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Review Article

Aquatic Biotechnology Sustainability and Innovative Solutions

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Abstract: Aquatic biotechnology plays a pivotal role in addressing the pressing sustainability challenges facing our planet's aquatic ecosystems. This abstract explores innovative solutions and their potential to enhance sustainability in this critical field. In recent years, aquatic environments have faced unprecedented threats, including pollution, overfishing, habitat degradation, and climate change. These challenges have spurred the development of novel biotechnological approaches aimed at conserving aquatic biodiversity and promoting sustainable resource management. One of the key areas of innovation in aquatic biotechnology is the development of aquaculture techniques that reduce environmental impacts while increasing food production. Sustainable aquaculture practices involve the use of genetically modified organisms (GMOs) to enhance disease resistance, improve feed efficiency, and reduce the environmental footprint of fish farming. Additionally, biotechnology plays a crucial role in restoring damaged aquatic ecosystems through techniques such as bioremediation and habitat restoration. Furthermore, advancements in genetic research and molecular biology have enabled scientists to better understand aquatic organisms' physiology, behavior, and adaptation mechanisms. This knowledge is instrumental in developing strategies to mitigate the effects of climate change on aquatic ecosystems, such as breeding programs for heat-tolerant and disease-resistant species. In conclusion, aquatic biotechnology offers promising and sustainable solutions to address the complex challenges facing our aquatic environments. By harnessing the power of innovation in this field, we can promote the conservation of biodiversity, responsible resource management, and the long-term health of our planet's aquatic ecosystems.

Keywords: Aquaculture, Aquatic organisms, Biotechnology, Aquatic ecosystems

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1. BIOTECHNOLOGY IN AQUACULTURE

1.1. Genetic Improvement of Aquatic Species for Enhanced Growth and Disease Resistance

The long-term survival of natural populations largely hinges on their genetic diversity, which enables them to adapt to ever-changing ecological conditions. Among various methods, genetic lineage has been demonstrated as a robust and reliable means of categorizing these subpopulations (Han et al., 2012; Behera et al., 2018).

Table 1. The relationship between genetic lineage and subpopulation categorization

Feature	Genetic Lineage	Subpopulation Categorization
Definition	A series of mutations or changes in the genetic code that connects an ancestor's genetic code to their descendant's genetic code	A distinct group of individuals within a larger population that shares unique genetic characteristics
Purpose	To identify and track the evolutionary history of different subpopulations	To understand the genetic diversity and structure of natural populations
Applications	Conservation biology, evolutionary genetics, population genetics	Ecological studies, evolutionary biology, resource management
Benefits	Provides a robust and reliable means of categorizing subpopulations	Can be used to identify and monitor threatened or endangered subpopulations

The assessment of genetic diversity in fish hatcheries often involves the use of molecular techniques, with a primary focus on mitochondrial DNA (Gong et al., 2018). In recent times, mitochondrial DNA has garnered increased attention in phylogenetic research and species identification because of its notable features, including a faster evolutionary rate compared to nuclear DNA, a relatively straightforward structure, maternal inheritance dominance, and absence of recombination (Barat et al., 2012; Kamran et al., 2020; Malkani et al., 2022). The practice of fish DNA barcoding, involving the sequencing of mitochondrial genes like Cytochrome C Oxidase subunit I (COI) and cytochrome b (Cyto b), is extensively employed for evaluating population structures, genetic diversity, inter-geographical relationships of fish species, understanding migration patterns, and estimating gene flow (Pramuk et al., 2007; Malkani et al., 2022). Quality fish seed availability is essential for the sustainable and profitable practice of fish farming. Typically, fish growth is influenced by both environmental factors and the genetic composition of the fish. Among these environmental factors, temperature plays a crucial role in regulating the normal life processes of organisms and directly impacts the metabolism, embryonic development, growth, and survival rates of fish (Pepin, 1991; Islam et al., 2007; Sandersfeld et al., 2017).

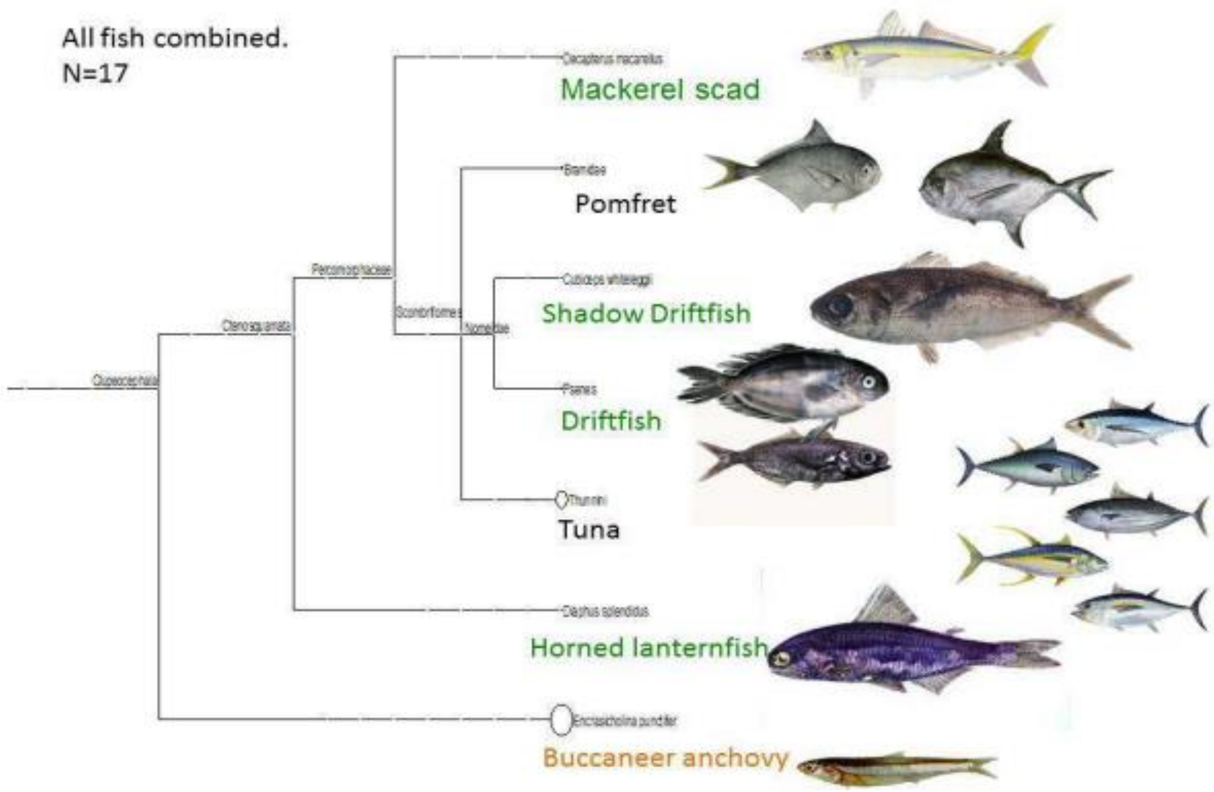

Figure 1. Fish DNA barcoding (Gleeson et al. 2015)

1.2. Advancements in Selective Breeding Techniques

In the realm of aquaculture, the initial step in a genetic enhancement program involves the gathering, choosing, and selectively breeding the most high-performing strains. This mechanism serves as the foundation for achieving genetic advancements, generation after generation, and enables rapid initial progress in enhancing the genetic quality of fish stocks (Gratacap et al., 2019). It is widely recognized that various fish strains display substantial variability in numerous traits, including growth rate, coloration, disease resistance, body shape, dressing percentage, age of maturity, spawning timing, and fecundity (Mohsin et al., 2015). As per numerous researchers, insufficient data regarding the genetic vitality of the stock and a disorderly breeding program have resulted in inbreeding depression and a decline in genetic quality. This decline ultimately results in reduced survival rates, sluggish growth, and increased susceptibility to disease among hatchery-produced fish seed (Ponzoni et al., 2007).

Table 2. The advancements in selective breeding techniques

Feature	Traditional Selective Breeding	Modern Selective Breeding Techniques
Selection Process	Based on observable traits	Based on genetic markers and genomic information
Precision	Limited by the complexity of traits and environmental influences	Highly precise due to direct targeting of genetic variants
Speed	Slow due to the need for multiple generations	Significantly faster due to marker-assisted selection and genomic selection
Accuracy	Lower accuracy in predicting offspring traits	Higher accuracy in predicting offspring traits
Applications	Primarily used for agricultural crops and livestock	Can be applied to a wider range of organisms, including non-agricultural species

1.3. Applications of Biotechnology in Fish and Shellfish Health Management

Aquaculture is currently experiencing exponential growth, making it the fastest-growing sector in animal food production, with an impressive annual expansion rate of nearly 7%. However, this rapid growth has not come without its challenges, particularly in the form of infectious diseases that are causing substantial economic losses within the aquaculture industry. To effectively address these challenges, the aquaculture sector is in need of innovative biotechnological solutions that encompass rapid disease diagnosis, the production of disease-free or high-health broodstock for seed production, and the development of efficient preventive and therapeutic measures for managing disease outbreaks. In recent years, molecular techniques have emerged as a critical component in the diagnosis of fish diseases. These molecular methods offer the potential for quicker and more sensitive disease diagnosis compared to traditional approaches such as culture, serology, and histology. DNA-based techniques, including polymerase chain reaction (PCR), real-time PCR (qPCR), multiplex PCR, DNA probe-based in situ hybridization, and microarrays, have found broad applications in the field of fish disease diagnosis. Polymerase chain reaction (PCR), for instance, allows for the amplification of specific DNA sequences associated with pathogens, enabling their rapid and accurate detection. Real-time PCR (qPCR) enhances this process by providing quantification capabilities, which are particularly valuable in assessing the severity of infections. Multiplex PCR allows for the simultaneous detection of multiple pathogens in a single test, streamlining diagnostics. DNA probe-based in situ hybridization enables the visualization of specific DNA or RNA sequences within infected tissues, aiding in disease confirmation. Microarrays can assess the presence of multiple pathogens in a single sample, making them a powerful tool for disease surveillance (Kralik & Ricchi, 2017; Islam et al., 2023). Furthermore, when coupled with computer-assisted pattern analysis, methods such as pulsed-field gel electrophoresis, amplified fragment length polymorphism, ribotyping, repetitive element sequence-based PCR, enterobacterial repetitive intergenic consensus-polymerase chain reaction, and genomic fingerprinting based on multilocus sequence typing have demonstrated their utility in typing and characterizing fish pathogens (Elnifro et al., 2000; Yang & Rothman, 2004). qPCR assays play a crucial role in aquaculture by facilitating the detection of specific genes and alleles, typing various strains and isolates, profiling antimicrobial resistance, and evaluating toxin production. Similarly, like in other animal sectors, aquaculture benefits from the application of probiotic and bioremediation products for both disease management and environmental preservation. These products are becoming increasingly popular in fish and shrimp farming, serving as effective measures to control disease outbreaks and maintain a healthy aquatic culture environment. In response to the growing challenges posed by aquatic diseases, there is an urgent demand for the development of prophylactic solutions. These include single or multivalent vaccines, DNA vaccines, immunostimulants, organic interventions, and nanotechnology-based approaches, all of which are essential for effectively managing disease outbreaks. These biotechnological innovations can be integrated as routine tools for swift field-based diagnosis of fish pathogens and play a pivotal role in conducting epidemiological studies on infectious diseases in aquatic ecosystems (Groner et al., 2016; Samsing et al., 2019; Mohr et al., 2020).

Table 3. The applications of biotechnology in fish and shellfish health management

Application	Description	Benefits
Disease diagnosis and monitoring	Development of molecular diagnostic tools to detect and monitor fish and shellfish pathogens	Early identification and control of diseases, reducing economic losses and improving food safety
Vaccine development	Development of innovative vaccines to protect fish and shellfish from infectious diseases	Enhanced disease prevention and reduced reliance on antibiotics
Genetic improvement	Use of selective breeding and gene editing techniques to enhance disease resistance, growth rate, and other desirable traits in fish and shellfish	Improved productivity, reduced environmental impact, and increased food security
Probiotics and microbial manipulation	Use of beneficial bacteria to promote gut health and reduce susceptibility to diseases in fish and shellfish	Enhanced immune function, improved growth, and reduced use of antibiotics
Nutritional genomics	Identification of genetic variants that influence nutrient utilization and disease susceptibility in fish and shellfish	Development of tailored diets and breeding strategies to optimize nutrition and health
Aquaculture bioremediation	Use of microorganisms to degrade organic waste and improve water quality in aquaculture systems	Reduced environmental impact and sustainable aquaculture practices

1.4. Environmental benefits of genetically modified aquatic organisms

The aquatic ecosystem is closely intertwined with the neighboring agricultural landscapes, often serving as a recipient of stressors, including agrochemicals. Additionally, genetically modified crops, which are extensively grown in numerous nations, can also introduce stressors. While genetically modified organisms (GMOs) have been in commercial use for more than two decades, it was only a decade ago that attention began to shift towards understanding their effects on the aquatic environment (Glare, 2000; James, 2007). The scientists also assessed the environmental exposure of small, upstream streams to Bt maize and the insecticidal Cry1Ab toxin produced by this genetically modified crop (Tank et al., 2010). In addition to experimental data indicating a potential threat to caddisflies (Trichoptera), an insect group with aquatic larval stages that are closely related to Lepidoptera, and hence, to the target insects of Bt maize, attention was drawn to the introduction of genetically modified plant material into aquatic ecosystems and the possible hazards associated with the cultivation of GM crops for aquatic invertebrates (Rosi-Marshall et al., 2007; Parrott, 2008).

2. BIOTECHNOLOGY FOR WATER QUALITY MANAGEMENT

2.1. Microbial Bioremediation in Aquatic Ecosystems

Aquatic pollution has detrimental effects on water bodies, marine ecosystems, public health, and the economy. Given the critical importance of safeguarding marine ecosystem health, there has been a global surge in interest in restoring contaminated habitats. Bioremediation offers a cost-effective and environmentally friendly approach to converting harmful, resilient contaminants into environmentally safe substances through a range of biological treatments. Fungi, due to their robust morphology and diverse metabolic capabilities, play a significant role in bioremediation. This review provides an overview of the strategies employed by aquatic fungi to detoxify and subsequently remediate various toxic and persistent compounds found in aquatic ecosystems. It also delves into how mycoremediation can transform chemically suspended particles, microbial contaminants, nutrients, and oxygen-depleting substances in aquatic environments into less ecologically hazardous products through multiple mechanisms. As a potential tool for sustainable management, mycoremediation could be considered in future research studies focused on aquatic ecosystems, including marine environments. This offers a foundation for the selection and utilization of fungi, either independently or as part of microbial consortia, to address contamination challenges effectively (Frid & Caswell, 2017; Turkoglu et al., 2018; Del Mondo et al., 2021; Yadav et al., 2021; Tarfeen et al., 2022; Vaksmaa et al., 2023).

2.2. Monitoring and Improving Water Quality Through Molecular Techniques

Water quality monitoring has become increasingly vital in response to rising pollution levels from growing global population and industrial activities. To address this, innovative detection methods like electrochemical and optical analysis have gained prominence in environmental monitoring. These methods offer advantages such as high sensitivity, selectivity, rapid analysis, cost-efficiency, and user-friendliness compared to conventional techniques. However, many sensors based on these methods are primarily suitable for laboratory use and require skilled experts for data analysis. Recent research has focused on adapting optical and electrochemical techniques for point-of-care (POC) applications in water quality monitoring. POC devices are designed for on-the-spot data collection related to specific analytes. These POC sensors have demonstrated exceptional sensitivity, reliability, and relevance when used at the point of need. Nevertheless, there are challenges in designing and implementing portable POC systems that can maintain high sensitivity, selectivity, affordability, quick analysis, and robustness when deployed in complex environmental conditions. Addressing these challenges and limitations requires further research and resources. Delaying the development, implementation, and commercialization of POCs, despite their urgent need and significant potential benefits, is a possibility. Therefore, it is essential to invest in additional investigations and research efforts to overcome these setbacks, ensuring that POC systems can effectively monitor and safeguard water quality in diverse and challenging environments. This research will be instrumental in advancing water quality monitoring and protecting aquatic ecosystems in the face of mounting environmental pressures (Terry et al., 1979; Izah et al., 2016; Zulkifli et al., 2018; Zamora-Ledezma et al., 2021; da Silva et al., 2022).

3. SUSTAINABLE AQUATIC PRODUCT PROCESSING

3.1. Innovative biotechnological approaches for seafood processing

Ensuring the quality and safety of aquatic food products is paramount, and a crucial aspect of this is the rapid and accurate identification of bacterial species. In this context, omics technologies have proven to be invaluable tools for assessing the quality and safety of seafood products. Omics encompasses various disciplines, including genomics, transcriptomics, proteomics, and metabolomics, which have advanced significantly due to recent technological breakthroughs. These omics technologies offer several key advantages. They enable the identification and detection of even trace levels of contamination by pathogenic and spoilage bacteria, enhancing the overall safety of seafood products. Additionally, they provide insights into the effects of processing and storage on these products, aiding in quality control and shelf-life extension. Integrating food processing with microbial monitoring using traditional microbiological assays, combined with molecular techniques, lays the foundation for developing faster, more sensitive, and reliable methods for screening seafood safety. This hybrid approach can streamline quality assurance processes and reduce the risk of contaminated products reaching consumers. Furthermore, the utilization of combined omics technologies, including metagenomics (studying entire microbial communities), proteomics (analyzing proteins), and metabolomics (studying small molecules), in conjunction with conventional quality indicators like color, texture, and flavor, presents a novel approach to optimizing seafood processing. This comprehensive approach ensures not only the safety but also the overall quality of seafood products, meeting consumer expectations and regulatory standards. In summary, omics technologies are revolutionizing the assessment of aquatic food product quality and safety. Their ability to identify bacterial species, detect contamination, and analyze the impact of processing and storage makes them invaluable tools for the seafood industry. Integrating these technologies with traditional methods and quality indicators offers a holistic approach to ensuring seafood quality and safety, benefiting both producers and consumers (Ferri et al., 2015; Cook & Nightingale, 2018; den Besten et al., 2018; Tsironi et al., 2021).

3.2. Conservation and Restoration Efforts

Biotechnology's role in conserving endangered aquatic species; Fluctuations in water temperature can lead to thermal stress, potentially affecting various aspects of fish life, including their survival, growth, reproduction, susceptibility to diseases, and more. An interesting phenomenon has been observed in the endangered catfish species *Clarias magur*, which appears to exhibit enhanced resilience to elevated thermal stress levels, although the precise underlying mechanism remains unidentified. Recent research has pointed to the involvement of specific genes, namely Nuclear protein 1 (Nupr1) and Parkin E3 ubiquitin protein ligase (Park2), which are known for their roles in safeguarding cells against damage and cell death induced by stress.

Table 4. The role of biotechnology in conserving endangered aquatic species, focusing on the example of the endangered catfish species *Clarias magur* and its enhanced resilience to thermal stress

Feature	Description
Challenge	Fluctuations in water temperature can lead to thermal stress in aquatic species, potentially affecting various aspects of their life, including survival, growth, reproduction, and susceptibility to diseases.
Endangered Species	The endangered catfish species *Clarias magur* exhibits enhanced resilience to elevated thermal stress levels.
Biotechnology's Role	Biotechnology can play a crucial role in understanding and enhancing the resilience of endangered aquatic species like *Clarias magur*.
Genes of Interest	Recent research has pointed to the involvement of specific genes, namely Nuclear protein 1 (Nupr1) and Parkin E3 ubiquitin protein ligase (Park2), in the thermal stress resilience of *Clarias magur*.
Mechanism of Action	Nupr1 and Park2 are known for their roles in safeguarding cells against damage and cell death induced by stress.
Conservation Implications	Understanding the genetic mechanisms underlying thermal stress resilience in *Clarias magur* can inform conservation strategies and selective breeding programs aimed at enhancing the resilience of endangered aquatic species to climate change-induced thermal stress.

During thermal stress, numerous genes, transcription factors, and molecular chaperones have been identified as essential for adaptation. While molecules like heat shock proteins (HSPs), nucleotide exchange factors (nef), and caseinolytic proteases have received extensive research attention and documentation, it is worth noting that NGS data analysis has revealed the involvement of many other genes that also hold significance in responding to thermal stress (Tort & Teles, 2012; Kushwaha et al., 2021). Through an extensive literature review on thermal stresses, we have identified two temperature-responsive genes: Nuclear Protein-1 (Nupr1) and Parkin E3 ubiquitin protein ligase (Park2). These genes have been recognized as thermal stress markers, as documented by Hori et al. in 2010. These stress-responsive genes have been shown to play a crucial role in shielding cells from stress-induced cell death. Notably, Nupr1 functions as a stress-responsive nuclear transcription factor with involvement in a broad spectrum of cellular stress conditions, including those related to endoplasmic reticulum stress, oxidative stress, and cancer-related stress (Chowdhury et al., 2009; Hori et al., 2010; Hamidi et al., 2012; Akbarzadeh et al., 2018).

4. FUTURE PROSPECTS AND CHALLENGES

4.1. Emerging trends and technologies in aquatic biotechnology

The application of modern biotechnological tools in aquaculture holds significant promise, not only for meeting the increasing demand for fish but also for enhancing the quality and quantity of fish production. Biotechnology plays a pivotal role in aquaculture by offering various advantages such as sex control, manipulation of breeding cycles, the creation of stocks with improved nutritional profiles, enhanced disease resistance, accelerated growth rates, and heightened tolerance to environmental fluctuations. As biotechnological techniques continue to advance rapidly, their importance and applications in sustainable aquaculture continue to expand, contributing to the improvement and sustainability of fish production to meet global demand.

4.2. Ethical and regulatory considerations in biotechnology applications

The increasing global demands for food, bioenergy, specialty products, and the ongoing environmental changes indeed pose significant challenges for agricultural production. Aquatic biotechnology emerges as a promising solution to address these challenges. However, it's crucial to recognize that alongside scientific advancements, we must also consider ethical and sociocultural dimensions. Building public trust and fostering widespread acceptance are essential components of harnessing the potential of aquatic biotechnology. For this technology to be effective and sustainable, we must prioritize ethical responsibility and social responsiveness. This means considering not only the potential benefits but also the potential risks and consequences of aquatic biotechnology, including its impact on ecosystems and communities. It also involves actively engaging with diverse stakeholders, including scientists, policymakers, and the public, to ensure that decisions and regulations are made collectively and reflect societal values and concerns. Moreover, the development and implementation of aquatic biotechnology solutions should be relevant to people from different cultural and social backgrounds. Recognizing that perspectives on biotechnology may vary across communities, regions, and countries, efforts should be made to incorporate cultural values and preferences into the decision-making process. Communication is key in this endeavor. Information about aquatic biotechnology should be conveyed to the public in a clear, transparent, and convincing manner. It's essential to provide educational resources and engage in open dialogue with the public to address questions and concerns effectively (Herring & Paarlberg, 2016; Bujnicki et al., 2017; Wickson et al., 2017; Bartkowski et al., 2018; Małyska et al., 2018).

Table 5. The ethical considerations for aquatic biotechnology

Ethical Considerations	Description
Environmental impact	Aquatic biotechnology should be developed and applied in a way that minimizes negative impacts on aquatic ecosystems and biodiversity.
Socioeconomic impact	Aquatic biotechnology should be developed and applied in a way that is equitable and does not exacerbate existing social and economic inequalities.
Public health and safety	Aquatic biotechnology products should be thoroughly tested to ensure their safety for human consumption and for the environment.
Animal welfare	Aquatic animals used in biotechnology research and development should be treated humanely and with respect.
Intellectual property rights	Access and benefit-sharing agreements should be in place to ensure that the benefits of aquatic biotechnology are shared fairly among all stakeholders.

Table 6. The sociocultural considerations for aquatic biotechnology

Sociocultural Considerations	Description
Public trust and acceptance	Public trust in aquatic biotechnology is essential for its widespread adoption. This can be achieved through transparent communication, education, and public engagement.
Indigenous knowledge and traditional practices	Indigenous knowledge and traditional practices should be respected and incorporated into the development and application of aquatic biotechnology.
Local communities and livelihoods	The potential impacts of aquatic biotechnology on local communities and livelihoods should be carefully considered and mitigated.
Cultural values and beliefs	Aquatic biotechnology should be developed and applied in a way that respects the cultural values and beliefs of different communities.
International cooperation	International cooperation is essential to ensure that the benefits of aquatic biotechnology are shared globally and that potential risks are managed effectively.

In conclusion, "Aquatic Biotechnology Sustainability and Innovative Solutions" embodies the vital intersection of science, ethics, and societal considerations. As we navigate the challenges of increasing global demands for food, bioenergy, and specialty products, while facing environmental changes, this field offers promising avenues for progress. To harness its full potential, we must ensure ethical responsibility, social responsiveness, cultural relevance, and transparent communication. By fostering collaboration among diverse stakeholders and prioritizing sustainable practices, we can pave the way for a future where aquatic biotechnology contributes to a more secure and environmentally resilient world.

Authors' Contributions
MRT: Manuscript design, Field sampling, Draft checking.
MK: Writing, Draft checking, Reading, Editing.

Conflict of Interest: The authors declare that there is no conflict of interest.

Ethical approval: For this type of study, formal consent is not required.

Data Availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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