Aquatic Life and Ecosystems
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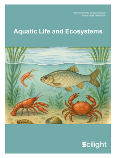

Review

Review and Outlook for Research and Development in Aquatic Life and Ecosystems

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Abstract: Aquatic life and ecosystems represent some of the most dynamic and biologically diverse components of the biosphere. It is vital in global biogeochemical cycles, food security, climate regulation, and ecosystem services. This review provides a comprehensive synthesis of current knowledge and emerging research areas in studying aquatic life and ecosystems for freshwater and marine environments. This paper uses a chronological approach to explore the research development in the past, present, and future. We traced the research advances in structural and functional diversity of aquatic organisms, from microbial communities to higher trophic levels, and examined the intricate ecological interactions underpinning ecosystem stability and productivity. We grasped key topics to reflect research progress and advancement in habitat degradation, pollution, climate change, and biological invasions, particularly aquatic biodiversity and ecological integrity. In the new century, scientists have applied genomic tools for ecological management and microbiome research to enhance our understanding of aquatic systems at the molecular level and explore underlying mechanisms. Applied research has emphasized conservation and management, including ecosystem-based management, aquaculture, and fisheries. By critically analyzing past developments and current knowledge gaps, this review paper provides readers with future research priorities and sustainable management of aquatic life and ecosystems in an era of rapid environmental change.

Keywords: diversity; pollution; microbiomes; aquaculture; fisheries; freshwater; marine

1. Introduction

Aquatic life and aquatic ecosystems represent the most diverse and dynamic components in the biosphere, encompassing an extraordinary range of organisms, habitats, and ecological processes [1]. From microscopic phytoplankton and zooplankton to apex predators such as sharks and marine mammals, aquatic environments sustain a wealth of biological diversity and underpin critical ecosystem services vital to human well-being. The aquatic ecosystems comprise freshwater (rivers, ponds, lakes, wetlands) and marine systems (estuaries, coastal zones, coral reefs, and the open ocean). As these cover approximately 71% of the Earth's surface, any change to them can play a pivotal role in global biogeochemical cycles, climate regulation, food security, and biodiversity conservation.

Research into aquatic life and ecosystems has expanded significantly over the past century, driven by a growing awareness of environmental degradation, unsustainable resource use, and the vulnerability of aquatic habitats to anthropogenic pressures. Early research primarily focused on taxonomy, life history traits, and community structure. It has been gradually progressing towards integrative approaches encompassing ecosystem dynamics, evolutionary biology, conservation science, and biotechnology [2]. Alongside threats of overfishing, habitat loss, pollution, and invasive species, the increasing frequency and severity of climate-related disturbances have further catalysed interest in understanding how aquatic systems function and respond to change.

In recent decades, various interdisciplinary approaches have emerged, combining ecological theory, molecular biology, remote sensing, and modelling to unravel the complexity of aquatic ecosystems [3]. Investigations into species interactions, nutrient dynamics, trophic connectivity, and ecosystem resilience have improved our ability to assess ecological health and predict future trajectories. Concurrently, advances in genomics, metagenomics, and environmental DNA (eDNA) have fostered excellence in scientific biodiversity monitoring, revealing hidden patterns of species distribution and population connectivity, particularly in previously underexplored deep-sea and polar regions.

This review synthesizes the significant developments, current challenges, and emerging research frontiers in studying aquatic life and ecosystems. It begins with a retrospective analysis of historical research milestones that formed our foundational ecological theory. It is followed by a critical appraisal of contemporary ecological studies, focusing on the integration of climate change and anthropogenic impact assessment. Special attention is given to the functions of microbial communities and biodiversity with aquatic food webs and trophic interactions, attempting to serve applied domains such as aquaculture, fisheries, and ecosystem-based management strategies.

In the perspective of accelerating environmental change and increasing societal reliance on aquatic resources, it is imperative to advance a holistic understanding of aquatic ecosystems that incorporates ecological integrity, adaptive management strategy, and sustainable development goals (Figure 1). This review aims to inform future research frameworks for the conservation and sustainable use of aquatic biodiversity by identifying key research achievements and highlighting interdisciplinary innovations.

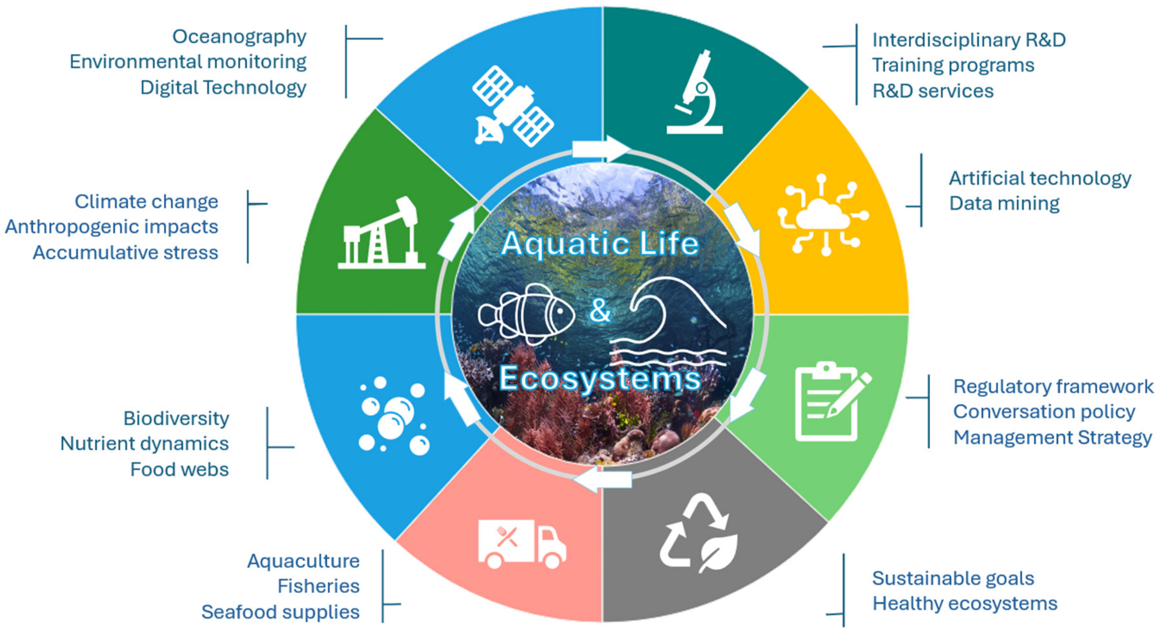

Figure 1. Conceptual overview of aquatic life and ecosystem dynamics.

2. Past Research: Foundations and Early Discoveries

The last century has witnessed a remarkable transformation in aquatic science, driven by technological advancement, environmental urgency, and interdisciplinary research. From foundational discoveries in marine biology to cutting-edge genomics, the evolution of aquatic science has played a pivotal role in understanding, conserving, and sustainably utilizing aquatic ecosystems. Table 1 is a chronological summary of significant research developments in aquatic science over the past century.

Historically, research into aquatic life and ecosystems has its roots in natural history and taxonomy, with early scientists such as Swedish biologist Carl Linnaeus laying the groundwork for the systematic classification of aquatic organisms. Initial studies primarily focused on descriptive biology—cataloguing species, habitats, and general ecological roles [4]. In the 19th and early 20th centuries, explorers and marine expeditions greatly expanded knowledge of marine biodiversity and oceanographic parameters.

Table 1. A chronological overview of significant research developments in aquatic science over the past century.

Years	Major Achievements	Specific Advances
1920s–1950s	Foundation of Modern Aquatic Sciences	• Development of Oceanographic Institutions: Establishment of key research institutions such as the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution laid the groundwork for systematic marine research. • Early Plankton and Primary Productivity Studies: Pioneering studies formulated the Critical Depth Hypothesis, linking light availability and nutrient levels to phytoplankton growth. • Advances in Limnology: Established freshwater ecology through the concept of the ecological niche and nutrient cycling in lakes.
1960s–1970s	Expansion of Ecosystem and Pollution Research	• Ecosystem Concept in Aquatic Sciences: Advancement in systems ecology approach, treating lakes, rivers, and oceans as interconnected ecological systems. • Marine Pollution Awareness: The Minamata mercury poisoning in Japan and rising oil spills spurred early research on contaminants and environmental risk assessments in aquatic systems. • Remote Sensing and Ocean Monitoring: The Introduction of satellite technologies enabled large-scale observation of ocean temperatures, currents, and chlorophyll concentrations. • Nutrient Enrichment Studies: The concept of eutrophication gained prominence, particularly from studies on the Great Lakes and the Baltic Sea
1980s–1990s	Biotechnology and Climate Change Integration	• Aquaculture Biotechnology: Genetic improvement of aquaculture species through selective breeding and chromosome manipulation. • Climate Change Impact Studies: Research on ocean warming, acidification, and sea level rise. • Coral Reef Science: The global bleaching event triggered intensive coral reef monitoring programs and ecological studies on coral-algae symbioses and resilience. • Development of Ecological Modeling Tools: Widespread application of models facilitated trophic interaction studies and ecosystem-based fisheries management.
2000s–2010s	Molecular, Genomic, and Integrated Approaches	• Aquatic Genomics and Environmental DNA (eDNA): The sequencing of model aquatic organisms enabled deeper insights into aquatic biodiversity and functional genomics. • Integrated Coastal Zone Management: Holistic frameworks integrating ecological, economic, and social dimensions in coastal and estuarine management were formalized and adopted globally. • Marine Protected Areas: This concept became central to conservation policy based on ecological principles and biodiversity hotspots, supported by GIS and remote sensing tools. • Sustainable Fisheries and Aquaculture Science: The concept of maximum sustainable yield evolved into more complex indicators for ecosystem-based fisheries management, supported by improved stock assessment methodologies.
2010s–2020s	Precision Technologies and Global Ecological Challenges	• Big Data and AI in Aquatic Sciences: Use of autonomous underwater vehicles, Internet of Things (IoT), and artificial intelligence for real-time monitoring of oceanographic and aquaculture systems. • Functional Aquafeeds and Microbiome Research: Advances in aquaculture nutrition led to the development of alternative proteins and research on gut microbiomes for health and performance optimization. • Plastic Pollution and Emerging Contaminants: Microplastics, pharmaceuticals, and personal care products became major areas of concern, driving interdisciplinary research in ecotoxicology and policy. • Blue Carbon and Nature-based Solutions: Recognition of seagrasses, mangroves, and salt marshes as carbon sinks positioned aquatic habitats within the global climate mitigation dialogue.

During the mid-20th century, research shifted toward understanding ecological interactions and biogeochemical processes. The ecosystem concept was advanced by pioneers like Raymond Lindeman on trophic dynamics, which establishes the energy flux law whereby only 10% of the energy consumed at one trophic level is transferred to higher trophic levels [5]. Eugene Odum proposed a holistic approach to exploring subjects and provided a framework for studying aquatic systems as integrated wholes [6].

Concurrently, limnology—the study of inland freshwater systems—emerged as a significant sub-discipline, elucidating nutrient cycling, primary productivity, and trophic dynamics in lakes and rivers. Technological advancements and the development of oceanographic instruments further enabled in-depth studies of aquatic habitats, leading to major discoveries in benthic ecology, coral reef biology, and pelagic food webs. The study of aquatic life and ecosystems has a long and dynamic history that reflects the evolving relationship between humans and aquatic environments. Historically rooted in descriptive natural history, the field has progressively integrated with molecular biology, ecosystem modelling, and environmental monitoring in recent years. Overall, past research has laid a critical foundation for understanding biodiversity, ecological function, and anthropogenic impacts on different aquatic ecosystems.

2.1. Natural History of Aquatic Life and Ecosystem Studies

Early investigations in aquatic life were primarily taxonomic, focusing on discovering, describing, and classifying aquatic species. The foundational work of naturalists such as Carl Linnaeus in the 18th century provided the taxonomic basis for biological classification. Through explorations and marine expeditions, such as those led by Charles Darwin and the HMS Challenger in the 19th century, researchers catalogued thousands of aquatic species, laying the groundwork for biogeographic studies and recognizing global aquatic biodiversity patterns [7].

In the early 20th century, freshwater and marine sciences began to diverge into more structured disciplines. The development of limnology, the study of inland waters, emerged through the work of scientists like G. Evelyn Hutchinson, who contributed for more than sixty years to the fields of limnology, systems ecology, radiation ecology, entomology, genetics, and biogeochemistry [8] and Walles T. Edmondson, whose research focused on the causation and effects of eutrophication by plankton and his early work on rotifer taxonomy in lakes across the United States [9]. These early limnologists examined the physical, chemical, and biological processes of lakes and rivers, emphasizing nutrient cycling, plankton dynamics, and trophic interactions.

Simultaneously, oceanography gained prominence with increasing attention to the physical and biological properties of marine environments. Investigations focused on currents, salinity gradients, and upwelling systems, and how these factors influenced the productivity and distribution of marine organisms. The 20th century witnessed the institutional expansion of oceanography through the establishment of research institutions, such as the Scripps Institution of Oceanography [10], the Woods Hole Oceanographic Institution (1930), and the British National Institute of Oceanography (1949). In China, the Institute of Hydrobiology was founded in 1950 in Wuhan. It has become a national freshwater biology, aquatic ecology, and fishery science center. Simultaneously, marine sciences took shape under the Institute of Oceanology, Chinese Academy of Sciences, established in 1950 in Qingdao. These centers played pivotal roles in advancing marine science.

2.2. Knowledge Expansion on Ecological Theory and Nutrient Dynamics

The mid-20th century marked a turning point in applying ecological theory to aquatic systems. Pioneering studies explored trophic structure, energy flow, and biomass pyramids in lakes, estuaries, and oceans. Notably, Raymond Lindeman's work on the trophic-dynamic aspect of ecology [5] established the concept of energy transfer across food webs, highlighting the importance of primary production and energy conversion efficiency across trophic levels.

Research into predator-prey interactions, competition, and succession in aquatic ecosystems helped clarify the structure and function of ecological communities [11–13]. Scientists delve into their research at least three trophic levels (algae, zooplankton, and fish) for marine and freshwater environments. These studies underscored the complexity of biotic interactions and their sensitivity to environmental fluctuations.

In freshwater and marine systems, the cycling of key elements—such as carbon, nitrogen, phosphorus, and silica—became a central research focus. Scientists investigated eutrophication, particularly in lakes and coastal estuaries, caused by excessive nutrient inputs and outflow from agriculture and urban runoff [14–16]. These studies underpinned the mainstream of ecological theory and shaped public awareness of water quality management in the ecosystem. Marine primary productivity, particularly about phytoplankton, was explored using early satellite technologies for chlorophyll measurements. Research revealed the spatial and temporal variability of oceanic productivity and its role in supporting fisheries and regulating global nutrient cycles, e.g., C and Fe [17]. Although knowledge and technologies are still evolving, progress in these areas has contributed significantly to the basis of contemporary ecological theory and the regulatory framework of ecosystem management.

2.3. Investigation of Pollutions and Ecotoxicity Studies

The health of aquatic ecosystems is under mounting threat from various anthropogenic stressors, with pollution as a major driver of ecological degradation. Aquatic pollution encompasses a broad spectrum of physical, chemical, and biological contaminants that disrupt ecosystem structure and function [18]. Over the past two decades, scientific research has expanded significantly in this field and explored the contamination sources, pathways, impacts in freshwater and marine systems, and potential mitigation solutions. This work is critical to supporting and developing conservation policy and management strategy for water resources in a sustainable manner, especially in light of escalating urbanization, industrialization, and climate change.

In the latter half of the 20th century, studies on the impact of pollution became more prevalent. Research addressed heavy metals, oil spills, persistent organic pollutants (POPs), and microplastics [19]. Concomitant with climate change concerns, the impacts of acidification, thermal pollution, and hypoxia on aquatic biota and habitat quality were also widely documented [20]. Aquatic toxicology emerged as a sub-discipline, developing standardized bioassays using indicator species such as *Daphnia*, *Artemia*, and zebrafish (*Danio rerio*). These methods facilitated the assessment of chemical stressors on reproduction, growth, and survival, contributing to environmental risk assessment and regulatory frameworks. For example, some standard detection methods have been employed in policy-making decisions at the Organisation for Economic Co-operation and Development (OECD) and the Society of Environmental Toxicology and Chemistry (SETAC).

2.4. Research Services for Fisheries, Aquaculture, and Ecosystem Management

The need to manage aquatic resources sustainably spurred the development of fisheries science, which integrated population dynamics, stock assessment, and harvest strategies. Early models, such as the Schaefer model, were used to assess the productive capacity of the fishery, rather than demand or economic costs [21]. The Ricker model predicted the number of fish in a fishery for stock and recruitment in management practices for commercially important species [22]. These studies have mainly altered the traditional consciousness and sustained the development of fisheries.

Concurrently, the rise of aquaculture in the 1960s and 1970s provided an important supplement to the decline of wild-capture fisheries. Research focused on hatchery techniques, nutrition enrichment, disease management, and species domestication [23]. Species such as carp, tilapia, Atlantic salmon, and shrimp were subject to intense study, forming the basis for modern aquaculture. From the 1970s, aquaculture research shifted from empirical trials to systematic science. Pioneering work in the breeding and larval rearing carp, tilapia, salmon, and shrimp revolutionized seafood production [24]. Research into fish nutrition, reproductive endocrinology, and disease control (especially viral and bacterial pathogens) laid the foundation for intensive aquaculture systems. The growth was further accelerated by genetic selection and hybridization techniques that emerged in the 1990s, particularly for improving growth rate, disease resistance, and environmental tolerance of some targeted aquatic animals.

Ecosystem-based management needs a holistic approach that considers the entire ecosystem rather than focusing on individual issues or species. This can form a solid basis for pursuing sustainable goals. From the 1980s onwards, ecosystem-based perspectives gained momentum. Researchers emphasized biodiversity conservation, habitat restoration, and the protection of critical ecosystems such as coral reefs, mangroves, seagrass beds, and wetlands [25]. Long-term ecological research programs were established in 1980, focusing on the ecological processes over extended temporal and spatial scales, enabling the detection of climate change trends and species invasions [26].

Past aquatic life and ecosystems research has evolved from foundational taxonomy and natural history to sophisticated ecosystem-level analyses integrating multiple disciplines. The legacy of these studies is evident in our growing knowledge of aquatic biodiversity, ecosystem function, and relevant risk assessment of human activities. This historical foundation has been critical in shaping contemporary approaches to aquatic resource management, conservation planning, and sustainable aquaculture development.

3. Current Research: Integration, Interdisciplinarity, and Technological Advancement

A convergence of ecological integration, technological innovation, and a growing awareness of the intricate linkages between aquatic systems and global environmental change increasingly drives current research on aquatic life and aquatic ecosystems. It has become a field that naturally brings together a range of disciplines, from biology and ecology to chemistry, physics, and, more recently, computational sciences. This interdisciplinary approach is helping us gain a better understanding of the complex dynamics within aquatic environments and providing new tools to tackle the challenges.

3.1. The Influence of Climate Change on Ecosystem Functioning

The primary focus in aquatic research today is the impact of climate change on aquatic biodiversity, productivity, and ecosystem resilience. Researchers are investigating ocean warming and acidification as the main factors that alter species distributions, reproductive timing, and physiological tolerances, particularly in sensitive organisms such as corals, plankton, and polar species [27]. Ocean warming, primarily resulting from the escalating levels of greenhouse gases in the atmosphere, leads to a rise in the temperature of the Earth's oceans. These gases act as heat-trapping agents, contributing to the overall phenomenon of global warming. Ocean acidification is the ongoing decrease in the pH of Earth's oceans, primarily caused by the absorption of excessive carbon dioxide (CO_2) from the atmosphere [28]. This absorption leads to chemical reactions that increase seawater acidity, making it difficult for some marine life to thrive, especially those that build shells and skeletons from calcium carbonate.

Climate changes also impact freshwater systems. Freshwater ecosystems are susceptible to warming because their chief drivers, water quality and water quantity, are strongly influenced by atmospheric temperature regimes [29]. Air temperature determines both water temperature and many chemical attributes contributing to water quality (e.g., dissolved oxygen levels), and its suitability for supporting freshwater biodiversity and maintaining critical ecological functions and services. Thus, water temperature change can shift hydrological regimes and affect fish spawning, invasive species dispersal, and nutrient dynamics in the food webs.

In marine environments, seagrass meadows and macroalgal beds provide important habitats for diverse invertebrate and fish communities [30]. Meanwhile, such assemblages can also function with greater resilience to external environmental stressors such as eutrophication and warming. Similarly, coral diversity can enhance reef accretion, carbonate production, and structural complexity while largely supporting the structure and diversity of fish assemblages [31]. A greater variety of coral species is generally associated with a more diverse fish community, with some coral species playing a more crucial role in promoting fish diversity than others. Notably, this was little understood in the past ecosystem research.

In freshwater ecosystems, invertebrate shredders in streams with different feeding strategies contribute additively or synergistically to leaf litter breakdown, affecting nutrient availability and microbial activity [32]. Algal periphyton form biofilms and promote efficient nutrient uptake to stabilize ecosystem functions under fluctuating light and nutrient regimes. In tropical and temperate river systems, fish with varying feeding strategies and body sizes influence ecosystem processes such as sediment transport, algal control, and nutrient cycling. In lake ecosystems, phytoplankton functional diversity is linked to productivity, while diverse zooplankton communities can enhance top-down control of harmful algal blooms [33]. Therefore, biodiversity is not merely a count of species but a foundational driver of ecological processes, resilience, and services.

In marine and freshwater systems, the relationship between biodiversity and ecosystem functioning has emerged as a pivotal theme in ecological research, with wide-ranging implications for conservation biology, ecosystem restoration, and sustainable resource management. Biodiversity in the ecosystem becomes more vulnerable to climate change, which is more severe than in any other decade in the past. Research on biodiversity and functions of aquatic ecosystems sheds light on the fundamental role of biological diversity in maintaining the stability, productivity, and resilience of aquatic environments

3.2. Knowledge Advances in Aquatic Microbiomes and Genomics

Aquatic microbiomes have emerged as one of the most dynamic frontiers in aquatic science [34]. Microbial communities, comprising bacteria, viruses, protists, and fungi, are not merely passive components of aquatic ecosystems but active drivers of biogeochemical cycles, ecosystem resilience, host health, and environmental responses to anthropogenic stress. Contemporary research on aquatic microbiomes, spanning both marine and freshwater systems, is increasingly recognized for linking microbial diversity to ecosystem function, aquaculture sustainability, and global environmental change.

Microbiomes play a vital role in the global carbon cycle by modulating the movement and storage of carbon in aquatic systems [35]. They contribute to several critical processes such as the introduction of carbon into ecosystems through autotrophs like phytoplankton, and the mineralization and recycling of organic matter by heterotrophs like bacteria and fungi. These microbial activities support carbon sequestration and facilitate the carbon export from surface waters to deeper ocean regions, thereby influencing the planet's overall carbon balance.

Microorganisms, especially bacterioplankton and microzooplankton, form the base of the microbial loop as a crucial component of aquatic food webs [36]. In this loop, dissolved organic matter (DOM) is metabolized by heterotrophic bacteria, which are then consumed by heterotrophic nanoflagellates and ciliates. This process transfers energy to the classical food chain via organisms like zooplankton and small fish. The microbial loop is important in oligotrophic systems where phytoplankton–zooplankton–fish pathways are limited. Overall, aquatic microbiomes underpin a wide range of ecological functions, supporting ecosystem stability, productivity, and resilience in the face of environmental changes.

Aquatic genomics is a multidisciplinary field that integrates molecular genetics and bioinformatics with marine and freshwater biology to investigate the structure, function, evolution, and regulation of genes in aquatic organisms [37]. There is immense potential to leverage this research to advance our understanding of aquatic biodiversity, improve aquaculture productivity, protect endangered species, and address environmental challenges. The rapid advancement in high-throughput sequencing technologies and computational biology has substantially accelerated genomic investigations in various aquatic species, such as fish, crustaceans, molluscs, algae, and marine microbes. Furthermore, depending on different purposes, developing pan-genomes and population-scale sequencing projects will enhance genomic selection and adaptive management strategies. Research in aquatic genomics is currently reshaping our understanding of and management of aquatic ecosystems.

With the rapid development of eDNA techniques, metagenomics has transformed microbial ecology and evolutionary biology by revealing previously hidden biodiversity and metabolic capabilities. Metagenomic sequencing offers new insight into microbial community structure, function, and interactions within host organisms in environmental matrices (e.g., sediments, water columns) [38]. Such studies have become a cornerstone of modern aquatic science, bridging fundamental biology and applying research to uncover microbiota's key roles in different ecosystems.

Together with other omics approaches (proteomics, metabolomics, and phenomics), artificial intelligence, and systems biology, aquatic genomics has provided unprecedented insights into elaborate organismal and ecosystem functions. Apparently, it is essential to keep investing in developing and deploying the right tools like genomic infrastructure, bioinformatics, and training across disciplines, to truly harness the power of genomics for sustainable aquaculture, biodiversity conservation, and healthy aquatic environment management.

3.3. New Developments in Aquatic Ecosystem Management

Water pollution has become a significant challenge for ecosystem management. Current research on aquatic pollution reflects a rapidly evolving field driven by escalating environmental concerns, technological advancements, and regulatory imperatives [39]. Pollution in aquatic ecosystems has become increasingly complex due to the diversity of contaminants, their synergistic effects, and negative ecological and health implications in rivers, lakes, estuaries, and oceans. From traditional pollutant detection, holistic research has been conducted to investigate contamination sources, transport mechanisms, ecotoxicological effects, bioaccumulation, remediation technologies, and relevant policy frameworks.

In recent years, emerging contaminants have triggered a lot of environmental attention. They include pharmaceuticals, personal care products, microplastics, and nanoplastics [40]. These contaminants have been widely detected in fresh and marine environments with evidence of ecotoxicological effects on aquatic organisms, such as endocrine disruption in fish, bioaccumulation, and biomagnification through food webs.

For example, it is revealed that microplastics (1 µm–5 mm) are ubiquitous in aquatic environments, and the uptake by plankton, invertebrates, and fish can lead to physical damage, inflammation, and altered feeding [41]. Meanwhile, nutrient over-enrichment, primarily nitrogen and phosphorus from agriculture and urban runoff, also remains a leading cause of eutrophication, harmful algal blooms, and hypoxia in the ecosystem. Aquatic pollution research is characterized by its interdisciplinarity, from eutrophication and antimicrobial resistance to microplastics and pharmaceuticals, confronting diverse and interacting threats.

Freshwater ecosystem management has become a critical domain of environmental science, particularly as anthropogenic pressures and climate change increasingly threaten freshwater biodiversity, water quality, and ecosystem services. This field integrates ecological theory, hydrological modelling, and conservation biology to ensure the sustainability of inland aquatic ecosystems such as rivers, lakes, wetlands, and reservoirs. With the rapid development of urbanization and industrialization, the ecological consequences of river damming, flow regulation, and water diversion projects are also under active scrutiny as an essential part of contemporary ecosystem management.

For example, in China's South to North Water Division projects, the reservoir operation will impact the downstream hydrological regime and ecological health [42]. Maintaining water quality is central to freshwater ecosystem health. Major concerns are nutrient loading from agriculture, industrial pollutants, and emerging contaminants such as pharmaceuticals and microplastics. The integration of microbial ecology into water quality research, particularly the study of microbial communities in pollutant degradation, is a growing frontier. Freshwater ecosystems are particularly vulnerable to biological invasions, which can disrupt native communities and ecosystem functions. For example, the water diversion projects provide pathways for introducing and spreading aquatic invasive species, which cause ecological impacts on food web structure and nutrient cycling [43].

Therefore, the management strategies must be reinforced, including mechanical removal, chemical control, and biological suppression. Freshwater ecosystem management is vital for conserving biodiversity, ensuring water security, and adapting to global environmental change. Research efforts must continue bridging ecological theory with applied management, incorporating technological innovations and ecosystem-based approaches. As freshwater systems face unprecedented stressors, effective management informed by robust scientific research is more essential than ever.

3.4. Ecological Demands for Aquaculture and Fishery Development

Aquaculture and fisheries research form the backbone of global efforts to ensure food security, sustainable resource use, and environmental stewardship [44]. Together, they support one of the world's most vital food-producing sectors, providing livelihoods to millions and supplying nearly 50% of the fish consumed globally. As global demand for aquatic products increases due to population growth and dietary shifts, research in aquaculture and fisheries has expanded significantly to address emerging biological, technological, economic, and ecological challenges.

Contemporary research in aquaculture has evolved into a highly interdisciplinary field that integrates biology, biotechnology, engineering, environmental science, sustainability, and marine farming [45]. The endeavours include genetic improvement and breeding, nutrition and functional feeds, disease management and health, precision aquaculture, and digital technologies. Research in fisheries covers fish stock assessment and ecosystem modelling, climate change and fisheries adaptation, biodiversity conservation and bycatch reduction. However, it remains crucial for understanding population dynamics, managing wild stocks, and conserving marine and freshwater biodiversity. In other words, the progress achieved in aquaculture and fisheries should be driven by the urgent need to balance production with sustainability, biodiversity conservation, and climate resilience. Future research must prioritize interdisciplinary collaboration, innovation in biotechnology, and digital tools, aiming for a sustainable and equitable blue economy.

4. Future Research Perspectives

Future research in aquatic life and ecosystems must address the growing environmental, technological, and socio-economic challenges reshaping freshwater and marine environments. The continued degradation of these aquatic environments demands a shift in how we approach research and conservation strategy to confront issues like pollution, climate change, overexploitation, habitat loss, and species invasions. Therefore, future research must be interdisciplinary, solution-focused, and globally coordinated to meet these complex challenges. Figure 2 provides a graphic summary to illustrate the directions of future aquatic biology research, including microbomes and holobionts, emerging contaminants and pollution remediation, blue carbon and ecosystem services, deep-sea exploration and mapping, AI, remote sensing and big data, restoration and nature-based solutions, climate resilience and biodiversity, and genomics and eDNA biodiversity mapping. The following thematic areas are recommended as key priorities and emerging frontiers for future research.

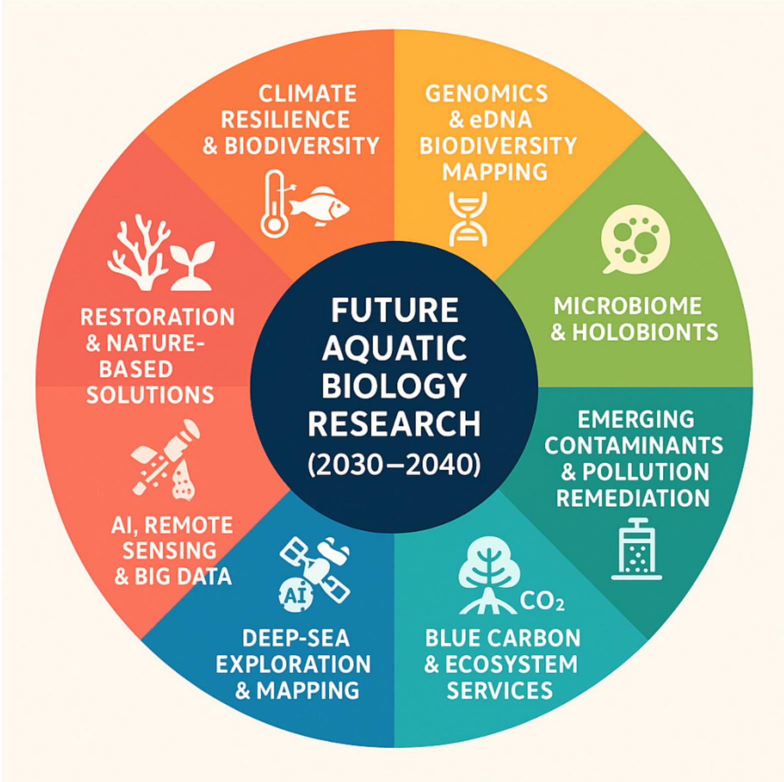

Figure 2. A graphic summary of the areas of future aquatic biology research.

4.1. Impacts of Climate Change on Aquatic Biodiversity and Ecosystem Functions

Climate change is widely recognized as a major driver of ecological change in aquatic ecosystems, exerting multidimensional impacts on biodiversity, species interactions, and critical ecosystem functions. Both freshwater and marine systems are increasingly vulnerable to alterations in temperature regimes, hydrological cycles, ocean chemistry, and extreme weather events. Research perspectives in this domain are with a growing emphasis on mechanistic understanding, predictive modelling, and ecosystem-based adaptation.

4.2. Advances in Aquatic Genomics, Biodiversity Monitoring, Microbial Ecology, and Biogeochemical Cycling

Aquatic ecosystems are highly dynamic and complex systems that provide vital ecological functions, biodiversity reservoirs, and services essential to global sustainability. Contemporary research increasingly integrates molecular, ecological, and geochemical approaches to understand aquatic biodiversity, ecosystem processes, and anthropogenic impacts. The convergence of genomic technologies with ecological monitoring, microbial research, and biogeochemical studies has opened transformative pathways for aquatic sciences.

4.3. Pollution, Emerging Contaminants, and Their Effects on Ecosystem Health

The proliferation of anthropogenic pollutants in aquatic environments poses an escalating threat to ecosystem integrity and biodiversity. While classical pollutants such as heavy metals, nutrients, and hydrocarbons have long been recognized and studied, the growing prevalence of emerging contaminants—including pharmaceuticals, microplastics, endocrine-disrupting compounds, and nanomaterials—has introduced complex challenges for ecosystem assessment and management. These substances often elude traditional monitoring programs and can negatively affect biota and ecological processes.

4.4. Integrated Management of Ecosystems and Watersheds

The integrated management of ecosystems and watersheds is a foundational strategy for sustaining freshwater and coastal ecosystems amid growing anthropogenic pressures. As natural hydrological units, watersheds provide the spatial framework through which ecological processes, human activities, and governance mechanisms interact. Managing these systems holistically is essential to protect biodiversity, maintain ecological functions, and ensure the provision of ecosystem services such as clean water, fisheries productivity, flood regulation, and nutrient cycling.

4.5. Innovations in Aquaculture and Sustainable Food Production

Aquaculture has emerged as the world's fastest-growing food production sector, supplying over half of the global fish and seafood consumed. As the demand for protein-rich food rises due to population growth and dietary shifts, aquaculture holds critical potential for contributing to sustainable food systems. However, the sector must navigate complex challenges, including environmental degradation, disease management, feed sustainability, and socio-economic equity.

5. Conclusions

The study of aquatic life and ecosystems has developed into a highly interdisciplinary field that integrates biology, ecology, genomics, environmental sciences, and biotechnology to address the complex challenges in both freshwater and marine environments. Biodiversity plays a role in maintaining the stability, productivity, and resilience of these ecosystems. From microbial assemblages to apex predators, the diversity of aquatic communities regulates biogeochemical cycles, influences water quality, and energy flows through food webs. Research advances in aquatic genomics, microbiome ecology, and environmental DNA (eDNA) have paved new pathways for detecting species profiles, exploring population genetics, and analysing functional traits. Despite these technological breakthroughs, significant knowledge gaps persist. There is still an urgent need to deepen our understanding of species interactions across trophic levels, assess ecosystem responses to cumulative stressors, and translate scientific insights and advice into effective policy and management strategies. This requires collaborative frameworks to bridge the gap between science and actions, which can bring together researchers, policymakers, industry stakeholders, and local communities. Table 2 summarises the major research themes, frontier research, and pressing questions in the next decade.

Table 2. Strategic research pillars in aquatic biology and pressing questions.

Major Pillars (2025–2035)	Frontier Research and Pressing Questions	Key References
Climate-change impacts & adaptation	Thermal tolerance limits, ocean acidification physiology, harmful algal bloom forecasting, climate refugia mapping	[46]
Genomics and eDNA biodiversity monitoring in water	Standardised field/lab pipelines, real-time species detection, population genoscapes for management	[47]
Aquatic microbiomes and meta-omics	Host–microbe holobiont resilience, virome discovery, metabolomic signatures of stress	[48]
Biogeochemical cycling and blue carbon	Carbon sequestration rates in seagrass/mangroves, methane dynamics, nutrient feedback	[49]
Pollution and emerging contaminants	Mixture toxicity of micro-/nanoplastics, pharmaceuticals; early-warning biosensors	[50]
Restoration ecology and nature-based solutions in water	Assisted evolution of corals, ecological engineering of wetlands, and integrated catchment-to-coast planning	[51]
Deep-sea and polar exploration	Autonomous landers, hadal-zone omics, cryo-preservation of extremophiles, Antarctic lake drilling	[52]
AI, remote sensing & big-data analytics in oceans	Satellite-linked animal telemetry, explainable AI for ecosystem forecasting, and digital-twin oceans	[53]

The research in aquatic life and ecosystems is at a critical juncture. Undoubtedly, the research community can help contribute to the long-term health and functionality of aquatic ecosystems. Still, the primary condition is to align ecological theory with technological development and inclusive governance worldwide. The decade ahead will call for continued scientific innovation. This will be underpinned by holistic and interdisciplinary approaches to ensure the sustainable use and protection of aquatic environments.

Author Contributions

J.Q. has made substantial contributions to the conception or design of the work and drafted the work. Z.M. and Y.L. substantively revised it; J.Q. has approved the submitted version and agreed to be personally accountable for the author's own contributions and for ensuring that questions related to the accuracy or integrity of any part of the work. All authors have read and agreed to the published version of the manuscript.

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