Common Name	Family	Region	Key Focus of Genetic Research	Reference
Barbus altinialis	Ripon barbel	Cyprinidae	Lake Victoria, Africa	Impact of introduced species (e.g., L. niloticus), population genetics, and conservation strategies	(Chemoiwa *et al.,* 2013)
Brycinus nurse	Nurse Tetra	Characidae	Lake Victoria, Africa	Species identification, population genetics, and phylogenetic relationships	(Hamid *et al.,* 2020)
Clarias gariepinus	African Catfish	Clariidae	Africa, Asia	Genetic improvement for growth rates, disease resistance, and aquaculture productivity	(Kebtieneh *et al.,* 2024)
Cyprinus carpio	Common Carp	Cyprinidae	Europe, Asia	Genetic improvement for aquaculture, disease resistance, and adaptation to environmental stress	(Xu *et al.,* 2014)
Danio rerio	Zebrafish	Cyprinidae	Global (Lab-based)	Biomedical Research, model organism for human health research, Androgenesis and vaccination research	(Teame *et al.,* 2019)
Esox lucius	Northern Pike	Esocidae	North America, Europe	Phylogeography, genetic variation and population structure	(Skog *et al.,* 2014)
Gambusia affinis	Mosquitofish	Poeciliidae	North America, Global	Genetic diversity, resistance to environmental stress, and invasive species management	(Mer Mosharraf Hossain *et al.,* 2019)
Haplochromine sp.	East African cichlids	Cichlidae	Lake Victoria, Africa	Speciation, genetic diversity, and adaptation to environmental changes	(Takuno *et al.,* 2019)
Ictalurus punctatus	Channel Catfish	Ictaluridae	North America	Disease resistance, growth rate, genome mapping	(J. Wang *et al.,* 2024)
Labeo victorianus	Ningu	Cyprinidae	Lake Victoria, Africa	Genetic variation, population decline, and conservation efforts	(Chemoiwa *et al.,* 2013)
Lates calcarifer	Barramundi	Latidae	Australia, Southeast Asia	Population genetics, aquaculture breeding, and genetic adaptation to environmental factors	(Prasertlux *et al.,* 2024)
Micropterus salmoides	Largemouth Bass	Centrarchidae	North America and Asia	Population genetics, conservation genetics	(Wang *et al.,* 2019)
Mormyrus kannume	Elephant-snout	Mormyridae	Lake Victoria, Africa	Genetic variation, reproductive strategies, and impact of environmental changes	(M.EL-Mahdi, 2018)
Oncorhynchus mykiss	Rainbow Trout	Salmonidae	North America, Europe	Genetic diversity, breeding programs, disease resistance, and adaptation to various environments	(Miebach *et al.,* 2023)
Oreochromis niloticus	Nile Tilapia	Cichlidae	Africa, Asia, South America	Genetic variation, breeding programs, resistance to diseases, and growth traits	(Shoemaker *et al.,* 2022)
Perca fluviatilis	European Perch	Percidae	Europe	Genetic differentiation, environmental adaptation, and selective breeding for aquaculture	(Vanina *et al.,* 2019)
Protopterus aethiopicus	Marbled Lungfish	Cyprinidae	East Africa	Genetic diversity, habitat preferences, and ecological adaptation	(Garner *et al.,* 2006)
Rastrineobola argentea	Silver Cyprinid (Dagaa in Swahili: Omena in Luo)	Cyprinidae	Lake Victoria, Africa	Population genetics, food web interactions, and adaptation to eutrophic conditions	(Ahnelt *et al.,* 2016)
Rutilus rutilus	Roach	Cyprinidae	Austria, Lithuania, England and Wales	Genetic diversity, population dynamics	(Butkauskas *et al.,* 2023)
Salmo salar	Atlantic Salmon	Salmonidae	North Atlantic	Population structure, migratory patterns, genetic markers for selective breeding	(Houston and Macqueen, 2019)
Synodontis victorianus	Lake Victoria squeaker	Mochokidae	Lake Victoria, Africa	Genetic structure and population dynamics in response to habitat changes	(Iyiola *et al.,* 2018)

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