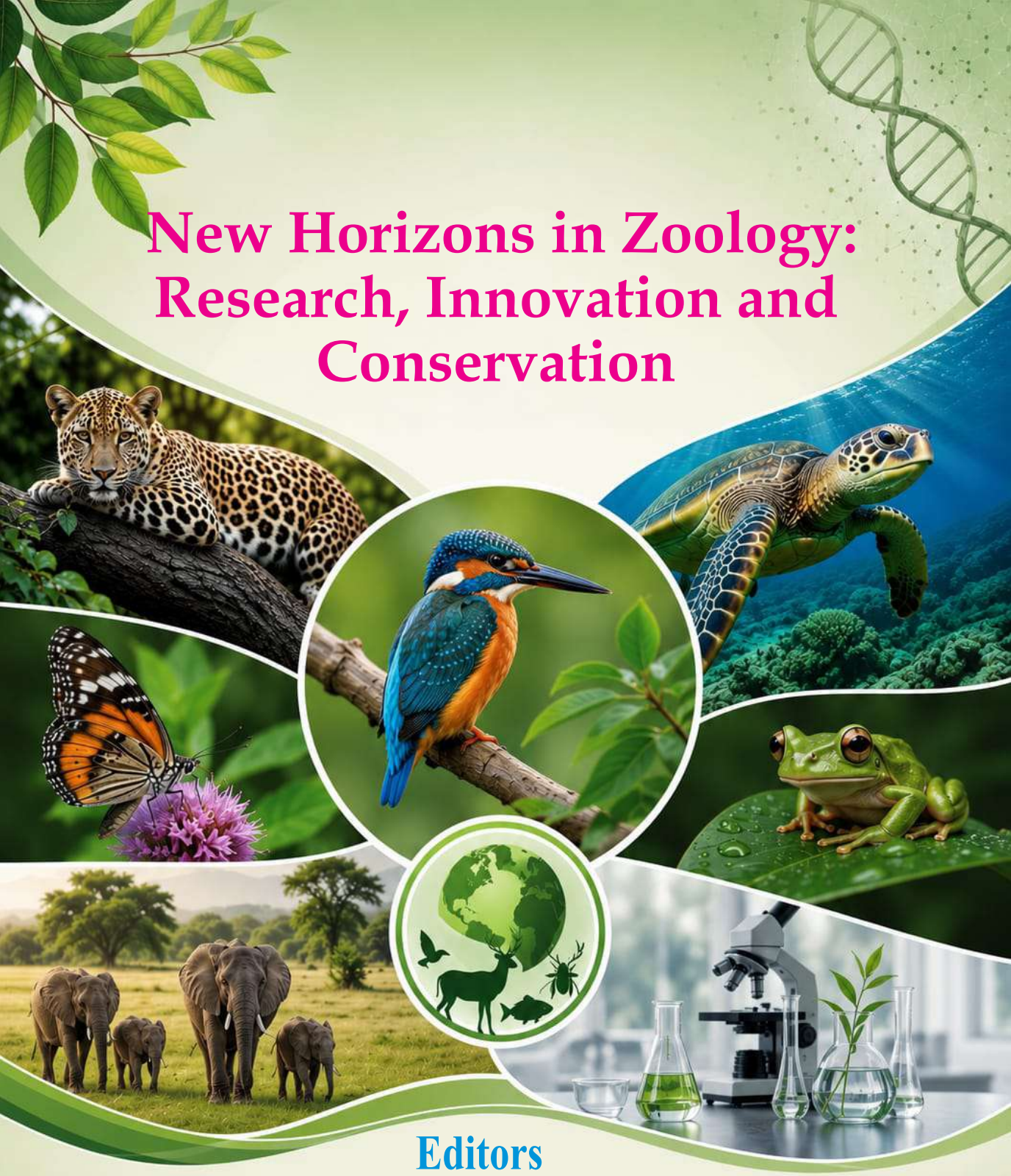
New Horizons in Zoology: Research, Innovation and Conservation



Editors

Dr. Dipanjan Ray
Dr. M. Venkata Chandrudu
Dr. K. Vanaja
Dr. R. Chandra Mouli

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Preface

New Horizons in Zoology: Research, Innovation and Conservation brings together contemporary research and emerging developments across diverse areas of zoological science. The book highlights the importance of biodiversity, animal biology, aquatic resources, ecology, wildlife conservation, and technological innovation in understanding the rapidly changing natural world.

The opening chapter explores invertebrate diversity, emphasizing the ecological significance and richness of invertebrate groups. The chapter on non-Newtonian blood flow demonstrates the application of mathematical and computational approaches to biological systems and arterial studies.

Aquatic sciences form an important part of the volume through discussions on aquaculture as a future food resource and the growing ornamental fish-farming industry in India. These chapters highlight opportunities for sustainable aquatic production and economic development. The book also examines aquatic biodiversity and water-quality dynamics in floodplain wetlands of Jorhat, Assam, emphasizing the ecological importance of wetlands and their conservation.

Modern technologies are transforming zoological research, and the chapter on Artificial Intelligence, GIS, and Bioinformatics illustrates their applications in biodiversity studies, ecological assessment, and biological data analysis. The volume further explores avian ecosystem services, demonstrating the important roles of birds in maintaining ecosystem functioning.

Wildlife and ecological challenges are addressed through discussions on human–tiger conflict, sustainable pest and disease management, and the physiological and behavioural adaptations of species living in urban environments. These topics underline the need for scientifically informed and sustainable approaches to wildlife management and conservation.

Overall, this edited volume presents zoology as a dynamic and interdisciplinary field connecting biological research with technology, ecology,

conservation, and sustainable development. It will be useful to students, researchers, educators, and professionals seeking a concise overview of emerging research and applications in modern zoology.

Editors

New Horizons in Zoology: Research, Innovation and Conservation

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Invertebrate Zoology and Diversity

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Abstract

Invertebrates constitute the most diverse and ecologically significant component of the animal kingdom, occurring across marine, freshwater, terrestrial, soil, and extreme environments. This chapter presents a comprehensive overview of invertebrate zoology and diversity, focusing on their classification, general characteristics, evolutionary significance, ecological functions, economic importance, and conservation challenges. Major invertebrate phyla, including Porifera, Cnidaria, Ctenophora, Platyhelminthes, Nematoda, Annelida, Mollusca, Arthropoda, Echinodermata, and Hemichordata, are examined in relation to their distinctive body plans, adaptations, habitats, and evolutionary relationships. The chapter explores major patterns of invertebrate diversity, including habitat, morphological, functional, and biogeographical variation. Invertebrates perform essential ecosystem functions such as pollination, decomposition, nutrient cycling, soil formation, biological control, and food-web regulation. They also provide important economic resources through apiculture, sericulture, lac production, fisheries, vermicomposting, and biomedical research. However, invertebrate populations face increasing threats from climate change, habitat destruction and fragmentation, pollution, pesticide exposure, invasive species, ocean acidification, and biodiversity loss. Modern approaches, including molecular taxonomy, DNA barcoding, environmental DNA, phylogenetic analysis, GIS, remote sensing, artificial intelligence, digital biodiversity databases, and citizen science, provide new opportunities for documenting and monitoring invertebrate diversity. Greater integration of traditional taxonomy with molecular and computational approaches is essential for identifying poorly studied species, understanding environmental

responses, and developing effective conservation strategies. The chapter emphasizes that improved knowledge of invertebrate diversity is fundamental for understanding animal evolution, maintaining ecosystem stability, supporting sustainable agriculture, and strengthening global biodiversity conservation.

Keywords: Invertebrates; Animal Diversity; Evolution; Biodiversity; Ecosystem Functions; Conservation; Taxonomy; DNA Barcoding

Introduction

Invertebrate zoology is a major branch of zoology concerned with the study of animals that do not possess a vertebral column. Invertebrates constitute the vast majority of animal diversity and occur in almost every habitat, including marine environments, freshwater ecosystems, terrestrial habitats, soil, forests, agricultural landscapes, and even extreme environments. Their enormous diversity is reflected in their body organization, morphology, physiology, reproduction, development, behavior, and ecological adaptations (Brusca et al., 2023). Invertebrates include several major phyla, such as Porifera, Cnidaria, Ctenophora, Platyhelminthes, Nematoda, Annelida, Mollusca, Arthropoda, Echinodermata, and Hemichordata. These groups display remarkable variation in body symmetry, levels of organization, germ layers, body cavities, segmentation, locomotion, feeding mechanisms, and reproductive strategies. Arthropods, particularly insects, represent one of the most diverse groups of animals and occupy almost every terrestrial ecosystem. Molluscs, annelids, echinoderms, cnidarians, and other groups also contribute substantially to aquatic and terrestrial biodiversity (Pechenik, 2015).

Invertebrates play essential roles in ecosystem functioning. They participate in decomposition, nutrient cycling, pollination, soil formation, predation, herbivory, and food-web interactions. Earthworms improve soil structure and nutrient availability, while bees and other insects contribute significantly to the reproduction of flowering plants. Aquatic invertebrates are also widely used as biological indicators for evaluating water quality and ecosystem health (Schowalter, 2022). Despite their importance, invertebrate biodiversity is increasingly threatened by habitat destruction, pollution, climate change, invasive species, agricultural intensification, and overexploitation (Cardinale et al., 2012).

General Characteristics and Evolutionary Significance of Invertebrates

Invertebrates comprise an exceptionally diverse assemblage of animals that lack a vertebral column and represent most of the described animal diversity. They exhibit considerable variation in body size, morphology, physiology, development, behavior, and habitat preference. Their body organization ranges from the cellular level in Porifera to highly developed organ systems in groups such as Arthropoda and Mollusca (Brusca et al., 2023). Another important characteristic is variation in embryonic organization. Invertebrates may be diploblastic, as in cnidarians, or

triploblastic, as in most bilaterian groups. Triploblastic animals may possess an acoelomate, pseudocoelomate, or true coelomate body plan. The evolution of the coelom provided space for internal organs and supported greater structural and functional specialization. Segmentation, particularly evident in annelids and arthropods, further contributed to body specialization and efficient locomotion (Brusca et al., 2023).

Evolutionary Significance

Invertebrates are central to understanding the evolutionary history of animals. They represent numerous major evolutionary innovations, including multicellularity, tissue organization, bilateral symmetry, organ-system development, segmentation, specialized appendages, and complex sensory systems. The transition from relatively simple body organizations to more complex forms illustrates progressive diversification of animal body plans. Molecular and developmental studies have also demonstrated that traditional morphological classifications require continuous revision because evolutionary relationships may not always correspond to superficial structural similarities (Giribet & Edgecombe, 2020).

Classification and Major Invertebrate Groups

Invertebrates represent a highly diverse assemblage of animals traditionally defined by the absence of a vertebral column. Modern zoological classification increasingly relies on comparative morphology, embryology, molecular phylogenetics, and genomic evidence rather than on a simple division between "invertebrates" and vertebrates. Most major invertebrate lineages belong to either Protostomia or Deuterostomia, while Porifera and several other early-diverging lineages occupy important positions near the base of the animal tree (Giribet & Edgecombe, 2020)

Table 1. Classification and Diagnostic Features of Major Invertebrate Groups

Major Phylum	Major Characteristics	Body Organization	Representative Examples
Porifera	Cellular level organization; canal system; choanocytes; mostly sessile	Mostly asymmetrical	*Sycon*, *Spongilla*, bath sponges
Cnidaria	Radial symmetry; diploblastic body; cnidocytes; polyp and/or medusa forms	Tissue level	*Hydra*, jellyfish, corals
Ctenophora	Marine; biradial symmetry; eight comb rows; colloblasts	Tissue level	*Pleurobrachia*

Platyhelminthes	Bilateral symmetry; dorsoventrally flattened; acoelomate	Organ level	Planarians, flukes, tapeworms
Nematoda	Cylindrical unsegmented body; pseudocoel; complete digestive tract	Organ-system level	*Ascaris*, hookworms
Annelida	Metameric segmentation; true coelom; well-developed organ systems	Organ-system level	Earthworms, leeches, polychaetes
Mollusca	Soft body; mantle; muscular foot; visceral mass	Organ-system level	Snails, oysters, squid
Arthropoda	Segmented body; jointed appendages; chitinous exoskeleton	Organ-system level	Insects, spiders, crabs
Echinodermata	Marine; water vascular system; pentaradial adult symmetry	Organ-system level	Starfish, sea urchins
Hemichordata	Marine; body divided into proboscis, collar and trunk	Organ-system level	*Balanoglossus*

Source: Compiled from Brusca et al. (2023), Pechenik (2015), and Giribet and Edgecombe (2020).

Major Invertebrate Groups



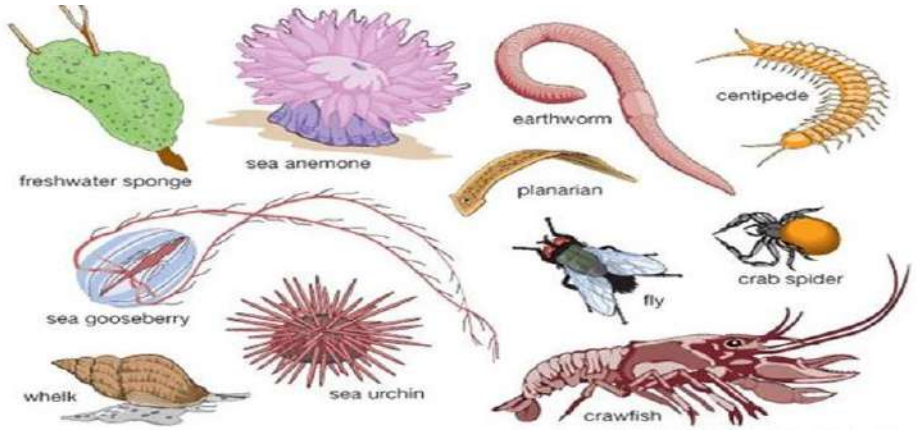
Porifera are among the simplest multicellular animals and possess a characteristic water canal system. Cnidarians include hydroids, jellyfish, sea anemones, and corals and are distinguished by specialized cnidocytes. Ctenophores are exclusively marine and use comb rows for locomotion. Platyhelminthes include free-living and parasitic flatworms, whereas Nematoda contains numerous free-living and parasitic species.

Types of Invertebrates

Annelids exhibit true segmentation and include earthworms, leeches, and polychaetes. Molluscs display extensive diversity in body form and include gastropods, bivalves, cephalopods, and other groups. Arthropoda is the most species-rich major animal phylum and includes insects, crustaceans, arachnids, and myriapods. Their jointed appendages and exoskeleton have contributed greatly to ecological diversification (Brusca et al., 2023).

Diversity of Major Invertebrate Phyla

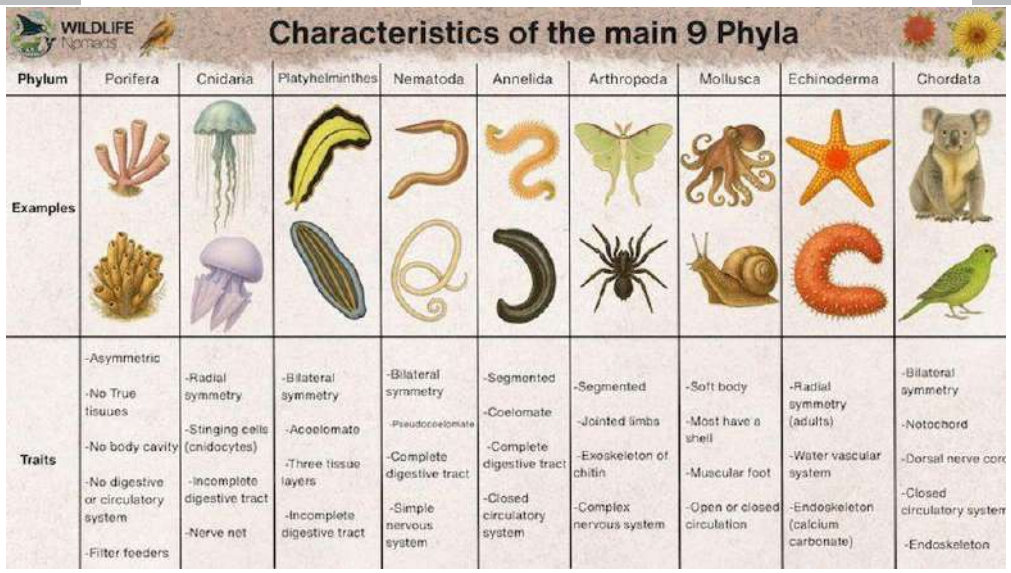
Invertebrates display extraordinary diversity in body structure, habitat, feeding strategy, reproduction, and ecological function. Modern classifications recognize numerous animal phyla, with major groups differing substantially in their evolutionary history and body plans (Brusca et al., 2023).



Diversity in Living Organism

1. Porifera

Poriferans, commonly known as sponges, are predominantly aquatic and are characterized by a porous body, canal system, choanocytes, and a relatively simple level of organization. Most species are marine, although freshwater forms also occur. Their body architecture permits continuous water circulation, allowing them to obtain food particles and oxygen while removing metabolic wastes. Sponges also provide habitat for numerous microorganisms and small aquatic organisms, contributing to marine biodiversity (Brusca et al., 2023).



Characteristics of Main 9 Phyla

2. Cnidaria

Cnidarians include hydras, jellyfish, sea anemones, and corals. They possess radial or modified radial symmetry, diploblastic organization, and specialized cnidocytes used for prey capture and defense. The occurrence of polyp and medusa forms contributes to their ecological diversity. Coral-forming cnidarians are particularly important because coral reefs provide habitat for a large variety of marine organisms. Coral-associated invertebrate communities can be highly diverse and closely dependent on coral habitat (Stella et al., 2011).

3. Platyhelminthes

Platyhelminthes are bilaterally symmetrical, dorsoventrally flattened animals. The group includes free-living planarians as well as parasitic flukes and tapeworms. Parasitic forms possess specialized adaptations for attachment, nutrient acquisition, reproduction, and survival within hosts. Their diversity demonstrates how similar basic body plans can evolve very different ecological strategies.

4. Nematoda

Nematodes are unsegmented, cylindrical worms occurring in marine, freshwater, soil, and host-associated environments. They include free-living species, plant parasites, animal parasites, and species involved in decomposition and nutrient cycling. Nematode communities are particularly useful for ecological studies because their composition can respond to environmental conditions. Modern DNA barcoding and metabarcoding techniques are increasingly useful for characterizing nematode communities that are difficult to identify using morphology alone (Schenk et al., 2020).

5. Annelida

Annelids are characterized by segmentation and include polychaetes, earthworms, leeches, and several specialized lineages. They occur in marine, freshwater, and terrestrial habitats. Recent molecular studies have substantially revised traditional views of annelid relationships and have revealed previously unrecognized diversity, including cryptic species (Capa & Hutchings, 2021).

6. Mollusca

Molluscs represent one of the most diverse invertebrate groups and include gastropods, bivalves, cephalopods, chitons, and several smaller lineages. Their body plan generally includes a mantle, muscular foot, and visceral mass, although these structures have undergone extensive modification. Gastropods have diversified into marine, freshwater, and terrestrial environments, while cephalopods exhibit advanced locomotion, sensory systems, and predatory adaptations. Bivalves play important roles as filter feeders and can influence water quality and nutrient cycling.

7. Arthropoda

Arthropods represent the largest and most diverse major animal phylum. They possess a segmented body, jointed appendages, and an external cuticle that provides protection and mechanical support. Major groups include insects, crustaceans, arachnids, and myriapods. Insects have achieved exceptional diversification across terrestrial and freshwater habitats. Recent standardized sampling has demonstrated that a substantial portion of arthropod biodiversity remains poorly characterized, particularly among insects (Meier et al., 2023).

8. Echinodermata

Echinoderms are exclusively marine and include starfish, brittle stars, sea urchins, sea cucumbers, and crinoids. Adults generally exhibit pentaradial symmetry, whereas their larvae are bilaterally symmetrical. The water vascular system and tube feet are distinctive features of the group. Echinoderms exhibit considerable morphological diversity, and their evolutionary history provides important evidence for understanding changes in animal body plans and developmental organization (Raff et al., 2021).

9. Hemichordata

Hemichordates are marine deuterostomes represented mainly by acorn worms and pterobranchs. Their body is divided into proboscis, collar, and trunk regions. They possess pharyngeal openings and share several developmental and anatomical features with other deuterostomes. Consequently, hemichordates are important for understanding the evolutionary history of deuterostomes and the transition toward chordate characteristics (Brusca et al., 2023).

Table 2. Comparative Diversity of Major Invertebrate Phyla

Phylum	Major Body Feature	Principal Habitat	Representative Examples	Major Ecological/Evolutionary Significance
Porifera	Porous body and canal system	Mainly marine	*Sycon*, *Spongilla*	Filter feeding and habitat formation
Cnidaria	Cnidocytes; polyp/medusa forms	Marine and freshwater	Hydra, corals, jellyfish	Coral reef formation and food webs
Platyhelminthes	Flattened acoelomate body	Aquatic, terrestrial, parasitic	Planarians, flukes, tapeworms	Free-living and parasitic adaptations
Nematoda	Cylindrical unsegmented body	Soil, water, hosts	*Ascaris*, plant-parasitic nematodes	Nutrient cycling and parasitism
Annelida	Segmented body	Marine, freshwater, terrestrial	Earthworms, leeches, polychaetes	Soil processes and benthic ecology
Mollusca	Mantle, foot and visceral mass	Marine, freshwater, terrestrial	Snails, oysters, squid	Grazing, filtration and predation
Arthropoda	Jointed appendages and exoskeleton	Almost all habitats	Insects, spiders, crabs	Exceptional species and ecological diversity
Echinodermata	Water vascular system	Marine	Starfish, sea urchins	Benthic ecosystem functioning
Hemichordata	Proboscis, collar and trunk	Marine	*Balanoglossus*, pterobranchs	Deuterostome evolution

Source: Compiled from Brusca et al. (2023), Capa and Hutchings (2021), Meier et al. (2023), and Schenk et al. (2020).

Patterns of Invertebrate Diversity

Invertebrate diversity shows strong variation across habitats, geographic regions, body forms, and ecological functions. Invertebrates occupy almost all major environments and collectively display exceptional morphological and functional diversity. Their distribution is influenced by temperature, moisture, productivity, habitat complexity, resource availability, dispersal ability, evolutionary history, and environmental disturbance (Eisenhauer & Hines, 2021).

1. Habitat Diversity

- **Marine Ecosystems:** Marine environments support a large proportion of invertebrate diversity, including sponges, cnidarians, molluscs, crustaceans, annelids, and echinoderms. Coral reefs, coastal sediments, mangroves, and deep-sea habitats provide distinct ecological conditions and support specialized communities (Marshall et al., 2012).
- **Freshwater Ecosystems:** Rivers, streams, lakes, ponds, and wetlands contain diverse aquatic invertebrates, including molluscs, crustaceans, annelids, nematodes, and insect larvae. Environmental factors such as water temperature, flow, dissolved oxygen, substrate, and nutrient availability strongly influence community composition.
- **Terrestrial Ecosystems:** Forests, grasslands, agricultural fields, deserts, and urban environments support enormous numbers of insects, spiders, mites, myriapods, and terrestrial molluscs.
- **Soil and Litter Habitats:** Soil and leaf litter contain numerous small invertebrates, including earthworms, mites, springtails, nematodes, and other microarthropods. These organisms contribute to decomposition, nutrient cycling, and soil structure.
- **Extreme Environments:** Invertebrates also occur in deserts, polar regions, high-altitude habitats, caves, hydrothermal vents, and hypersaline environments. Their survival in such habitats demonstrates considerable physiological and ecological adaptability (Chown et al., 2015).

2. Morphological Diversity

Locomotory adaptations include cilia, muscular feet, parapodia, tube feet, jointed appendages, swimming structures, and wings. Protective structures include shells in molluscs, calcareous skeletons in corals, spicules in sponges, and chitinous exoskeletons in arthropods. Such morphological innovations have contributed to the diversification of animal lineages (Wiens, 2017).

3. Functional Diversity

Invertebrates perform a wide range of ecological functions. Filter feeders, including sponges and bivalves, remove suspended particles from water. Herbivores consume plants and influence vegetation dynamics, whereas carnivores regulate populations of other organisms. Detritivores and decomposers break down dead organic matter and contribute to nutrient cycling. Parasites influence host populations and community structure. Insects, particularly bees, butterflies, moths, and some beetles, act as important pollinators. Functional diversity therefore represents differences in the ecological roles and traits of organisms within communities (Petchey & Gaston, 2006; Schmera et al., 2017).

4. Biogeographical Patterns

Invertebrate diversity generally follows broad biogeographical patterns. Species richness often increases toward tropical regions, although the strength of this pattern differs among taxonomic groups and habitats (Kinlock et al., 2018). Temperate and polar regions contain fewer species overall, but many species possess specialized adaptations to seasonal or extreme climatic conditions. Endemism is particularly important in isolated mountains, islands, caves, and other geographically restricted habitats. Island diversity is influenced by area, habitat heterogeneity, isolation, immigration, speciation, and extinction. Temperature, precipitation, productivity, habitat structure, historical climate, and dispersal capacity collectively determine the distribution of invertebrate species (Gaston, 2000; Marshall et al., 2012).

Ecological Importance of Invertebrates

Invertebrates are fundamental components of terrestrial, freshwater, and marine ecosystems. Their ecological importance arises from the wide range of trophic and functional roles they perform. As primary consumers, herbivorous insects, molluscs, and other invertebrates regulate plant abundance and influence vegetation dynamics. As secondary consumers, spiders, predatory insects, centipedes, and predatory aquatic invertebrates regulate populations of herbivores and smaller organisms. These interactions contribute to ecosystem stability and energy transfer through food webs (Schowalter, 2022).

- **Pollination and Plant Reproduction:** Insects such as bees, butterflies, moths, beetles, and flies are important pollinators. By transferring pollen between flowers, they facilitate sexual reproduction and seed production in many flowering plants. Pollination by animals also supports agricultural production and contributes to the maintenance of plant diversity (Ollerton, 2017).
- **Decomposition and Nutrient Cycling:** Invertebrates contribute substantially to the breakdown of dead plant and animal material. Earthworms, termites, millipedes, springtails, mites, and insect larvae fragment organic matter and facilitate microbial decomposition. This process releases nutrients and supports soil fertility and primary productivity.
- **Soil Formation and Aeration:** Earthworms are particularly important ecosystem engineers. Their burrowing activities increase soil porosity, improve aeration and water infiltration, and redistribute organic matter and minerals. Termites and other soil-dwelling invertebrates also modify soil structure and influence nutrient availability (Lavelle et al., 2006).
- **Biological Control:** Predatory invertebrates, including ladybird beetles, lacewings, spiders, predatory bugs, and parasitoid wasps, naturally suppress populations of agricultural pests. Conservation of these beneficial organisms can reduce dependence on chemical pesticides and support integrated pest management (Wyckhuys et al., 2019).

- **Environmental Indicators:** Invertebrates are valuable bioindicators of environmental pollution because many species respond rapidly to changes in temperature, dissolved oxygen, nutrients, heavy metals, pesticides, and organic pollution. Aquatic macroinvertebrates, particularly insect larvae, are widely used to assess freshwater ecological quality because different taxa vary in their tolerance to pollution (Rosenberg & Resh, 1993).

Economic and Medical Importance of Invertebrates

Invertebrates have substantial economic and medical importance because they provide valuable products, ecosystem services, research models, and biological resources. Honeybees (*Apis spp*.) are important in apiculture because they produce honey, beeswax, propolis, and other products, while their pollination services contribute significantly to agricultural production. Silkworms (*Bombyx mori*) form the foundation of sericulture and silk production. Lac insects, particularly Kerria lacca, are commercially important for producing natural lac resin used in several industrial applications. Earthworms contribute to vermicomposting by converting organic waste into nutrient-rich material that can improve soil fertility. Crustaceans such as shrimp and crabs and molluscs such as oysters and mussels are important food and fishery resources. Predatory insects and parasitoids are also valuable biological control agents for managing agricultural pests (Brusca et al., 2023; Schowalter, 2022).

However, many invertebrates have harmful economic and medical effects. Agricultural insects can damage crops directly through feeding or indirectly by transmitting plant pathogens. Stored-grain pests, including beetles and moths, cause substantial quantitative and qualitative losses during storage. Invertebrates such as mosquitoes, ticks, and sand flies act as disease vectors, transmitting pathogens to humans and animals. Parasitic worms, including nematodes and flatworms, cause important diseases in humans, livestock, and crops. Plant-parasitic nematodes can reduce crop productivity and affect agricultural sustainability (Jones et al., 2013).

Invertebrates are also valuable in biomedical research. Organisms such as *Drosophila melanogaster, Caenorhabditis elegans,* and *Daphnia* are widely used as model organisms in genetics, developmental biology, toxicology, and molecular research. Their relatively short life cycles and experimentally tractable biology make them useful for investigating fundamental biological processes. In addition, marine invertebrates have yielded numerous biologically active compounds with potential pharmaceutical applications (Molinski et al., 2009).

Invertebrate Diversity and Environmental Change

Invertebrate diversity is increasingly affected by rapid environmental changes associated with climate change, land-use transformation, pollution, and biological invasions. Rising temperatures can alter species distributions, seasonal activity, reproduction, and population dynamics. Many insects are particularly sensitive to

temperature and precipitation changes, causing shifts in their geographic ranges and phenology. Such changes can disrupt interactions between predators, prey, plants, and pollinators (Harvey et al., 2020).

Habitat destruction and fragmentation caused by urbanization, agricultural expansion, deforestation, and infrastructure development reduce suitable habitats and isolate populations. Small and specialized invertebrates may be particularly vulnerable because habitat fragmentation can restrict dispersal and reduce access to food and breeding sites. Pollution and pesticide exposure can further reduce invertebrate abundance and diversity. Insecticides may affect target pests as well as beneficial organisms such as pollinators, predators, and decomposers (Sánchez-Bayo & Wyckhuys, 2019).

In marine environments, ocean warming and acidification create serious challenges for calcifying invertebrates. Corals, molluscs, and other organisms that construct calcium carbonate structures may experience reduced calcification and increased physiological stress. Coral decline can consequently affect numerous species that depend on reef habitats (Hoegh-Guldberg et al., 2017). Invasive species can alter native invertebrate communities through competition, predation, habitat modification, or disease transmission. At the same time, documented declines in insect abundance in several regions have raised concerns about the long-term stability of terrestrial ecosystems (Wagner et al., 2021).

Modern Approaches to Invertebrate Diversity Studies

The study of invertebrate diversity has shifted from traditional morphology-based identification toward integrative approaches combining classical taxonomy, molecular biology, geographic technologies, and computational methods. Classical taxonomy remains essential because diagnostic characters such as body structure, appendages, shells, reproductive organs, and other morphological features provide the foundation for species description and identification (Wheeler et al., 2012). Molecular taxonomy uses DNA sequences to identify species and resolve relationships among closely related or morphologically similar organisms. DNA barcoding, particularly the use of standardized genetic markers such as mitochondrial COI in many animals, has become an important tool for rapid species identification and biodiversity assessment (Hebert et al., 2003).

Environmental DNA (eDNA) allows researchers to detect organisms from DNA present in water, soil, or other environmental samples without necessarily collecting the organisms themselves. This approach is increasingly useful for biodiversity monitoring and detecting rare or difficult-to-sample species (Takahara et al., 2023). Geographic Information Systems (GIS) and species-distribution modelling help map species occurrence and identify areas of high biodiversity, endemism, or conservation concern. Remote sensing provides information on habitat characteristics and environmental changes over large areas. Artificial intelligence

and computer-vision systems are increasingly being applied to automated identification of insects and other invertebrates from photographs or images (Cardinal et al., 2022).

Research Gaps and Future Perspectives

Despite the extraordinary diversity of invertebrates, major gaps remain in their taxonomy, distribution, ecology, and conservation status. A large number of species are still undescribed, particularly in tropical ecosystems, deep-sea habitats, soil communities, and other poorly explored environments. Tropical and developing regions often have limited taxonomic expertise, biodiversity infrastructure, and long-term monitoring programmes, resulting in substantial knowledge gaps (Costello et al., 2013). Traditional morphology-based identification should increasingly be integrated with molecular taxonomy, DNA barcoding, and genomic approaches to identify cryptic species and improve biodiversity inventories (Hebert et al., 2003).

Conclusion

Invertebrates represent an extraordinary component of global animal diversity and occupy almost every terrestrial, freshwater, and marine environment. Their remarkable variation in body organization, morphology, physiology, reproduction, feeding mechanisms, and ecological adaptations reflects a long history of evolutionary diversification. Major groups such as Porifera, Cnidaria, Platyhelminthes, Nematoda, Annelida, Mollusca, Arthropoda, Echinodermata, and Hemichordata demonstrate the wide range of body plans that have evolved within the animal kingdom. The ecological importance of invertebrates extends far beyond their species richness. They contribute to pollination, decomposition, nutrient cycling, soil formation, biological control, food-web regulation, and aquatic ecosystem functioning. They also provide important economic resources through apiculture, sericulture, lac production, fisheries, vermicomposting, and biomedical research. At the same time, certain invertebrates create agricultural, veterinary, and public-health challenges as pests, parasites, and disease vectors. Invertebrate diversity is increasingly threatened by habitat destruction, climate change, pollution, pesticide exposure, invasive species, and other anthropogenic pressures. Effective conservation therefore requires improved biodiversity assessment, habitat protection, sustainable resource management, and long-term monitoring. Future research should integrate classical taxonomy with molecular techniques, DNA barcoding, environmental DNA, GIS, remote sensing, artificial intelligence, and citizen science. Greater attention should also be given to poorly studied and less conspicuous groups. A comprehensive understanding of invertebrate diversity is essential for conserving biodiversity, maintaining ecosystem functioning, and supporting sustainable environmental management.

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Non-Newtonian Blood Flow: Theory, Computation and Arterial Applications

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Abstract

Non-Newtonian blood flow modeling has become increasingly important in biomedical engineering because blood exhibits shear-dependent rheological behavior, particularly in small vessels and diseased arterial regions. This chapter reviews the major constitutive models used to describe blood rheology, including the power-law, Casson, Carreau, Carreau-Yasuda, and Herschel-Bulkley models. The governing conservation equations, boundary conditions, and important dimensionless parameters associated with biomedical fluid mechanics are presented. Recent advances in computational modeling, including computational fluid dynamics, finite element methods, fluid-structure interaction, and machine learning-based approaches, are also discussed. An illustrative case study comparing Newtonian and Carreau fluid flow through a stenosed artery is included to demonstrate the practical application of non-Newtonian theory in hemodynamic analysis. Finally, current challenges and future research directions in patient-specific and data-driven modeling are highlighted.

Keywords: Non-Newtonian Fluid · Arterial Stenosis · Wall Shear Stress · Magnetohydrodynamics · Machine-Learning Surrogates · Computational Fluid Dynamics

Introduction

Background

In fluid mechanics, fluids are said to be Newtonian if the shear stress developed by the fluids is directly proportional to the local shear strain rate, where a single constant of proportionality, viscosity, relates the two variables. The classic examples of such fluids are water and air, while this simplifying assumption helps to formulate Navier-Stokes equations. However, many physiological fluids violate this direct proportionality in their behavior to a large extent. For example, blood is one of the most investigated fluids, which is a concentrated suspension of deformable erythrocytes, platelets, and plasma proteins, whose aggregation and deformation under the influence of flow lead to a decrease in its apparent viscosity at higher shear rates (i.e., the phenomenon of shear thinning) (Wajihah & Sankar, 2023).

As the blood passes through the aorta and other large arteries at high shear rates, its viscosity becomes close to a constant, and the Newtonian model suffices. In contrast, the case is different for small-sized arteries, in the vicinity of stenosis, and low-flow areas where the shear rates become smaller, and cell aggregation becomes important. Under such conditions, a non-Newtonian approach must be adopted to obtain physical solutions for wall shear stress and pressure drop predictions (Liu et al., 2021; Stamou, Radulovic & Buick, 2023). Since the conditions related to atherosclerosis, aneurysm, and surgery recovery processes occur in precisely such low-shear areas, non-Newtonian modelling has come to play a crucial rather than marginal role in biomechanics.

Importance of Fluid Modelling in Biomedical Engineering

The mathematical and computational models of fluids have an important role in biomedical engineering studies because they provide the opportunity to estimate those parameters which cannot be measured in living patients due to various reasons such as wall shear stress distribution, local pressure gradients, and particle residence time, based on easily measurable factors like geometry of vessels and flow waveforms at inlet locations.

- **Cardiovascular Disease Modelling:** Wall shear stress and oscillatory shear index determined using patient anatomy serve as markers for regions at risk of atherosclerotic plaque formation (Wajihah, Sankar & Nagar, 2022).
- **Drug Delivery:** Fluid-mass transfer transport models guide the development of catheterization techniques and nanoparticles for drug delivery aiming to deliver the medication to the targeted lesion with as little systemic loss as possible (Fanelli et al., 2022).
- **Device Design:** Computational fluid-structure interaction studies of artificial heart valves and stents make use of blood rheology to estimate flow-induced blood injury and potential thrombus formation (Chauhan & Sasmal, 2024).

- **Diagnostic Aid:** Patient-specific flow simulations based on images supplement traditional medical imaging for stenosis and aneurysm risk evaluation, and machine learning surrogates are currently decreasing the computational time from hours to mere seconds (Morgan et al., 2023).

Scope

In this chapter, we will focus our discussion on the continuum, single and two-layer constitutive theories for non-Newtonian physiological fluid flows, which continue to form the prevalent paradigm in applied mathematics and biomedical engineering research. The modeling at the molecular or cellular scale level of blood is referred to only when it concerns closure of the continuum constitutive model.

Non-Newtonian Fluid Models

1. Classification of Non-Newtonian Fluids

Non-Newtonian fluids are usually classified based on the behaviour of their apparent viscosity against shear rate and the presence or absence of yield stress or memory effects.

- **Shear-Thinning (Pseudo Plastic) Fluids:** Apparent viscosity reduces with increase in shear rate. Physiological shear rates of blood belong to this category because the Rouleau structures disintegrate and cells elongate under the influence of shear.
- **Shear-Thickening (Dilatant) Fluids:** Apparent viscosity increases with shear rate; high shear concentrations of particles form dilatant fluids, which have little relevance to blood mechanics.
- **Viscoelastic Fluids:** Show properties of elasticity and viscosity, and therefore stress depends on both the rate of deformation and its history; plasma and whole blood exhibit viscoelastic behaviour at low shear rates.
- **Yield-Stress Fluids:** Flow does not start until a certain stress level is reached; blood is modelled to behave like a yield-stress fluid due to Rouleau formation at low shear rates.

Constitutive Equations

There are a few constitutive relationships that consistently emerge within the literature in recent years for this very reason, namely that each provides a unique trade-off between mathematical convenience and physiological accuracy. Here, τ represents shear stress and $\dot{\gamma}$ shear rate.

The power-law constitutive relationship describes shear stress as a power of the shear rate,

$$\tau = K\dot{\gamma}^n \qquad 1$$

where K is the consistency index and n < 1 for a shear-thinning fluid. Although simple from an algebraic perspective, this model has been seen to over predict viscosity at very high shear rates and predict an unbounded viscosity as the shear rate approaches zero – neither of which occur in reality (Wajihah & Sankar, 2023).

The Casson model incorporates a yield stress τ_y, below which no flow occurs,

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu_c \dot{\gamma}^{1/2}} \qquad 2$$

where μ_c is the Casson plasticity coefficient. Historically, the Casson model was more popular for blood flow in narrow conduits or low flow rates, although it may suffer from numerical stiffness near the yield surface.

The Carreau model is a generalized Newtonian model with four parameters, smoothly transitioning between a zero-shear viscosity μ_0 and infinite-shear viscosity μ_∞ according to a power law.

$$\mu(\dot{\gamma}) = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (\lambda\dot{\gamma})^2]^{\frac{n-1}{2}} \qquad 3$$

where λ is a characteristic relaxation time and n is the power-law index of the transition region. Because it avoids the singular behaviour of the power-law model at very low or very high shear rates, the Carreau model has become one of the most widely used descriptions of blood rheology in recent arterial-flow studies (Alsemiry, Sayed & Amin, 2022; Zaman & Khan, 2021). Its close relative, the Carreau-Yasuda model, adds a fifth parameter a controlling the sharpness of the transition,

$$\mu(\dot{\gamma}) = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (\lambda\dot{\gamma})^a]^{\frac{n-1}{a}} \qquad 4$$

and is frequently used in device-scale computational fluid dynamics work (Chauhan & Sasmal, 2024).

The Herschel-Bulkley model combines a yield stress with power-law shear-thinning behaviour above that threshold,

$$\tau = \tau_y + K\dot{\gamma}^n, \ \tau \geq \tau_y \qquad 5$$

offering a compromise between the Casson and power-law descriptions and appearing frequently in studies of blood flow through severely constricted or thrombosed vessels (Elgendi et al., 2024).

Table 1. Comparison of commonly used non-Newtonian constitutive models and their biomedical applications.

Model	**Key characteristics**	**Representative biomedical application**
Power-law	Two-parameter form; viscosity diverges at zero shear; no yield stress	First-order estimates of shear-thinning in moderate-to-high shear regions
Casson	Explicit yield stress; good fit to blood at low shear rates	Flow in narrow arterioles and low-flow-rate vessels
Carreau	Four parameters; bounded viscosity at zero and infinite shear; smooth transition	Stenosed and tapered artery flow; MHD arterial-flow modelling
Carreau-Yasuda	Extension of Carreau with adjustable transition sharpness	Device-scale CFD (stents, valves, catheters)
Herschel-Bulkley	Yield stress combined with power-law shear-thinning	Severely stenosed or thrombosed vessel segments

Mathematical Modelling: Governing Equations and Dimensionless Parameters

1. Conservation Equations

Regardless of which constitutive relation is chosen, the flow field must satisfy the fundamental conservation laws of continuum mechanics. For the incompressible flow assumption that is standard in physiological fluid mechanics, conservation of mass reduces to a statement that the velocity field u is divergence-free,

$$\nabla \cdot u = 0 \qquad 6$$

The momentum equation is the vector statement of Newton's second law applied to a fluid element,

$$\rho(\partial u/\partial t + (u \cdot \nabla)u) = -\nabla p + \nabla \cdot \tau + F \qquad 7$$

where ρ is density, p is pressure, τ is the deviatoric stress tensor and F is a body-force density. What distinguishes a non-Newtonian formulation from its Newtonian counterpart is that τ is no longer a linear function of the strain-rate tensor; instead it follows the chosen constitutive law Carreau, Casson or another so that the effective viscosity $\mu(\dot{\gamma})$ itself becomes a field variable that depends on the local shear rate. When an externally applied magnetic field B is present, F includes an additional Lorentz-force term $J \times B$, giving rise to the magnetohydrodynamic (MHD)

formulation used to study the effect of external fields on arterial flow (Shahzad et al., 2021),

$$F_{Lorentz} = J \times B = \sigma(u \times B) \times B \qquad 8$$

with σ the electrical conductivity of blood. The energy equation, included when heat transfer is of interest for example in hyperthermia treatment or viscous heating in narrow vessels balances convection and conduction of thermal energy against viscous dissipation Φ, which itself depends on the non-Newtonian stress field and therefore couples back to the momentum solution,

$$\rho c_p \left(\frac{\partial T}{\partial t} + (u \cdot \nabla)T\right) = k\nabla^2 T + \Phi, \Phi = \tau : \nabla u \qquad 9$$

2. Boundary Conditions

Physiologically motivated boundary conditions distinguish biomedical fluid models from generic engineering flows. A no-slip condition at the vessel wall is standard, though a small slip velocity is sometimes introduced to represent the endothelial glycocalyx layer or catheter surface roughness. The vessel wall itself is frequently represented as an axially varying, and in some studies elastic or tapered, boundary to capture the geometry of a stenosis or aneurysm realistically; a stenosis is commonly prescribed through a cosine or Gaussian bump superimposed on an otherwise uniform or tapered duct radius,

$$R(z) = R_0 - \frac{\delta_0}{2}\left[1 + \cos\left(\frac{2\pi(z - z_0)}{L_0}\right)\right], |z - z_0| \leq \frac{L_0}{2} \qquad 10$$

At the inlet and outlet, either a prescribed flow rate or a pulsatile waveform representative of the cardiac cycle is applied, and symmetry conditions are typically imposed along the vessel centreline for axisymmetric geometries.

3. Dimensionless Parameters

Non-dimensionalization of the governing equations reveals a small number of parameter groups that control the qualitative behaviour of the solution and allow results from different studies to be compared on a common basis, where U and L are characteristic velocity and length scales:

$$Re = \frac{\rho UL}{\mu}, W_e = \frac{\lambda U}{L}, Ha = B_0 L\sqrt{\frac{\sigma}{\mu}}, Br = \frac{\mu U^2}{k\Delta T} \qquad 11$$

The Reynolds number Re is the ratio of inertial to viscous forces; physiological flows in small arteries are typically low-to-moderate Reynolds number, which justifies the lubrication-theory and perturbation approaches common in this literature. The Weissenberg number W_e is the ratio of the fluid's characteristic relaxation or shear-thinning time scale to the flow time scale; it governs how far

non-Newtonian shear-thinning departs from Newtonian behavior and is the natural small parameter for perturbation expansions of the Carreau model. The Hartmann number Ha quantifies the relative strength of magnetic (Lorentz) forces to viscous forces in MHD arterial-flow studies; increasing Hartmann number is associated with flattening of the velocity profile and a rise in flow resistance (Shahzad et al., 2021). The Brinkman number Br compares heat generated by viscous dissipation to heat transported by conduction, and becomes relevant whenever thermal effects of non-Newtonian shear-thinning are analyzed.

Recent Advances in Computational Modelling

1. Computational Fluid Dynamics (CFD)

Direct numerical simulation using finite-volume CFD solvers remains the workhorse method for resolving complex, patient-realistic geometries that resist closed-form or perturbation solution. Recent CFD studies of intracranial arterial stenosis have systematically

Newtonian and non-Newtonian closures and found that the choice of rheological model has a measurable, geometry-dependent effect on predicted wall shear stress and recirculation extent, with the largest discrepancies occurring in low-shear, disturbed-flow regions (Liu et al., 2021). A recent Lattice-Boltzmann comparison at the carotid bifurcation similarly found that near-wall reverse-flow levels differ between Newtonian and Carreau-Yasuda closures even though bulk plaque-deposition predictions were broadly similar, underscoring that non-Newtonian effects concentrate in near-wall haemodynamic quantities rather than in bulk flow metrics (Stamou, Radulovic & Buick, 2023). Two-fluid CFD formulations, which separate a cell-rich core region from a cell-depleted plasma layer near the wall, have also been used to examine nanoparticle-laden hemodynamic in diseased vessels combining stenosis and aneurysm (Dubey et al., 2020).

2. Finite Element Method and Fluid-Structure Interaction

Finite element formulations are especially advantageous for cases where there is an irregular or dynamic domain, like vessels having elastic or dynamic walls, and multiphysics systems involving fluid dynamics together with structural deformation or heat conduction. The fluid-structure interaction analysis of bileaflet mechanical heart valves serves as an example of this capability: using a finite element or immersed boundary model for structure in conjunction with a Carreau model for flow enables the time-varying behaviour of the valve leaflets to be analyzed along with the resulting jets and recirculation regions; this shows that non-Newtonian rheology significantly influences the leaflet kinematics and blood damage index compared to Newtonian rheology (Chauhan & Sasmal, 2024).

3. Machine Learning and AI Surrogates

Machine learning has recently emerged as a powerful tool for accelerating hemodynamic simulations by developing surrogate models trained using high-fidelity computational fluid dynamics (CFD) and fluid-structure interaction (FSI) data. Deep-learning techniques, particularly convolutional neural networks and graph neural networks, have been successfully applied to reconstruct wall shear stress directly from medical imaging, predict pressure and flow fields from vascular geometries, and estimate hemodynamic parameters with significantly lower computational costs than conventional CFD methods (Liang, Mao, & Sun, 2020; Ferdian et al., 2022; Morgan et al., 2023; Alamir et al., 2024; Sarkhosh et al., 2025). Consequently, AI-assisted modeling is expected to become an essential component of future non-Newtonian hemodynamic studies.

4. Patient-Specific Modeling

Patient-specific modeling integrates vascular geometries reconstructed from computed tomography (CT) and magnetic resonance angiography (MRA) with realistic physiological boundary conditions. This approach allows computational models to represent individual patients rather than idealized blood vessels. Comparative studies have demonstrated that the differences between Newtonian and non-Newtonian models become more pronounced in low-shear regions associated with disease progression, highlighting the clinical importance of accurate constitutive modeling (Liu et al., 2021).

Biomedical Applications

1. Hemodynamics and Blood Flow Through Stenosed Arteries

The primary motivation for non-Newtonian modeling remains the description of blood flow itself. Analytical and semi-analytical treatments using lubrication theory and perturbation expansions in the Weissenberg number have been used to obtain closed-form expressions for velocity, wall shear stress and flow resistance in narrow and tapered arterial segments, offering a computationally inexpensive complement to full CFD and useful physical insight into how each rheological parameter influences the flow (Alsemiry, Sayed & Amin, 2022). Stenosed-artery models occupy a central place in this literature because they combine geometric complexity with the low-shear, recirculating flow conditions where non-Newtonian effects are most pronounced. Recent studies have examined time-dependent and curvature effects in irregularly shaped (for example, w-shaped) stenoses (Zaman & Khan, 2021), the combined influence of catheter insertion, stenosis and thrombosis on flow resistance (Wajihah, Sankar & Nagar, 2022), and biomagnetic flow through bifurcated, elastic-walled stenosed arteries under an applied magnetic field, where increasing Hartmann number was shown to reduce velocity and increase resistance

to flow, suggesting a possible route to magnetically assisted flow control (Shahzad et al., 2021).

2. Drug Delivery Systems

Non-Newtonian transport models play an important role in the design of drug-delivery systems because wall shear stress and particle residence time strongly influence the transport, deposition, and uptake of therapeutic agents. Mathematical models have been widely used to investigate magnetic nanocarrier transport, catheter-based therapies, and nanoparticle-mediated drug delivery in diseased arteries. Previous studies have shown that rheological behavior significantly affects particle capture efficiency, magnetic targeting, and overall drug distribution, emphasizing the need to incorporate realistic blood properties into biomedical transport models (Fanelli et al., 2022; Dubey et al., 2020; Giri et al., 2023).

3. Artificial Organs and Biomedical Devices

Non-Newtonian rheology significantly influences the performance and safety of artificial organs and biomedical devices. Fluid-structure interaction analyses have shown that shear-thinning models affect valve kinematics, wall shear stress, and blood-damage predictions when compared with Newtonian assumptions (Chauhan & Sasmal, 2024). Similar considerations apply to dialysis circuits, extracorporeal membrane oxygenation systems, and vascular stents, where accurate rheological modeling improves the prediction of thrombogenic risk and enhances device performance.

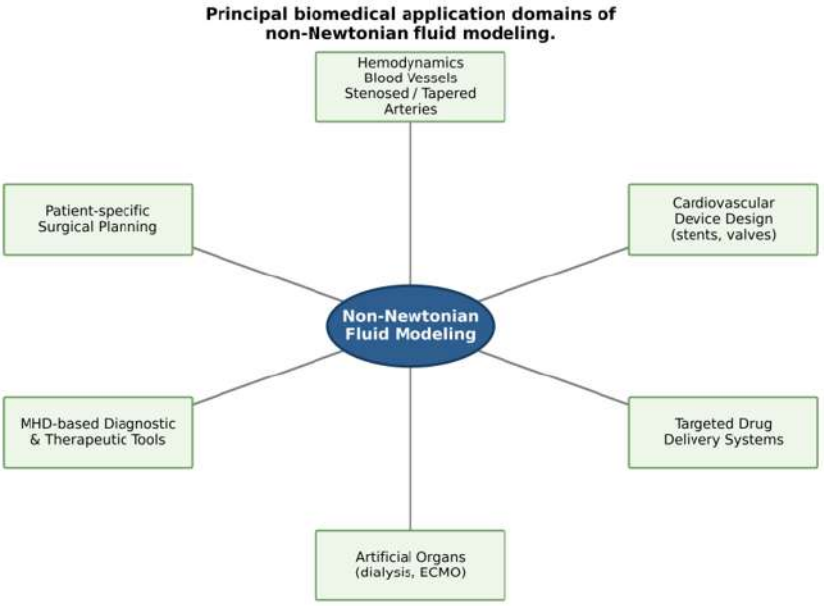


Figure 1. Principal biomedical application domains of non-Newtonian fluid modelling.

Illustrative Worked Example: Lubrication-Theory Model of Stenosed-Artery Flow

In order to provide a concrete application of the constitutive theory in Section 2 and the governing equations of Section 3 to an easily reproducible result, this section considers a model problem involving the lubrication theory solution of steady flow through a cosine shaped artery having a stenosis, considering the comparison of a Newtonian fluid with the Carreau model of Section 2.2. The purpose is simply for illustration, since more complicated CFD and FSI models are considered in Section 4. The usefulness of this example is that every aspect is completely reproducible from the equations here.

1. Model Formulation

The vessel is modeled as an axisymmetric tube of local radius R(z) following the cosine stenosis profile of Equation (10), with healthy radius $R_0 = 0.15\ cm$ throat radius $R_{min} = 0.075\ cm$ (a 50% diameter reduction), stenosis length $L_0 = 2cm$ centered at $Z_0 = 3cm$ along a 6 cm vessel segment. Under the lubrication-theory (locally-parallel-flow) approximation widely used in this literature (Alsemiry, Sayed & Amin, 2022; Fanelli et al., 2022), the flow at each axial station is treated as a fully developed, unidirectional flow in a straight tube of the local radius R(z), and the volumetric flow rate Q is held fixed along the vessel by mass conservation. Force balance on a coaxial fluid cylinder of radius r gives the shear stress distribution

$$\tau(r) = \frac{r}{2}G(z), \quad G(z) \equiv -\frac{dp}{dz} \qquad 12$$

For a Newtonian fluid of constant viscosity μ_N, Equation (12) integrates in closed form to the Hagen-Poiseuille relation

$$G = 8\mu_x \frac{Q}{(\pi R^4)}), \ \tau_w = \frac{GR}{2} \qquad 13$$

For the Carreau fluid, $\tau(r) = \mu(\dot{\gamma})\dot{\gamma}$ from Equation (3) is nonlinear in $\dot{\gamma}$, so at each radius r the local shear rate $\dot{\gamma}(r)$ is found by numerical root-finding of $\mu(\dot{\gamma})\dot{\gamma} - \tau(r) = 0$, after which the velocity profile follows from $u(r) = \int_r^R \dot{\gamma}(r')dr'$ and the flow rate from $Q = 2\pi \int_0^R u(r)r\ dr$ Because Q must equal the prescribed value at every station, the pressure gradient $G(z)$ is itself found by an outer root-finding (shooting) loop that adjusts G until the computed Q matches the target flow rate. The Carreau parameters used are the widely cited blood-rheology values of Cho and Kensey (1991): zero-shear viscosity $\mu_0 = 0.56$ poise, infinite-shear viscosity $\mu_\infty = 0.0345$ poise, relaxation time *λ=3.313* s and power-law index n=0.3568; the Newtonian comparison uses the constant viscosity $\mu_N =$

μ_∞, consistent with the common practice of taking the high-shear asymptote as the "Newtonian" reference viscosity. The prescribed flow rate is $Q = 0.30\ cm^3/s$, giving a mean healthy-vessel velocity of about 4.2 cm/s, representative of a small muscular artery.

Results

Figure 2 provides the answer. In panel (a), the cosine stenosis geometry that is imposed in the problem is depicted. The wall shear stress as predicted by the Newtonian and Carreau closures is compared in panel (b). While both show sharp increases as the narrowing of the lumen approaches the throat position, the Carreau closure prediction shows higher values all through the stenotic region since the high local shear rate is compensated by higher local apparent viscosity as compared to the high-shear asymptotic value assumed for the Newtonian closure. The model predicts that the wall shear stress will be 3.12 dyn/〖cm〗^2at the throat location using the Newtonian closure while the Carreau closure would give a prediction of 3.45 dyn/〖cm〗^2; the corresponding total pressure loss in the modeled segment will increase from 788 to 962 dyn/〖cm〗^3 (22% increase). Panel (c) depicts the comparison of the velocity profile at the throat; the Carreau profile is slightly flatter near the centerline (as compared to the parabolic profile of the Newtonian closure) with peak velocities of 33.2 cm/s versus 34.0 cm/s at the same flow rate, consistent with the shear-thinning fluid offering less resistance to deformation in the high-shear core while its elevated near-wall viscosity increases the wall gradient needed to satisfy the no-slip condition.

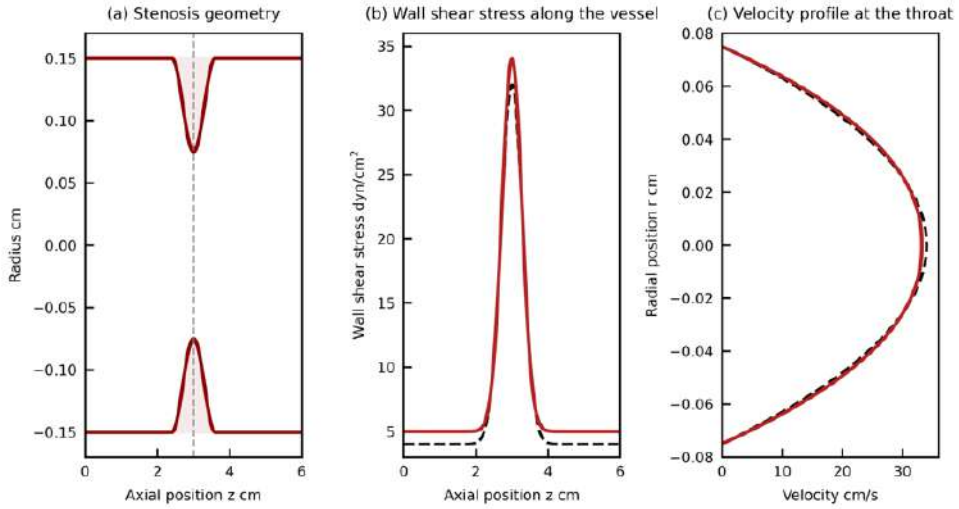


Figure 2. Original lubrication-theory case study: (a) cosine-shaped stenosis geometry $(R_0 = 0.15\ cm)$***, 50% diameter reduction; (b) wall shear stress along the vessel, Newtonian vs. Carreau; (c) velocity profile at the throat, Newtonian vs. Carreau, at matched flow rate*** $Q = 0.30\ cm^3/s$

Discussion

Two points from this worked example reinforce the survey findings of Sections 4 and 5. First, the magnitude of the Newtonian/non-Newtonian discrepancy found here (11% in throat wall shear stress, 22% in overall pressure drop) is consistent with the moderate but non-negligible differences reported in CFD-based comparisons at similar vessel scales (Liu et al., 2021; Stamou, Radulovic & Buick, 2023), and it illustrates why the choice of rheological model matters most for exactly the near-wall, low-to-moderate shear quantities -- wall shear stress and pressure drop -- that drive clinical indicators such as the oscillatory shear index and predicted plaque risk, rather than for bulk quantities such as total flow rate, which is prescribed here by construction. Second, the fact that a reduced-order, lubrication-theory calculation of this kind reproduces the qualitative trend of full three-dimensional CFD studies at a tiny fraction of the computational cost is precisely the motivation behind the perturbation and lubrication-theory literature summarized in Section 5.1, and it suggests that such reduced-order models remain a useful complement for rapid parameter sweeps, teaching, or generating training data for the machine-learning surrogates discussed in Section 4.3 -to the higher-fidelity but more expensive simulations that dominate the recent literature.

Conclusion

Non-Newtonian fluid modeling has become an essential component of biomedical fluid mechanics because it provides more accurate predictions of blood flow behavior in complex arterial geometries. Constitutive models such as the Carreau and Casson models, combined with computational approaches including CFD, fluid-structure interaction, and image-based simulations, have significantly improved the understanding of hemodynamics in diseased vessels. The worked example presented in this chapter further demonstrates that even simplified lubrication-theory models can successfully capture the influence of shear-thinning behavior on wall shear stress and pressure drop in stenosed arteries. Future research is expected to focus on experimental validation, machine learning-assisted simulations, and patient-specific modeling for more personalized clinical applications.

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Aquaculture: As a Source of Food for the Future

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Abstract

Aquaculture, the farming of aquatic organisms such as fish, crustaceans, molluscs, and aquatic plants, has become one of the most important components of the global food system. Rapid population growth, urbanization, changing dietary preferences, pressure on agricultural land and freshwater resources, and the biological limits of capture fisheries have increased the need for sustainable sources of nutritious food. Aquaculture is increasingly positioned to meet this demand because aquatic animals can provide high-quality protein, essential fatty acids, vitamins, and minerals, while many aquatic farming systems can produce food efficiently in comparatively limited land areas. The sector has already reached a major turning point: according to the Food and Agriculture Organization of the United Nations (FAO), aquaculture production of aquatic animals exceeded capture fisheries for the first time in 2022. More recent FAO reporting indicates that this growth continued, with global aquaculture production of aquatic animals exceeding 100 million tonnes in 2024. However, aquaculture is not automatically sustainable. Environmental pollution, disease, dependence on feed ingredients, water use, habitat modification, climate change, biodiversity concerns, and social inequalities can limit its contribution to future food security. The future of aquaculture therefore depends on responsible intensification, technological innovation, improved feeds, climate-resilient species and systems, integrated multi-trophic aquaculture, recirculating systems, aquaponics, seaweed farming, stronger biosecurity, and inclusive governance. This review examines the importance of aquaculture as a future food source, its nutritional and economic contributions, environmental opportunities and challenges, technological developments, and the policies required to make future growth sustainable and equitable.

Keywords: aquaculture, food security, blue transformation, sustainable development

Introduction

The global food system faces a complex challenge: it must provide sufficient nutritious food for a growing population while reducing pressure on land, water, ecosystems, and the climate. Conventional agriculture has made enormous contributions to human development, but continued expansion of terrestrial food production faces constraints associated with land availability, freshwater demand, soil degradation, biodiversity loss, and greenhouse-gas emissions. At the same time, wild fisheries cannot indefinitely provide increasing quantities of fish because many aquatic ecosystems are already subject to ecological limits. These circumstances have increased interest in aquaculture as an important component of future food systems.

Aquaculture can be broadly defined as the controlled cultivation of aquatic organisms. It includes the farming of freshwater species such as carp, tilapia and catfish; marine and brackish-water species such as shrimp, salmon and sea bass; molluscs such as oysters and mussels; and aquatic plants such as seaweeds. Production occurs in ponds, tanks, cages, raceways, reservoirs, coastal areas and increasingly sophisticated land-based systems.

The importance of aquaculture is demonstrated by its rapid expansion over recent decades. The FAO reported that global aquaculture production reached 130.9 million tonnes in 2022, including 94.4 million tonnes of aquatic animals. In that year, aquaculture supplied 51% of global aquatic animal production, surpassing capture fisheries for the first time (Food and Agriculture Organization of the United Nations [FAO], 2024). More recently, FAO's 2026 reporting estimated that global fisheries and aquaculture production reached 235 million tonnes in 2024, while aquaculture production of aquatic animals exceeded 100 million tonnes for the first time (FAO, 2026). These figures demonstrate that aquaculture has moved from being a supplementary activity to becoming a central pillar of the global aquatic food system.

The potential importance of aquaculture extends beyond the production of fish. Aquatic foods can contribute to healthy diets, livelihoods, economic development and food-system resilience. Research has also demonstrated that aquaculture can contribute to several Sustainable Development Goals (SDGs), although its effects vary substantially according to species, production system, location and management practices (Troell et al., 2023). Therefore, the question is not simply whether aquaculture can produce more food, but whether it can produce more nutritious food while maintaining environmental integrity and social equity.

Aquaculture Scenario in India

Aquaculture in India has seen substantial growth and has become a crucial part of the country's economy. India has a long tradition of practicing aquaculture, and in

recent years, the government has focused on encouraging modern aquaculture methods and promoting sustainable development within the sector. The country has a vast coastline of more than 7,500 kilometres, alongside many rivers, lakes, and reservoirs, which offer numerous opportunities for aquaculture activities. The main focus of the sector is on freshwater aquaculture, involving the cultivation of fish species such as carps, catfish, tilapia, and other native fish.

In addition, shrimp farming, especially the rearing of vannamei shrimp, has become very popular in coastal areas. India is one of the world's top producers of fish and shrimp through aquaculture. Indian aquaculture products, especially shrimp, have a strong presence in export markets. The country sends seafood to various international markets, including the United States, Europe, and Southeast Asia. The adoption of proper aquaculture practices, traceability systems, and compliance with international standards for quality and safety have helped Indian aquaculture products gain international recognition.

The Indian government has launched several initiatives to support and expand the aquaculture sector. The National Fisheries Development Board (NFDB), which operates under the Ministry of Fisheries, Animal Husbandry, and Dairying, is a key player in developing policies, offering financial aid, and providing technical support to the aquaculture industry. The government has also introduced programs like the Blue Revolution and the Pradhan Mantri Matsya Sampada Yojana (PMMSY) to improve productivity, develop infrastructure, and strengthen market connections in aquaculture.

Aquaculture and Global Food Security

Food security exists when people have reliable access to sufficient, safe and nutritious food. Aquaculture can strengthen food security in several ways. First, it directly increases the supply of aquatic foods. Second, it provides employment and income that allow households to purchase food. Third, aquatic foods can improve dietary quality by supplying nutrients that may be limited in diets dominated by staple crops.

The growth of aquaculture is particularly significant because capture fisheries have remained relatively stable at the global level for several decades. According to FAO (2024), global capture fisheries production was approximately 92.3 million tonnes in 2022, while aquaculture production of aquatic animals reached 94.4 million tonnes. The increasing contribution of aquaculture therefore reflects not simply a decline in fishing but the continued expansion of farming.

The geographical distribution of production is, however, highly uneven. Asia dominates global aquaculture, and countries such as China, India, Indonesia, Vietnam and Bangladesh are major producers (FAO, 2024). This concentration reflects the long history of aquatic farming in Asia, strong consumer demand, favorable climatic conditions, established value chains and substantial technical

expertise. At the same time, the uneven distribution indicates considerable opportunities for responsible development in regions where aquaculture remains relatively underdeveloped.

Types of Aquacultures

Aquaculture is the controlled farming, breeding, rearing, and harvesting of aquatic organisms such as fish, prawns, crabs, oysters, mussels, and aquatic plants. It can be classified in several ways, mainly according to water type, organisms cultured, and farming system.

1. Freshwater Aquaculture

Freshwater aquaculture is carried out in water with very low salt content. It is commonly practiced in ponds, tanks, reservoirs, lakes, and raceways.

Examples: Rohu, Catla, Common carp, Tilapia, Catfish, Trout

Advantages

- Freshwater species are widely available.
- Farming can be carried out inland.
- It provides food and employment.
- Fish can be grown in ponds and tanks using relatively simple systems.

2. Marine Aquaculture (Mariculture)

Marine aquaculture, also called mariculture, involves farming organisms in seawater. It is generally practiced along coastal areas and sometimes in offshore cages.

Examples: Marine fish such as salmon and sea bass, Oysters, Mussels, Clams, Seaweed

Marine aquaculture is important because it supplies seafood while reducing pressure on some wild fish populations.

3. Brackish-Water Aquaculture

Brackish water contains more salt than freshwater but less salt than seawater. It is commonly found in estuaries, lagoons, and coastal areas.

Examples: Shrimp/prawn, Milkfish, Mullets, Some species of tilapia

Shrimp farming is one of the major forms of brackish-water aquaculture in many coastal regions.

4. Fish Culture (Pisciculture)

Pisciculture means the farming and breeding of fish for food, commercial purposes, or stocking water bodies.

Fish may be raised in: Ponds, Tanks, Cages, Raceways, Reservoirs

It includes species such as carp, tilapia, catfish, and trout.

5. Shellfish Aquaculture

This involves farming molluscs and other shell-bearing aquatic organisms.

Examples: Oysters, Mussels, Clams, Scallops

Shellfish may be cultivated on ropes, racks, trays, or other structures in suitable marine or coastal waters.

6. Crustacean Aquaculture

Crustacean farming involves organisms such as shrimp, prawns, crabs, and lobsters. Shrimp and prawn farming are particularly important commercially. They are commonly raised in specially prepared ponds or tanks.

7. Algal or Seaweed Culture

Aquaculture is not limited to animals. Aquatic plants and algae can also be cultivated.

Examples: Seaweeds, Microalgae, Certain freshwater algae

They are used as food, animal feed, fertilizers, medicines, cosmetics, and industrial raw materials.

8. Integrated Aquaculture

In integrated aquaculture, fish farming is combined with another agricultural activity, such as crop or livestock farming.

Example: Fish + rice farming, Fish + poultry, Fish + duck farming, Fish + pig farming

The waste or by-products from one activity can sometimes provide nutrients for another, improving resource use.

Classification at A Glance

Type	Environment	Examples
Freshwater aquaculture	Freshwater	Carp, tilapia, catfish
Marine aquaculture	Seawater	Salmon, oysters, mussels
Brackish-water aquaculture	Estuaries/coastal water	Shrimp, milkfish
Pisciculture	Mainly freshwater/marine	Fish
Shellfish culture	Mainly marine/coastal	Oysters, clams, mussels
Crustacean culture	Freshwater/brackish/marine	Shrimp, prawns, crabs
Algal culture	Freshwater/marine	Seaweed, microalgae
Integrated aquaculture	Agricultural systems	Fish + rice, fish + poultry

In short: The major types based on the water environment are freshwater, marine, and brackish-water aquaculture. Based on the organisms cultivated, aquaculture includes fish, shellfish, crustacean, and algal culture.

Role of Freshwater Aquaculture in Food Production

- **Provides Animal Protein:** Fish such as carp, tilapia, catfish, and freshwater prawns provide high-quality protein, vitamins, minerals, and healthy fats.
- **Increases Food Availability:** Aquaculture supplements capture fisheries and helps meet the growing demand for fish as populations increase.
- **Efficient Use of Resources:** Fish can convert feed into edible protein relatively efficiently, and freshwater farming can make productive use of ponds and other water bodies.
- Supports rural livelihoods: Fish farming creates employment and income for farmers, fishers, traders, processors, and others involved in the supply chain.
- **Improves Nutritional Security:** Affordable farmed fish can provide an accessible source of nutritious food, particularly in communities where other animal proteins are expensive.
- **Reduces Pressure on Wild Fish Stocks:** Producing fish through aquaculture can help reduce dependence on harvesting wild populations when farming is managed responsibly.
- **Generates Economic Benefits:** Freshwater aquaculture contributes to agricultural economies through the sale of fish, feed, equipment, and related services.
- **Supports Integrated Farming:** In some systems, fish farming can be combined with crops or livestock, allowing nutrients and water resources to be used more efficiently.

Role of Ocean in Sustainable Food Production

The ocean plays a vital role in sustainable food production by providing nutritious food while supporting livelihoods and ecosystems. Fish, shellfish, seaweed, and other marine resources are important sources of protein, minerals, and other nutrients for millions of people.

Key contributions include:

- **Source of Nutritious Food:** Marine fish and shellfish provide high-quality protein and essential nutrients.
- **Aquaculture:** Sustainable marine aquaculture can produce food efficiently while reducing pressure on wild fish populations.
- **Seaweed Production:** Seaweeds can be cultivated without requiring freshwater, fertilizers, or large areas of farmland. They are used as food and in various food products.

- **Employment and Livelihoods:** Fishing, aquaculture, processing, and related industries provide income for many coastal communities.
- **Climate Benefits:** Healthy marine ecosystems, including mangroves, seagrass beds, and coastal wetlands, store carbon and help protect coastal areas.
- **Biodiversity:** Sustainable management of fisheries helps maintain marine ecosystems and ensures food resources remain available for future generations.

However, overfishing, pollution, habitat destruction, and climate change threaten the ocean's ability to provide food sustainably. Therefore, responsible fishing practices, protection of marine habitats, reduction of pollution, and sustainable aquaculture are essential.

The nutritional contribution of aquaculture also depends on the species produced and the way food is distributed. A production system that produces large quantities of high-value seafood for export may generate economic benefits without necessarily improving local nutrition. Consequently, future aquaculture policies should consider affordability, availability and local dietary needs rather than focusing exclusively on export revenues.

Advantages of Aquaculture

Aquaculture provides many advantages that go beyond simply producing food. One of the main benefits is its role in enhancing global food security. With the world's population increasing, the need for seafood and other protein sources is also rising. Aquaculture offers a sustainable way to meet this growing demand by producing fish and other aquatic life in a controlled environment. This helps reduce the strain on wild fish populations. By ensuring a steady and reliable supply of seafood, aquaculture supports food availability and stability, especially in areas where traditional fishing is not feasible. Aquaculture also has important economic effects, both locally and worldwide. It creates job opportunities, particularly in rural and coastal areas. Running fish farms requires skilled workers for tasks like managing fish hatcheries, feeding the fish, monitoring water conditions, and harvesting. Moreover, aquaculture supports related sectors such as feed manufacturing, equipment supply, and transportation, which helps drive economic growth. When managed correctly, aquaculture can be environmentally friendly and have a smaller impact on the environment than other food production methods. Modern aquaculture methods focus on reducing pollution, improving how efficiently fish convert feed into body mass, and limiting the use of antibiotics and chemicals. Technologies like recirculating aquaculture systems and integrated multi-trophic aquaculture help reduce waste, recycle nutrients, and protect water quality. By using these methods, aquaculture helps preserve natural environments and lowers the environmental impact of food production.

Nutritional Importance of Aquatic Foods

The value of aquaculture as a future food source cannot be assessed only in terms of tonnes produced. The nutritional quality of the food is equally important. Fish and other aquatic animals generally provide high-quality protein and can contribute essential micronutrients. Many species provide omega-3 long-chain polyunsaturated fatty acids, vitamin D, vitamin B12, iodine, selenium, zinc and other nutrients.

FAO (2024) reported that aquatic foods supplied approximately 15% of animal protein and 6% of total protein globally. In 2021, aquatic foods contributed at least 20% of per-capita animal-source protein for approximately 3.2 billion people. These figures show that aquatic foods already have a substantial role in global nutrition.

Aquaculture can also improve access to aquatic foods in inland and landlocked communities. Fish farming can bring production closer to consumers, reducing dependence on wild-caught fish transported from coastal regions. Small-scale ponds, cages and integrated farming systems may allow households to produce fish for both home consumption and local markets.

Major Challenges to Sustainable Aquaculture

Despite its potential, aquaculture should not be considered an automatic solution to future food insecurity. Rapid expansion without effective environmental management can create serious problems.

Water Quality and Pollution

Aquaculture systems release nutrients and organic matter into surrounding environments. Uneaten feed and animal waste can increase nutrient concentrations, potentially contributing to eutrophication and oxygen depletion. Poorly managed systems can therefore damage water quality.

Modern aquaculture increasingly emphasizes improved feeding strategies, waste treatment, water-quality monitoring and efficient stocking densities. Recirculating aquaculture systems (RAS), for example, treat and reuse water, potentially reducing water consumption and limiting direct discharge. However, these systems can have high energy requirements and capital costs, meaning that their sustainability depends partly on the source of electricity and the economic context.

Feed Sustainability

Feed is one of the most important sustainability challenges for intensive aquaculture. Carnivorous species may require protein and lipid sources derived from fishmeal and fish oil. Although technological improvements have reduced dependence on these ingredients, complete replacement remains challenging for some species.

Researchers are therefore investigating alternative feed ingredients, including plant proteins, algae, insects, microbial proteins and other novel sources. Future feeds

must meet nutritional requirements while minimizing environmental impacts, competition with human food crops and dependence on finite marine resources.

Naylor et al. (2021) observed that aquaculture has made significant progress in feed efficiency, but dependence on marine ingredients persists and the increasing use of terrestrial ingredients introduces additional sustainability considerations. Consequently, feed innovation should be assessed across the entire supply chain rather than simply replacing one ingredient with another.

Disease and Biosecurity

Disease outbreaks can cause major economic losses and threaten the stability of food production. High stocking densities, movement of animals, poor water quality and inadequate biosecurity can increase disease risks. The expansion of aquaculture therefore requires strong health-management systems.

Prevention is generally preferable to excessive dependence on treatments. Improved hatchery practices, vaccination where appropriate, genetic selection for disease resistance, water-quality management, quarantine and responsible movement of aquatic animals can reduce risks. Strong biosecurity also protects wild populations from the introduction of pathogens associated with farming.

Climate Change

Climate change represents both a threat and an opportunity for aquaculture. Increasing water temperatures, changing rainfall patterns, sea-level rise, ocean acidification, extreme weather events and harmful algal blooms can affect production (Yadav et al., 2024).

Species have specific environmental requirements. Temperatures outside their optimal range can reduce growth, reproduction and survival. Extreme weather can damage ponds, cages and other infrastructure. Coastal farms may also face increased risks from storms and sea-level rise.

Climate-resilient aquaculture therefore requires species diversification, selective breeding, improved infrastructure, ecosystem-based management and technologies such as recirculating systems and aquaponics (Yadav et al., 2024). Climate adaptation should become an integral part of future aquaculture planning rather than an emergency response after losses occur.

Technological Innovations and the Future of Aquaculture

Technology will be central to increasing aquaculture production while controlling environmental impacts. Digital technologies can provide continuous monitoring of water temperature, dissolved oxygen, pH and other variables. Automated feeding systems can reduce feed waste by adjusting feeding to animal behavior and environmental conditions.

Artificial intelligence and data analysis may further improve production by identifying patterns in water quality, animal growth and disease risk. Sensors and

remote monitoring can allow farmers to detect problems earlier and improve decision-making.

Recirculating aquaculture systems represent another important technological pathway. These systems filter and reuse water, allowing fish production in controlled environments and potentially reducing dependence on large water bodies. Their advantages include biosecurity, year-round production and proximity to urban markets. Their limitations include high capital and energy requirements, technical complexity and the need for skilled management.

Aquaponics combines aquaculture with hydroponic plant production. Nutrients generated by aquatic animals can be used to support plant growth, while plants and associated microbial processes help treat water. Such systems illustrate the possibility of moving toward more circular food production.

Integrated multi-trophic aquaculture (IMTA) is another promising approach. In IMTA, species occupying different ecological niches are cultured together so that the waste or by-products from one component can become resources for another. For example, fed fish can be integrated with shellfish and seaweeds. Properly designed systems can improve resource utilization and reduce waste.

Seaweed and Shellfish Aquaculture

Future discussions of aquaculture should not focus exclusively on finfish. Seaweed and shellfish can play important roles in sustainable aquatic food systems.

Seaweeds are particularly interesting because they do not require conventional agricultural land and can be used directly as food or processed into ingredients. A review by Khan et al. (2023) highlighted seaweed's nutritional, ecological and socioeconomic potential. Seaweed production can provide minerals, dietary fiber, vitamins, bioactive compounds and other useful substances.

Shellfish farming, including oysters, mussels and clams, can also contribute to diversified food production. Many bivalves filter food particles from the water rather than requiring externally supplied feed. Under suitable environmental conditions, this can give them different resource requirements from fed aquaculture species.

Diversifying aquaculture production can increase resilience. If future food systems depend on a narrow range of species, they may be vulnerable to disease, climate change and market disruptions. A broader portfolio of fish, shellfish and aquatic plants can distribute these risks.

Social and Economic Contributions

Aquaculture is not only a method of producing food; it is also a livelihood system. According to FAO (2024), fisheries and aquaculture employed approximately 61.8 million people in primary production in 2022. Aquaculture therefore contributes to employment, household income, rural development, processing, transportation and trade.

Small-scale aquaculture can be particularly important for rural households. A pond or small fish-farming operation may provide food for family consumption while generating income through local sales. The benefits can extend to hatcheries, feed suppliers, traders, processors and retailers.

Nevertheless, aquaculture development can also produce social conflicts. Competition for land and water, unequal access to finance, displacement of communities and poor working conditions can undermine the benefits of expansion. Women are particularly important in processing and value-chain activities, but their contributions are sometimes poorly recognized. FAO (2024) reported that women represented 24% of the overall fisheries and aquaculture workforce but 62% of workers in processing.

Future aquaculture policies should therefore promote inclusion. Small producers should have access to training, finance, technology and markets. Workers should receive fair treatment, and communities should have meaningful participation in decisions concerning resource use.

Aquaculture and the Sustainable Development Goals

Aquaculture has potential connections with numerous Sustainable Development Goals, including SDG 2 (Zero Hunger), SDG 1 (No Poverty), SDG 3 (Good Health and Well-Being), SDG 5 (Gender Equality), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action) and SDG 14 (Life Below Water).

Troell et al. (2023) emphasized that aquaculture's contribution to the SDGs depends heavily on context. Different species and production systems generate different environmental, social and economic outcomes. Consequently, there is no single model of "sustainable aquaculture."

For example, a small freshwater pond integrated with agriculture may have different impacts from a large offshore cage farm. Similarly, seaweed farming and intensive shrimp production cannot be evaluated using exactly the same indicators. Sustainability assessment must consider local ecosystems, resource availability, employment, food security, economic returns and community interests.

This context-specific perspective is essential because maximizing one objective may create trade-offs with another. Increased production may generate employment but also increase pressure on water resources. Export-oriented farming may generate foreign exchange but may not directly improve local food access. Intensive systems may produce high yields but require energy and advanced infrastructure.

The Future of Food from Ocean

Fish and plant production from the sea has grown over time, serving as a key source of food for many people around the world. Fish are especially important in providing global food supplies, contributing about 20 percent of the animal protein and 6.7 percent of all protein consumed by humans. In some developing regions,

such as Indonesia, Sri Lanka, and many small island states, fish and other aquatic foods provide 50 percent or more of the animal protein people eat (FAO 2018). The ocean plays a major role in supplying fish products, with nearly 90 percent of fish caught from capture fisheries coming from the sea, and about a third of farmed fish also being produced in marine environments. As the world's population and incomes increase, the demand for food from the sea is expected to rise. Some estimates suggest that almost 500 million metric tons of animal meat will be needed to feed the global population by 2050, and food from the sea has significant potential to help meet this demand (FAO 2018).

The Future Role of Aquaculture

The evidence suggests that aquaculture will become increasingly important in meeting future demand for food. FAO's 2026 assessment indicates that global aquaculture production of aquatic animals exceeded 100 million tonnes in 2024, confirming the continuing expansion of the sector (FAO, 2026). This trend is likely to continue as aquatic foods become increasingly integrated into global diets. However, future success should not be measured solely by production volume. The goal should be to produce more nutritious food with lower environmental impacts and greater social benefits.

Several Priorities Are Particularly Important

- First, sustainable intensification should increase productivity without proportionally increasing environmental pressure. Better genetics, nutrition, disease control, water management and digital technologies can contribute to this objective.
- Second, feed systems must become more sustainable. Alternative proteins, algae, microbial ingredients, improved feed formulation and better feed conversion can reduce pressure on marine and terrestrial resources.
- Third, climate resilience must become a central design principle. Farms should be located and engineered according to future climate risks, while species and strains should be selected for tolerance to changing conditions.
- Fourth, aquaculture should become more geographically inclusive. FAO has emphasized the need to expand production sustainably in regions such as Africa where current production remains relatively low (FAO, 2024).
- Fifth, governments must strengthen governance. Clear environmental standards, disease-control regulations, spatial planning, traceability and monitoring can help ensure that aquaculture expansion does not create unacceptable ecological or social costs.

Finally, consumers have an important role. Demand for responsibly produced aquatic foods can encourage farmers and companies to adopt better practices.

Certification, transparent supply chains and accurate environmental information can support informed choices.

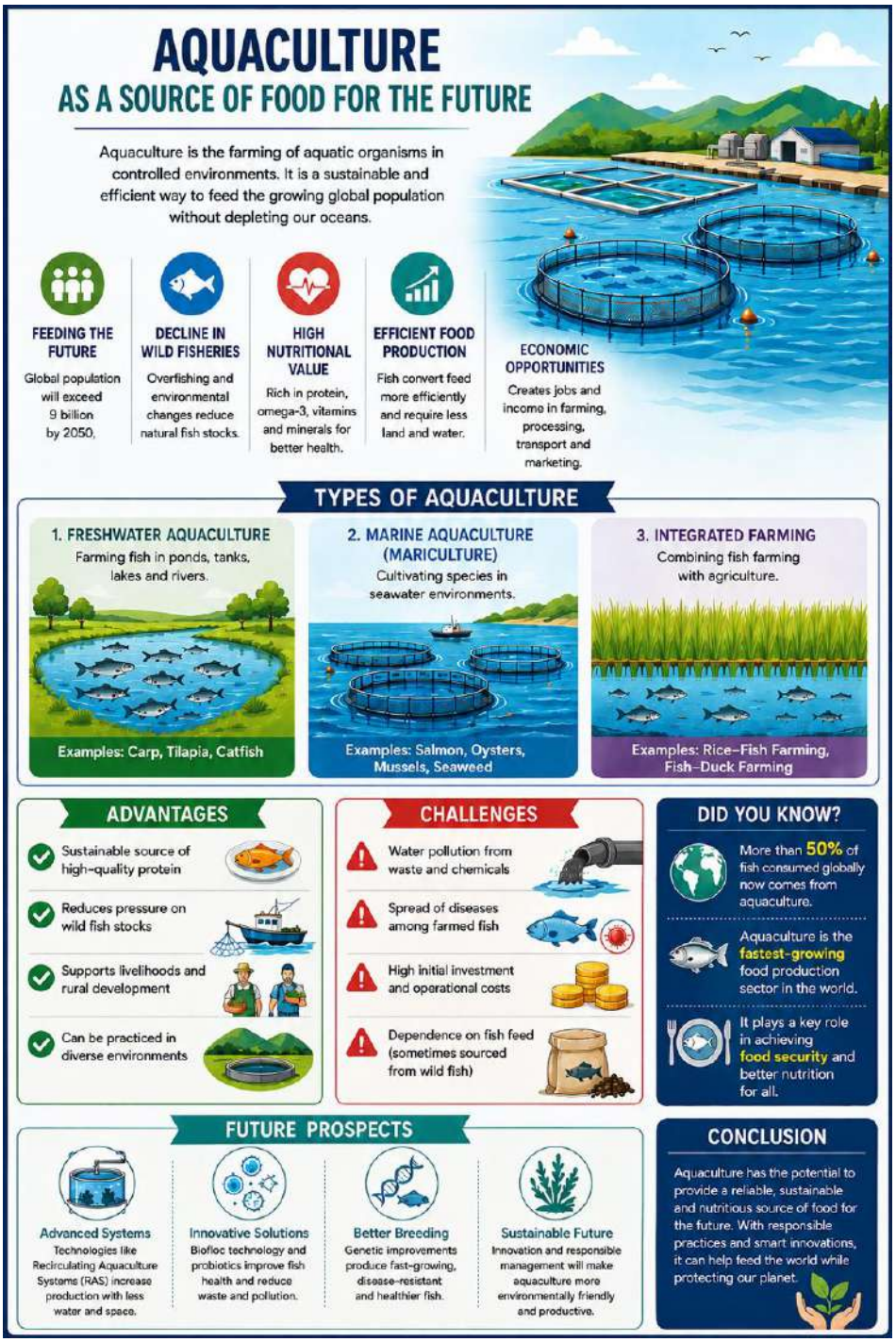


Fig. 1. Overview of Aquaculture: As a Source of Food for the Future

Conclusion

Aquaculture has emerged as one of the most significant developments in the global food system and is likely to become even more important in the future. Its rapid growth has already transformed the balance between farmed and wild aquatic food production. Aquaculture surpassed capture fisheries in aquatic animal production in 2022, and recent FAO data show that production continued to grow through 2024 (FAO, 2024, 2026).

The sector offers several major advantages as a future food source. It can supply high-quality protein and essential nutrients, provide employment and income, diversify food production and produce food in aquatic environments where conventional agriculture may be limited. Innovations in feed, genetics, digital monitoring, recirculating systems, aquaponics, integrated multi-trophic aquaculture, seaweed farming and climate-resilient production can further increase its potential.

At the same time, aquaculture should not be portrayed as a universally sustainable technology. Pollution, disease, feed dependency, energy use, habitat impacts, climate change and social inequalities remain significant concerns. The sustainability of aquaculture depends on how, where and for whom it is developed.

Therefore, aquaculture should be viewed not as a replacement for agriculture or capture fisheries, but as a complementary component of a diversified and resilient global food system. The future of food will require multiple production systems working together. Responsible aquaculture can make a major contribution by producing nutritious aquatic foods while protecting ecosystems and supporting livelihoods.

The central challenge for the coming decades is consequently not simply to produce more fish, but to produce more nutritious aquatic food responsibly, efficiently, equitably and within ecological limits. If technological innovation is combined with strong environmental governance, climate adaptation, sustainable feed development and social inclusion, aquaculture can become one of the foundations of a food-secure future.

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Emerging Technologies in Modern Zoology: Integrating Artificial Intelligence, GIS and Bioinformatics

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Abstract

Zoological research has entered a transformative era shaped by rapid advances in computational and spatial technologies. Artificial Intelligence (AI), Geographic Information Systems (GIS), and Bioinformatics have individually reshaped how researchers study animal behaviour, distribution, physiology, and genetics, and their convergence is now generating integrated frameworks capable of addressing complex ecological and conservation questions at scales previously unattainable. This chapter reviews the emerging role of these three technologies in contemporary zoology, examining how machine learning and deep learning algorithms are

automating species identification, behavioural classification, and population estimation from camera-trap and acoustic data; how GIS-based spatial modelling supports habitat mapping, species distribution prediction, and wildlife corridor planning; and how bioinformatics tools enable genomic, transcriptomic, and phylogenetic analyses that inform conservation genetics and evolutionary biology. Particular attention is given to the synergistic integration of these domains, wherein AI-driven predictive models are combined with spatial datasets and molecular data to produce multidimensional insights into species distribution, adaptive potential, and ecosystem health. Representative applications, including automated wildlife monitoring, disease surveillance, invasive species tracking, and landscape genetics, are discussed to illustrate the practical value of this convergence. The chapter further considers persistent challenges, such as data heterogeneity, computational infrastructure limitations, taxonomic bias in training datasets, and the need for interdisciplinary expertise, which constrain the widespread adoption of these tools in resource-limited settings. Finally, future directions are outlined, including the development of open-access integrated platforms, citizen-science data pipelines, and explainable AI models tailored to ecological applications. This review underscores that the integration of AI, GIS, and bioinformatics is not merely a technical upgrade but a paradigm shift that is redefining the methodological foundations of zoological science, with significant implications for biodiversity conservation and wildlife management in the twenty-first century.

Keywords: Artificial Intelligence; Geographic Information Systems; Bioinformatics; Wildlife Conservation; Species Distribution Modelling

Introduction

Zoology, the scientific study of animal life, has traditionally relied on field observation, morphological examination, and manual data collection. However, the twenty-first century has witnessed an unprecedented technological transformation across biological sciences, driven largely by advances in computing power, satellite technology, and molecular sequencing. Among these developments, Artificial Intelligence (AI), Geographic Information Systems (GIS), and Bioinformatics have emerged as particularly influential tools reshaping the methodological landscape of zoological research. AI, through machine learning and deep learning algorithms, enables the automated analysis of vast datasets—ranging from camera-trap images to bioacoustic recordings—allowing researchers to identify species, quantify populations, and interpret behavioural patterns with a speed and accuracy that manual methods cannot match. GIS technologies provide the spatial framework necessary to map habitats, model species distributions, and understand the ecological processes that govern animal movement and dispersal across landscapes. Bioinformatics, meanwhile, has revolutionized the study of animal genetics, enabling researchers to sequence genomes, reconstruct phylogenies, and assess

genetic diversity within and among populations at a molecular resolution that was inconceivable a few decades ago.

While each of these technologies has independently advanced zoological science, their true potential is realized when integrated into unified analytical frameworks. The convergence of AI, GIS, and bioinformatics allows researchers to link spatial, behavioural, and genetic data into cohesive models that capture the multidimensional complexity of animal life. Such integration is particularly valuable in the context of biodiversity conservation, where understanding species distribution, genetic connectivity, and habitat suitability simultaneously is essential for designing effective management strategies. This chapter examines the individual contributions of AI, GIS, and bioinformatics to zoology, explores their integration through illustrative applications, and discusses the challenges and future prospects of this rapidly evolving interdisciplinary field.

Artificial Intelligence in Zoological Research

Artificial Intelligence has become one of the most transformative tools in modern zoology, particularly through its application in image and audio recognition. Deep learning algorithms, especially convolutional neural networks (CNNs), have been widely adopted for automated species identification from camera-trap photographs. Norouzzadeh et al. (2018) demonstrated that deep neural networks could classify wildlife species from millions of camera-trap images with accuracy comparable to human experts, drastically reducing the time required for data processing in large-scale monitoring programs. Similarly, Willi et al. (2019) combined deep learning with citizen-science platforms to improve the efficiency and scalability of camera-trap image classification, illustrating how AI can complement rather than replace human expertise.

Beyond species identification, AI is increasingly applied to behavioural analysis. Machine learning models can detect and classify complex behavioural patterns—such as foraging, mating displays, or predator avoidance—from video footage, enabling researchers to study animal ethology without continuous manual observation. Weinstein (2018) highlighted the growing role of computer vision in animal ecology, noting its capacity to automate tasks such as individual identification, pose estimation, and movement tracking, which were previously labour-intensive. AI also plays a crucial role in bioacoustic monitoring, where machine learning algorithms are trained to recognize species-specific vocalizations from audio recordings collected via passive acoustic sensors. This approach is particularly valuable for monitoring cryptic or nocturnal species, such as owls, bats, and cetaceans, which are difficult to observe directly. Automated acoustic classification allows for continuous, non-invasive monitoring across large temporal and spatial scales.

Population estimation represents another area where AI has made significant contributions. Traditional mark-recapture and transect-based methods are often labour-intensive and prone to observer bias. AI-based approaches, including automated counting from aerial drone imagery and satellite data, offer scalable alternatives for estimating population sizes, particularly for large mammals in open habitats such as savannas and polar regions. Despite these advances, AI applications in zoology face limitations. Deep learning models require large, well-labelled training datasets, often unavailable for rare or understudied species. Taxonomic bias in existing datasets—skewed toward charismatic or economically important species—can limit the generalizability of trained models. Furthermore, the 'black-box' nature of many deep learning algorithms raises concerns regarding interpretability, particularly when model outputs inform conservation policy decisions.

Table 1 summarizes the core functions, representative zoological applications, and commonly used tools associated with AI, GIS, and bioinformatics, providing a comparative overview before each domain is discussed in greater detail.

Table 1. Comparative Overview of AI, GIS, and Bioinformatics Applications in Zoology

Technology	**Primary Function**	**Key Zoological Application**	**Representative Tools**
Artificial Intelligence	Pattern recognition and predictive modelling	Species identification, behavioural classification, population estimation	TensorFlow, MegaDetector, Wildlife Insights
GIS	Spatial data integration and mapping	Habitat mapping, species distribution modelling, movement tracking	ArcGIS, QGIS, Movebank
Bioinformatics	Genomic and molecular data analysis	Conservation genetics, phylogenetics, eDNA metabarcoding	BLAST, Geneious, QIIME2

Geographic Information Systems in Zoology

Geographic Information Systems have become indispensable tools for spatial analysis in zoology, enabling researchers to visualize, quantify, and model the spatial dimensions of animal ecology. GIS integrates diverse data types—including satellite imagery, climate variables, land-use data, and field observations—into a common spatial framework, facilitating comprehensive analyses of habitat characteristics and species distributions.

One of the most prominent applications of GIS in zoology is species distribution modelling (SDM), which uses statistical or machine learning algorithms to predict

the geographic distribution of a species based on environmental variables and known occurrence records. Guisan and Zimmermann (2000) provided a foundational framework for predictive habitat distribution modelling, emphasizing the ecological principles underlying these models. Elith and Leathwick (2009) further reviewed the theoretical and practical considerations of SDMs, highlighting their utility in predicting range shifts under climate change scenarios and identifying areas of conservation priority.

GIS is also central to wildlife tracking and movement ecology. The integration of GPS telemetry with GIS platforms allows researchers to analyse animal movement patterns, home ranges, and migratory routes with high spatial and temporal resolution. Kays, Crofoot, Jetz, and Wikelski (2015) described how advances in animal tracking technology, when combined with GIS-based spatial analysis, have transformed movement ecology into a data-intensive discipline capable of addressing questions related to habitat connectivity, corridor design, and human-wildlife conflict mitigation.

Habitat mapping and landscape connectivity analysis represent additional key applications of GIS in zoology. By overlaying land-cover data with species occurrence records, researchers can identify critical habitats, fragmentation patterns, and potential wildlife corridors essential for maintaining genetic connectivity between populations. This information is particularly valuable for designing protected area networks and mitigating the impacts of habitat fragmentation caused by urbanization and agricultural expansion.

GIS also supports disease ecology and epidemiological surveillance in wildlife populations, mapping the spatial spread of zoonotic diseases and identifying environmental risk factors associated with disease transmission. Despite its utility, GIS-based analysis faces challenges related to data resolution and the computational complexity of integrating multiple environmental layers, though continued advances in remote sensing are steadily improving accessibility and precision.

Bioinformatics in Zoology

Bioinformatics has fundamentally transformed the study of animal genetics, enabling researchers to analyse genomic data at a scale and resolution previously unattainable through conventional laboratory techniques. The advent of high-throughput sequencing technologies has generated vast quantities of genomic, transcriptomic, and proteomic data, necessitating sophisticated computational tools for data storage, analysis, and interpretation.

In conservation biology, bioinformatics tools are widely used to assess genetic diversity, population structure, and inbreeding levels within threatened species. Frankham (2010) emphasized the importance of genetic approaches in conservation, noting that molecular data can reveal cryptic population structure and inform management units that are not apparent from morphological or ecological data

alone. Such analyses are critical for designing effective breeding programs, translocation strategies, and genetic rescue interventions for endangered populations.

Phylogenetics and molecular systematics represent another major application of bioinformatics in zoology. Computational tools enable researchers to reconstruct evolutionary relationships among species using DNA sequence data, resolving taxonomic ambiguities and clarifying evolutionary histories that were previously difficult to establish through morphological comparison alone. This has led to significant revisions in the classification of numerous animal taxa, particularly among cryptic species complexes that are morphologically indistinguishable but genetically distinct.

Bioinformatics also plays a critical role in landscape genetics, a field that integrates molecular data with spatial information to examine how landscape features influence gene flow and genetic connectivity among populations. This approach bridges bioinformatics and GIS, providing insights into how habitat fragmentation affects genetic diversity and adaptive potential. Comparative genomics, facilitated by bioinformatics platforms, allows researchers to identify genes associated with adaptive traits, disease resistance, and evolutionary novelty across species, with practical applications in understanding species resilience to environmental change.

Additionally, environmental DNA (eDNA) analysis, which relies heavily on bioinformatics pipelines for sequence identification and species assignment, has emerged as a powerful non-invasive tool for biodiversity monitoring, enabling detection of multiple species from water or soil samples. Despite these advances, bioinformatics applications in zoology face challenges related to computational infrastructure, specialized expertise, and standardization of analytical pipelines across studies.

Integration of AI, GIS, and Bioinformatics: Toward a Convergent Framework

While AI, GIS, and bioinformatics have each independently advanced zoological research, their integration offers a more comprehensive understanding of animal biology by linking behavioural, spatial, and genetic dimensions within unified analytical frameworks. This convergence is particularly evident in the emerging field of spatial genomics, which combines GIS-based habitat modelling with genomic data to examine how environmental heterogeneity shapes genetic variation across landscapes. By overlaying genetic diversity metrics onto spatial habitat models, researchers can identify populations that are genetically isolated due to habitat fragmentation and prioritize them for conservation intervention.

AI further enhances this integration by enabling predictive modelling that incorporates spatial, genetic, and behavioural data simultaneously. For instance, machine learning algorithms can be trained to predict species distribution not only from environmental variables, as in traditional SDMs, but also from genetic

adaptation patterns, thereby producing more ecologically realistic models of species range shifts under climate change. Similarly, AI-driven image and acoustic classification data, when geotagged and integrated into GIS platforms, generate spatially explicit maps of species occurrence and behaviour, enhancing the precision of population monitoring programs.

Disease surveillance represents another domain where the integration of these three technologies proves particularly valuable. Bioinformatics tools enable the identification of pathogens from wildlife samples, GIS platforms map the spatial distribution of disease occurrence, and AI algorithms analyse environmental and climatic risk factors to predict future outbreak hotspots. This integrated approach supports early-warning systems for zoonotic diseases, which is particularly relevant given the increasing frequency of disease spillover events at the human-wildlife interface (Pyšek & Richardson, 2010).

Invasive species management similarly benefits from this convergence. AI-based image recognition facilitates rapid identification of invasive species from field or citizen-science data, GIS enables spatial tracking of invasion fronts, and bioinformatics tools assist in tracing the genetic origin and spread pathways of invasive populations. Together, these technologies provide a comprehensive toolkit for early detection and management of biological invasions. The development of integrated digital platforms that combine AI, GIS, and bioinformatics functionalities is an emerging trend in conservation technology, aiming to provide researchers and wildlife managers with unified interfaces for data collection, analysis, and visualization, thereby reducing the technical barriers associated with using multiple specialized software tools.

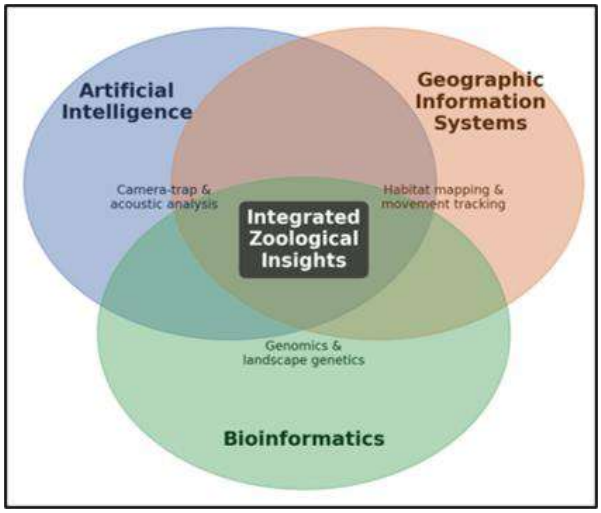


Figure 1. Conceptual diagram illustrating the convergence of Artificial Intelligence, GIS, and Bioinformatics in generating integrated zoological insights.

Table 2. Key Challenges and Potential Solutions in Integrating AI, GIS, and Bioinformatics in Zoology

Challenge	Description	Potential Solution
Data heterogeneity	Difficulty combining datasets of differing formats, resolutions, and scales	Standardized, interoperable data protocols
Computational infrastructure	Limited access to high-performance computing in biodiverse regions	Cloud-based, open-access computing platforms
Taxonomic and geographic bias	Training data and reference databases skewed toward charismatic species and well-studied regions	Expansion of datasets for understudied taxa and regions
Interdisciplinary expertise gap	Shortage of researchers trained across computational and biological domains	Dedicated interdisciplinary curricula and training programs
Model interpretability	'Black-box' AI outputs complicate use in conservation policy	Development of explainable AI (XAI) methods

Beyond these technical challenges, ethical and data-sharing concerns—including data ownership, indigenous data sovereignty, and the potential misuse of location data for poaching or exploitation—must be carefully addressed when developing and disseminating spatial and genetic datasets.

Conclusion

The integration of Artificial Intelligence, Geographic Information Systems, and Bioinformatics represents a paradigm shift in zoological research, enabling more comprehensive, efficient, and scalable approaches to studying animal behaviour, distribution, and genetics. While each technology offers substantial individual contributions, their convergence provides a powerful framework for addressing complex conservation challenges, from disease surveillance to habitat connectivity and genetic rescue. Realizing the full potential of this integration requires overcoming challenges related to data standardization, computational infrastructure, and interdisciplinary training. As these emerging technologies continue to evolve and become more accessible, they are poised to play an increasingly central role in advancing zoological science and supporting evidence-based biodiversity conservation in the twenty-first century.

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Ornamental Fish Farming: A Booming Industry in India

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Abstract

Ornamental fish farming has emerged as a rapidly growing and lucrative industry worldwide, particularly in Southeast Asian countries including India, Indonesia, Thailand, Singapore, and Sri Lanka. Driven by the increasing popularity of aquarium keeping as a hobby, urban lifestyle changes, and aesthetic appeal, the industry offers high income potential with low space requirements and initial investment. This profitable agribusiness though, requires proper technical knowledge, infrastructure, and market linkages, but is proven to hold great promise for sustainable income generation, especially in rural and peri-urban areas. Its low land and water requirements make it especially suited for small-scale entrepreneurs. The most common & easy to breed fish typically selected for ornamental fish farming are Goldfish, Guppy, Molly, Platy, Swordtail, Angelfish, Barbs, Clownfish, Mandarin fish, Flowerhorn Cichlid etc. These species represent both freshwater and marine varieties. Ornamental fish farming plays a vital role in the aquaculture sector, contributing significantly to economic development, employment generation, environmental education, and mental well-being. In addition to

promoting awareness of aquatic biodiversity and environmental conservation, ornamental fish serve as valuable models for research in genetics, breeding techniques, disease management, and water quality control. The industry offers wide-ranging benefits, including environmental and aesthetic value, entrepreneurial opportunities, and substantial economic potential.

Keywords: Ornamental fish farming, ornamental fishes, Importance of ornamental fishes, Prospect in India.

Introduction

Aquarium fish or ornamental fish farming is an age-old practice that was started in China with goldfish several hundred years ago. They used a variety of containers, such as dishes, bowls, and small tanks, for maintaining long days and viewing from the top of such containers. The Hongwu Emperor of China in 1369 inaugurated a company that first produced commercially large porcelain tubs for maintaining fish. Over time, people produced tubs that approached the shape of modern fish bowls. In 1805 first ornamental fish aquarium exhibition was held for common people in England. In 1832, a pioneering French marine biologist became the first person to create aquaria for experimenting with aquatic organisms. During the 17th century, the goldfish was introduced to several countries and became most popular in England and Scotland between 1854 – 1862. In 1928 were 85 such aquariums, but it was reported that now, throughout the world, such aquariums more than 500. Since 1850, the hobby of keeping fish in an aquarium has become popular in the USA. In 1996, the United States was the second most popular in the aquarium fish keeping hobby. In 1999, an estimated 9.6 million US households owned an aquarium for fish keeping. In India, the ornamental fish-keeping hobby started in the early 20th century. Today, the culture of aquarium ornamental fish is a rewarding industry, and fish keeping inside the room (even in corporate and non-corporate sectors) is very popular. The number of domesticated fish continued to grow and breed generation after generation in captivity. The guppy, platy, swordtail, molly, zebra fish, and angel. Fighting, etc., have been hybridized, selectively bred, and consequently all of them now differ significantly from their wild ancestors in colour, shape, and reproductive cycle. In India, the hobby of keeping ornamental fish bloomed with the opening of the 'TARAPOREVALA' aquarium in Mumbai in 1951 and several aquarium societies (Saha, 2021, 2022 and Saha et al., 2024).

Scopes in the Ornamental Fish Farming

- **Main or Side Business:** The Fisheries sector occupies a very important place in the socio-economic development of the country. It has been recognized as a powerful income and employment generator as it stimulates the growth of a number of subsidiary industries and is a source of cheap and nutritious food, besides being a foreign exchange earner. Most importantly, it is the source of

livelihood for a large section of the economically backward population of the country. The sector provides livelihood to over 14.49 million people engaged fully, partially or in subsidiary activities in the sector.

- **High Demand:** In the fisheries sector, ornamental fish breeding is also a highly professional and attractive avenue for youth. In India, 95% of ornamental fish exports are based on wild collection. The majority of the indigenous ornamental fish trade in India is from the North Eastern states, and the rest is from Southern states, which are the hot spots of fish biodiversity in India. The capture-based export is not sustainable, and it is a matter of concern for the industry. In order to sustain the growth, it is necessary to shift the focus from capture to culture-based development. Most of the fish species grown for their ornamental importance can be bred in India successfully. For organized trade, however, it depends on an assured and adequate supply of demand, which is possible only by mass breeding.
- **Less Competition in Business:** However, the market for ornamental fish in the world for public aquaria is less than 1% at present, and over 99% of the market for ornamental fish is still confined to hobbyists. Ornamental fish is regarded today as a consumer-based commodity and is the star product of the pet markets. It supports thousands of rural people in developing countries, and more people are entering into this lucrative business of culturing and breeding these fish through farming. As a result, many ancillaries as pet shops, are also coming up in cities and even small towns. One of the basic requirements is a clear understanding of the habits and biological requirements of the fish. The hobbyists can study the behaviour and biology of the fish during aquarium maintenance & can breed several varieties of fish.
- **Job Opportunities:** Considering the relatively simple technique involved in fisheries and aquaculture, it has the potential to create substantial job opportunities, besides helping export earnings. There is a very good domestic market too, which is mainly based on domestically bred exotic species.

  India's rich biodiversity offers great scope for the expansion of ornamental fish breeding. The export is also contributing to ornamental fish production, having a great potential for its breeding, as large varieties of ornamental fish have not yet been explored. The domestic ornamental fish market is worth around Rs. 50 Crores, and the demand is increasing at 20%. The earning potential of this sector has hardly been understood, and the same is not being exploited in a technology-driven manner. Considering the relatively simple technique involved, this activity has the potential to create substantial job opportunities, besides helping export earnings.
- **Required New Concept and Technology:** There are more than 120 countries involved in the ornamental fish trade. About 60-65% of ornamental fish were supplied from the developing countries. Altogether, about 1,800 species of fish

are traded, of which over 1200 are of freshwater origin. More and more species are being added to the list as a result of advancements in breeding, transport, and aquarium technology. The global ornamental fish industry, although it relies largely on captive-bred fishes of freshwater origin, includes significant numbers of fish and invertebrates from the wild are also included. The marine fish species constitute more than 15% of the market by value. About 98% of marine fish are collected from the wild, while the rest are captive-bred. It has been estimated that about 30 freshwater species dominate the market, such as guppies, platies, swordtails, mollies, neon tetra, angel fish, gold fish, zebra danio, discus, and barbs. The guppies and the neon tetra alone represent more than 25% of the global market in volume and fetch more than 14% in value. To expand trade, new technologies and policies will have to be developed, which will help in attaining a sustainable ornamental fish industry. The present demand is more for freshwater ornamental fish as they are easily accessible for breeding, and there is no requirement for salinity.

- **Research Opportunities:** The Western Ghats and the North-Eastern Region of India are considered to be two of the 34 'hotspot' areas of the world for biodiversity conservation with a variety of vegetation types, climatic zones, and remarkable endemism. These regions are also endowed with a variety of brilliantly colored ornamental fishes. With an abundance of these living jewels, India has a distinctive edge over other countries in trade potential.

  The ornamental fish industry has enormous potential in tropical countries like India, and a large number of species can only foster the needs of the industry. Various indigenous, exotic ornamental fish species and ornamental shrimp species are being exported from India. The high demands for ornamental breeds are Molly, Guppy, Platy, Swordtail, Gouramis, Barbs, Gold Fishes, Siamese fighter fish, Catfish, Angel, Cichlid, Tetra, and Carps. New cross-breeds are also developed, which are more attractive and have a higher price in the export market, including the Vastu fish ().
- **Self-Employment Opportunity:** As an entrepreneur, after obtaining a professional degree in B.F.Sc., one can start one's enterprise. The financial support can be obtained through NABARD, MPEDA, NFDB, or through other nationalized banks. The main areas in which fisheries enterprise can be developed are feed manufacturing, marketing and sales, ornamental fish culture and breeding, aquaculture, hatchery and seed production, commercial pearl production, fish processing and marketing, net making, fish disease diagnostic centre, consultancy services, and establishment of agri-clinics. Fishery graduates are also engaged as aquarium curators to acquire new specimens for displays and exhibits for execution and for the safe transportation and delivery process.

Ornamental Fish Breeding Practice

Breeding protocol and management methods are different for different fishes. The fishes can be broadly classified into two based on the mode of reproduction as egg layers and live bearers.

Breeding of Egg-Layers

The majority of aquarium fish are egg-layers with external fertilization. Egg-layers can be divided into four groups: egg-scatterers, egg-depositors, egg-burriers, and nest-builders.

1. **Egg-Scatterers (Srivastava, 2022)**

- **Laying Non-adhesive Eggs:** Zebra fish or zebra danio is considered an egg-scatterer that lays non-adhesive eggs. Other important varieties of danios include giant danio (*Danio aequipinnatus*), pearl danio (*Brachidanio albalineatus*) and zebra danio (*Brachidanio rerio*). Before setting up the breeding pair in any aquarium tank, the broods are to be well fed with live food. The male and female ratio should be maintained at 2:1 or 3: 1. The female is introduced into the breeding tank one day earlier than the males. It is very difficult to know whether a female has already laid eggs or not, because of the smaller size of eggs, and they remain hidden behind pebbles. After the successful hatching of eggs, hatchlings are seen in the aquarium tanks, and at that time their parents are removed. Hatchlings take two days to absorb the yellow yolk sac. After that, they are fed with infusorians for 4 days. Subsequently, rotifers and smaller zooplanktons can be fed for a week, after which they are provided with powdered formulated feed.
- **Laying Adhesive Eggs:** Gold fish (*Carassius auratus*) is an example of an egg scatterer laying adhesive eggs. The varieties seen in the market are gold fish, fringe tail, lion head, oranda, comet, shubunkin, telescopic eye, veil tail, and red cap. When secondary sexual characters appears, male and female goldfishes are selected and kept in circular tanks or ferrocement tanks after disinfecting containers with a 1 ppm solution of potassium permanganate (KMnO4). The water should be mixed preferably with 50% groundwater and 50% filtered pond water. The containers should be kept in such a place where it can receive early morning sunshine, and no sunlight afterwards. Since gold fish eggs are sticky in nature, they require some surface for adherence such as submerged aquatic plants like hydrilla or artificial nets like split nylon ropes and food grade polythene strips etc. The nest should float close to the Water surface, and additional nests should be spread on the bottom of the spawning tanks for the eggs that sink instead of adhering. The water temperature should be maintained between 20 and 280 C, and the ideal temperature is 24-280. Females and Male in the ratio of 1: 2 are released into the breeding tank in the late evening hour. The male chases female, presses its operculum against -laying usually takes

place within 6-12 hr of releasing males and females. The moment spawning is over nest is transferred to a different container or alternatively parent fishes are transferred from the breeding tank. If this is not done, the parents are most likely to eat away eggs to compensate post-spawning loss of energy. Generally female lays about 2000-3000 eggs. Healthy eggs are golden transparent at the beginning and gradually transparent area decreases. Under ideal conditions within three days, eggs hatch out with a hatching rate of 80-90%.

2. Egg-Depositors

Angel fish (*Pterophyllum Scalare*) one of the egg-depositers, has originated from Amazon region of South America. The ideal water quality pH remains between 6.5 and 6.9, and successful breeding occurs at pH 6.8. The water should be soft with an alkalinity of 50-100 CaCO3 mg/litre. In mature fish, breeding can he stimulated by a partial change in water and a rise in temperature between 26 and 28°C. One sure sign that spawning is about to occur is the appearance of the genital papillae, nipple-like projections called ovipositors or egg-placers in slender and pointed. These protuberances, which appear at the vent, are used respectively for depositing eggs and fertilizing them. The differences in genital papillae are the first reliable indication of the sex. The pair selects a spawning site and thoroughly cleans it about two to three days before actual spawning. Female fish lay egg in the cleaned spawning site. The male then moves over the string of eggs just laid and fertilizes them. Male and female angel fish take turns making passes over the spawning site until several hundred or more eggs have been laid, depending on the size and condition of the female prior to spawning. Generally, a healthy angel lays a maximum of 500 eggs at a time; rarely an angel lays more than 700 eggs. The parents hover closely over spawn and fan continuously with their pectoral fins to create a circulation of water over and around the eggs. Some unfertilized eggs turn white in a matter of hours and are removed by parents. It has been observed that male guard eggs and continuously fans eggs till hatching.

3. Egg-Buriers

Killifishes are egg burriers. *Aplochelius panchax*, *A. lineatus* and *A. blochii* are important killifishes. They are shade sensitive fishes. Their egg laying is naturally in a soft peat at the bottom of the tank. In drought conditions, parents may die but fertilized eggs remain dormant until next rains. A tank of 10 to 20 litres is used with fresh de-chlorinated water and a sponge filter. The fishes are kept in the tank with spawning mops to receive eggs. After ten days adult fishes are removed and eggs are left to hatch. Fry can be raised in the tank until they attain stockable size. They accept brine shrimp nauplii and infusorians with addition of finely crumbled protein rich supplementary diets, when they get little bigger. In a well-planted aquarium, they lay eggs in leafy environment.

4. Nest-Builders

Among nest-builders gouramis and their relatives are most popular. The species under this group are dwarf gourami (*Colisa lalia*), banded gourami (*C. fasciata*), pearl gourami (*Trichogaster leeri*) and siamese fighter fish (Betta splendens) and the Chinese paradise fish (*Macropodus Opercularis*). For breeding purposes, males and females are kept separately in different tanks for a few weeks with all kinds of prepared feed and also live-foods. When the abdomen of the female becomes grossly distended with eggs, it is transferred to a smaller breeding tank with water level of 12.7 cm -15.2 cm at a temperature of 28-300C. The tank should contain plenty of fine-leaved plants such as Cabomba or Myriophyllum and some of the floating weeds like Eichhornia or Pistia. The required ideal hardness and pH of water is at 100-200 ppm and 7.0-7.5 respectively. After one or two days, a good male is introduced in the breeding tank. A transparent perforated plastic sheet or a glass is placed over the tank to keep humidity and temperature at high level which helps maintain bubble nest in a good condition. The male soon begins building a bubble nest. During and after making the nest, the male displays it to female, and this usually ends with both fishes embracing near nest resulting deposition of a large numbers of eggs in the nest. After breeding, female is removed. The male guards eggs, which remain attached to floating bubble nest. Hatching takes place within 24-30 hours. The moment, the fry begins leaving nest, male is also removed from the tank.

Breeding of Live Bearers

Livebearers are fish that bear live young ones. The important live bearers are guppy, molly, swordtail and platy. Usually, live bearers mature between 4 and 6 months. However, guppy and platy may mature even within two months. Male and female can be easily distinguished. Males are small and attractive with bright colour, whereas female is larger and dull coloured. Mature females possess bulged belly and males possess gonopodium which is a tube-like modification of anal fin. In live bearing fish, the eggs are situated in the egg duct where they are fertilized. The female is fertilized by the nearest touch of the gonopodium on her vent (Mahapatra, 2015). Male inserts its period is 20-35 days. Gravid females need to be removed from community tank as soon as they start swelling with developing young ones and are placed in the breeding tank (30 x 20 x 20 cm), individually or in pairs. Tank should be provided with plants like cobomba or hydrilla. Once the female has given birth to the full brood she can be removed. After 2-3 days the female again becomes pregnant even without the contact of male. The sperm transferred during first mating is stored in the female body and when eggs are formed the sperm will join with eggs and form young ones. Thus by single mating young ones can be released 8-10 times. In a year it is possible to get young ones 10 times from one female.

Prospects of Ornamental Fish Culture & Trade in India and West Bengal

In India, the ornamental fish-keeping hobby started in the early 20th century. In the fisheries sector, ornamental fish breeding is also a highly professional and attractive avenue for youth. In India, 95% of ornamental fish exports are based on wild collection. The majority of the indigenous ornamental fish trade in India is from the North Eastern states, and the rest is from Southern states, which are the hot spots of fish biodiversity in India. The capture-based export is not sustainable, and it is a matter of concern for the industry. In order to sustain the growth, it is necessary to shift the focus from capture to culture-based development. Most of the fish species grown for their ornamental importance can be bred in India successfully. For organized trade, however, it depends on an assured and adequate supply of demand, which is possible only by mass breeding. Today culture of aquarium ornamental fish is a rewarding industry, and fish keeping inside the room (even corporate and non-corporate sectors) is very much popular. The number of domesticated fish continued to grow and breed generation after generation in captivity. The guppy, platy, swordtail, molly, zebra fish, angel, fighter, etc, have been hybridized, selectively bred, and consequently all of them now differ significantly from their wild ancestors in colour, shape, and reproductive cycle (Saha, 2022). According to a 2002 report, the Indian domestic ornamental fish trade is growing at the rate of 20% annually, and in 2012, Indian turnover was US$ 362 million, which is 0.32% of the total world export. Now India is trying to be a strong competitor in the international ornamental fish trade. India contributes a very low (only 1%) share in the total export volume of ornamental fish from Asian countries (Saha, 2021; Saha, 2022). Most of the States in the country have ornamental fish farms and trade outlets, but export activities are taking place in only six of these States. Calcutta (West Bengal) is the top export port for ornamental fish from India, followed by Mumbai (Maharashtra), Chennai (Tamil Nadu), Bangalore (Karnataka), and Kochi (Kerala). Presently, about 150 indigenous ornamental fish species are listed in the export portfolio. Barbs, catfishes, and loaches form the main group of fish exported from India. Of these, only selected varieties of indigenous ornamental fishes are exported continuously, most important of which are redline torpedo (*Sahyadria denisonii*), reticulated loach (Botialohacata, Botiastriata), puffer fish (*Carinotetraodon travancoricus*), and snakeheads (*Channa sp.).*

Ornamental Fish Farming in West Bengal

West Bengal is a pioneer in the ornamental fish trade, and the state has contributed 90% of the total earnings of India from the export of ornamental fish. Ornamental fish or aquarium fish trading is an emerging profitable, and secure livelihood in rural areas of West Bengal due to its low-cost management and high production. In West Bengal, key districts popularly known for ornamental fish breeding & culture are Howrah (Bally-Jagacha, Domjur, Panchla, Sankrail & Jagatballavpur) and South

24 Parganas (Bishnupur, Magrahat, Falta & Budge Budge). The other districts in West Bengal where ornamental fish trade (OFT) is also prevalent are East Burdwan, East Midnapore, Nadia, Jalpaigudi, Murshidabad, & Hooghly. Kolkata is the main distribution centre and the largest wholesale ornamental fish market in India, and the fish trade in Kolkata involves collectors, suppliers, retailers, and exporters. From Kolkata, most of the fish are distributed to different states of India by air or road (train, bus, etc.), and also abroad. As ornamental fish trading is one of the fastest and most trustworthy sectors for generating employment opportunities and augmenting economic status from the domestic to the state level, and from the state to the national level. So, the government of West Bengal is showing interest by giving loans for cottage industries with admissible interest (Silpa Sathi, the Policy may be called the West Bengal Fisheries Investment Policy, 2015 for Micro, Small, Medium & Large Enterprises in the Fisheries Sector). The object of the "Silpa Sathi" policy is to extend fiscal incentives to encourage entrepreneurs for setting up new Micro, Small, Medium & Large Enterprises in the Fisheries sector with a view to encourage the dispersal of such enterprises to lesser developed areas as well as to propel the growth of the Fisheries Sector in the State. The government of West Bengal has also been promoting ornamental fish farming as a livelihood option for women. The promotional campaign involves organizing an Annual Bengal Fish Festival and opening doors for corporate investment in the sector. More than 30 thousand housewives of different districts of West Bengal are engaged in ornamental fish breeding, rearing, and marketing. During this trading, rural farmers also develop the skill of feed preparation, treatment of fish diseases, proper rearing of young, proper management of business, etc. Household women of different districts rearing the tiny fish with all care, and they have shown interest in different activities of the backyard culture of ornamental fish. The majority of the people gained knowledge through experience and the experience of the people involved in the industry by cultured live fishes (Goldfish, Angels, Gouramies, Barbs, Oscars, Zebras, Discus, Cichlids, Catfish, Fighters, tetras, guppies, platys, swordtails & mollies). West Bengal has a wide variety of ornamental fish with more than 176 indigenous varieties, adding up to a comparable number of exotic varieties that are possible to breed in captivity. It is reported that total value of domestic turnover per year is about 300 crore from 50,000 households of rural areas of West Bengal by rearing 210 species. An estimated 5000 women of Self-Help Groups and more than 150 women fisher co-operative societies are in West Bengal. The average income of each member of a Self-Help Group (SHG), involved in ornamental fish trade, ranged from Rs. 3000-4500/ month, and they manage to earn around 10,000/- every month. Almost 1500 – 1800 fish collectors are engaged in this business in the state, and more than 1500 rural youths are occupied in the trade as collectors and earn a livelihood. Ornamental fish farming can be a promising alternative for livelihood as a suitable trade for rural people of West Bengal due to favourable climatic

conditions and a large number of rivers, lakes, ponds, and estuaries (Saha, Mandal & Das, 2024). So, more scientific and systematic exploration in the future of this potential cottage industry would build a big industry in every district of West Bengal for improving rural livelihood, generating income and improving their livelihoods. Ornamental fish keeping and its propagation has been an interesting activity for many, which provides not only aesthetic pleasure but also financial opportunities. About 600 ornamental fish species have been reported worldwide from various aquatic environments. India's overall ornamental fish trade was about 1.06 million US$ during year 2009, our county possesses a rich diversity of ornamental fish, with over 100 indigenous varieties, in addition to a similar number of exotic species that are bred in captivity. It is an excellent business opportunity in India since there is strong demand from domestic and export markets. Ornamental fishes have a good potential due to enormous geographical spread, extensive species diversity and intensive research and development effort that are already put in by the associated institutions. Expansion of ornamental fish exporters, subsidies in the industry may be impetus over the increase export earnings, this seasonal enterprise as the breading and consequence seed productions during certain period are taking place. For better utilization of the ornamental fish culture facility, it is obligatory to campaign breeding operations with major species suitable for each season. An innovative entrepreneur can earn much higher profits by implementing such activities.

Present Status of Ornamental Fish Culture and Trade in India

1. Freshwater Ornamental Fishes

India is blessed with a rich diversity of freshwater fishes, both in the Western Ghats and the North Eastern hills. The Western Ghats of India are one of the 34-Biodiversity 'hotspots' of the World. Among the 300 species of freshwater fishes in the Western Ghats, 155 are considered ornamental fishes, of which 117 are endemic to the Western Ghats. At present, only a small fraction of the endemic fish diversity is utilized in the ornamental fish trade. All the ornamental fish marketed in India are exotic. Even though there are quite a lot of indigenous fish species, having high potential as ornamental fish, they have not been properly exploited. The fish fauna of the Western Ghats includes a variety of barbs, rasboras, killifishes, glass fishes, catfishes, catopras, hill trouts, and danios, which are ideal candidates for the ornamental fish industry. In India, reservoir fisheries, carp farming, prawn farming, shrimp farming, and hatchery production of fish and shrimp seeds are aquaculture-based research activities. More than 100 varieties of indigenous freshwater ornamental fish species are known in Indian waters. Some of the species fetch a high price in the world market and support trade outside the country. These ornamental fish, due to the nature of breeding, are broadly classified as livebearers and egg layers. Mollies, Platies, Guppies, and Swordtails are typical examples of

livebearers. Gold fish, tiger barbs, golden rosy barbs, Koi carp, Gouramis, and fighters are egg layers. The list of popular ornamental fish distributed in freshwater is given in Annexure 1.

Annexure-I (Jayashree et al.))

Freshwater Ornamental Fishes

- Badis: *Badisbadis*
- Indian garfish: *Xentodoncancila*
- Siamese fighing fish: *Bettasplendens*
- Dwarf gourami: *Colisalalia: Colisachuna*
- Chinese paradise: *Macropodusopercularis*
- Pearl gourami: *Trichogasterleeri*
- Silver gourami: *Trichogastermicrolepis*
- Snake skinned gurami: *Trichogasterpectoralis*
- Blue gourami: *Trichogastertrichopterus*
- Kissing gourami: *Helostomatemminki*
- Zebra danio: *Brachydaniorerio*
- Goldfish: *Carassiusauratus*
- Koicarp: *Cyprinuscarpiovar koi*
- Redtailed black shark: *Labeobicolor*
- Bridle shark: *Labeofrenatus*
- Rosy barb: *Puntiusconchonius*
- Black spot barb: *Puntiusfilamentosus*
- Tiger barb: *Puntiustetrazona*
- Red rasbora: *Rasboraeinthoveni*
- Striped aplocheilus: *Aplocheiluslineatus*
- American flsg fish: *Jordanellaflorida*
- Black widow tetra: *Gymnocorymuscallistus*
- Serpea tetra (Jewal): *Hemigrammuscallistus*
- Buenos aires tetra: *Hemigrammuscaudovitatus*
- Lemon tetra: *Hyphessobryconpulchripinnis*
- Neon tetra: *Paracheirodoninnesi*
- Indian glass fish: *Chandaranga*
- Oscar (Velvet cichlid): *Astrnonotusocellatus*
- Firemouth cichlid: *Cichlasomameekithorichthysmeeki*
- Zebre cichlid (Convict cichlid): *Cichlasomanigrofasciatum*
- Auratus (Nyasa golgen cichlid): *Melanochromisauratus*
- Ramirez (Butterfly cichlid): *Papiliochromisramirezi*
- Blue morph: *Pseudotropheuslombardoi*

- Angel fish: *Pterophyllumscalar*e
- Discus: *Symphysodon discus*
- Tiger loach: *Botiahymenophysa*
- Clown loach: *Botiamacracantha*
- Pencil loach: *Nannostomustrifasciatus*
- White spotted spiny eel: *Mastacembelusarmatus*
- Finger fish: *Monodactylusargenteus*
- Sebea sliver fish: *Monodactylussebea*
- Indian knife fish: *Notopterusnotoprterus*
- Scat: *Scatophagusargus*
- Glass catfish (Three striped): *Eutropiellusbicirrhis*
- Indian glass catfish: *Kryptopterusbicirrhis*
- Somphongs puffer: *Carinotetradonsomophogsi*

2. Marine Ornamental Fishes

The marine ornamental fish industry has been expanding in recent years, and the global marine ornamental fish trade is estimated at US$ 200-330 million. The ornamental fishery resources of India and its territories are greater than those of Sri Lanka, Africa, Singapore, Malaysia, and the Maldives put together. India has a vast coastline of 8,129 km with around 400 species of ornamental fishes belonging to 175 genera, coming under 50 reef families occurring in the Indian seas. Potential marine ornamental fish species resources are clown fish, damsel fish, moorish idol, lion fish, parrot fishes, box fishes or trunk fishes, marine angels, butterfly fish, cleaner wrasse, cardinal fishes, surgent fishes/unicon fish, hawk fishes, bat fishes, puffer fishes, trigger fish, rabbit fish, squirrel fish, scorpion fish, blennies fish, sand smelt fish and seahorses. Very few works have been made on the acclimatization and culture of marine ornamental fishes in captivity. At present, studies on the breeding of marine ornamental fishes in India are in their infant stage (annexure-II).

Annexure- II (Saha, 2022)

Marine Ornamental Fishes

- Clown fish: *Amphiprionalkallopisos*
- Tomato clown: *Amphiprionfrenatus*
- Rose clown: *Amphiprionpreideration*
- Sea angle: *Holacanthusannularis*
- Moorisidol: *Zanclus spp.*
- Scorpion fish: *Pterois spp. P. antennata, P.vadiata, P.volitans*
- Bloonion fish: *Canthegasterspp*
- File fishes: *Rhinecanthus spp., Odonusniger, Pseudobalistesfusech*

- Butterfly fish: *Chelmonrostratus*
- *Forciper longirostris*
- *Forciper flavissimus*
- Therapon: *Theraponjarbua*
- Cardinal fish: *Apogon spp.*
- Blue stripe wrasses: *Labroidesdimidatus*
- Sea horse: *Hippocampus spp.*
- Mandarin fish: *Synciropus spp.*

Marketing and Economics

The primary distribution hub is Kolkata, the capital of West Bengal. The fish are then transported by air or land to several Indian states. A reasonable amount is exported as well. There are two distinct marketing strategies for native and exotic fish. Over 99 percent of exotic species are consumed domestically, with a small number, such as angelfish and goldfish, being exported. However, in order to satisfy export demand, 90% of natural ornamental species are gathered and raised. There is very little trade in marine ornamental fish in this region. The following channels are typically used in the marketing process:

- Firstly, the producers sell the ornamental fish directly to the wholesalers, but the amount is very negligible
- Secondly, some big middle-aged men buy large volumes of fish at very low prices from the producers, rearing the fish for 2-3 months before selling at the wholesale markets again for increased profit.
- Lastly, from the wholesale markets, retailers and others purchase the ornamental fish.

For export, the Marine Products Export Development Authority has 20 registered exporters. They either have their farm or collect the fish from different areas for export. The USA, Japan, and Singapore are the main markets.

There are three different kinds of ornamental fish production units: breeding, rearing, and combination breeding and rearing units. The infrastructure and candidate species' carrying capacities determine the profit. Because they lack the necessary equipment, the marginal farmers who raise or breed the fish must sell them sooner and make less money. However, wealthy farmers raise the fish to their ideal size and make more money.

Conclusion

India's inland and coastal waters are home to a wide variety of ornamental fish, including almost 400 species from marine habitats and over 195 native species from the North-East Region and Western Ghats. About 85% of India's total exports of ornamental fish of all kinds are wild varieties that are gathered from rivers in the North-East and Southern States. Of the North-East Region's 195 known fish

species, 155 are valuable for their aesthetic qualities. Concerning freshwater ornamental fishes, the area also has remarkable biodiversity and a high degree of endemism. West Bengal, especially Kolkata, is a significant center for the production and trade of ornamental fish, which is a burgeoning and profitable sector in India. Low-input, low-output systems that frequently rely on easily accessible labor and simple infrastructure, such as backyard units, are what define the sector. Due to its modest space and early investment needs, it can be developed as a cottage industry and offers entrepreneurial chances, particularly for young people without jobs.

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Aquatic Biodiversity and Water-Quality Dynamics in Floodplain Wetlands of Jorhat, Assam: Seasonal and Spatial Perspectives

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Abstract

Floodplain wetlands are dynamic and productive ecosystems that support diverse aquatic communities and provide essential ecological services, yet increasing hydrological alteration, habitat modification and anthropogenic pressures threaten their ecological integrity. This study assessed aquatic biodiversity and water-quality dynamics in two floodplain wetlands, 2 No. Puronigohain Gaon Wetland and Potiasola Wetland, in Jorhat district, Assam, focusing on seasonal and spatial variation from March 2025 to February 2026. Aquatic fauna were surveyed across ten sampling stations, alongside assessment of key physicochemical parameters. The study recorded 56 fish species, comprising 43 small indigenous fishes and 13 large fishes, and 19 aquatic invertebrate taxa representing Annelida, Arthropoda and Mollusca, indicating substantial aquatic biodiversity. Water quality exhibited marked seasonal variation, with monsoon conditions characterised by higher temperature and free CO_2 but lower transparency and dissolved oxygen (DO), whereas post-monsoon conditions showed increased transparency, DO, alkalinity and TDS. Water remained predominantly neutral to slightly alkaline (pH 7.0–7.9). Spatial variation in faunal diversity was associated with differences in habitat structure, aquatic vegetation, depth, substrate and hydrological connectivity. Higher

DO generally coincided with greater fish diversity, while elevated turbidity and TDS appeared associated with reduced fish occurrence at some stations. The findings highlight the conservation importance of these wetlands and support integrated habitat protection, sustainable fisheries management, hydrological connectivity and long-term biodiversity monitoring.

Keywords: Floodplain wetlands; Aquatic biodiversity; Water quality; Fish diversity; Wetland conservation.

Introduction

Wetlands are among the most productive ecosystems on Earth and provide essential ecosystem services, including nutrient cycling, primary production, flood attenuation, groundwater recharge, water purification and food production (Millennium Ecosystem Assessment, 2005). They also serve as important breeding, nursery, feeding and habitats for fishes and diverse groups of aquatic fauna. Hydrological connectivity with adjoining river systems, seasonal fluctuations in water level and habitat characteristics strongly influence the composition and diversity of wetland communities. Water quality is a major factor regulating aquatic biodiversity. Physicochemical parameters such as temperature, pH, transparency, dissolved oxygen, free carbon dioxide, alkalinity and total dissolved solids influence physiological processes, productivity and habitat suitability, thereby affecting species abundance and community composition. Studies from diverse Indian aquatic ecosystems have demonstrated that spatial and seasonal variations in physicochemical conditions can substantially influence aquatic faunal composition, abundance, and diversity, with parameters such as pH, nitrate, dissolved oxygen, and temperature emerging as important environmental drivers (Lianthuamluaia et al., 2019; Sandhya et al., 2019; Chakraborty & Saha, 2021).

Assam's floodplain wetlands, locally known as beels, are particularly important for maintaining aquatic biodiversity, sustaining fisheries, and supporting diverse ecosystem services. Studies from individual wetlands have demonstrated clear associations between physicochemical conditions and aquatic faunal diversity. For example, Hazarika (2013) documented the relationship between water-quality characteristics and fish diversity in Satajan Wetland, while Das et al. (2021) reported significant associations between physicochemical parameters and ichthyofaunal diversity in Dhir Beel, particularly across monsoon and post-monsoon periods. More recently, Duarah et al. (2025) synthesised evidence on the biodiversity, limnology, ecological functions, socioeconomic significance, and conservation challenges of wetlands across Assam. Similarly, Das et al. (2025) demonstrated that environmental variables including water temperature, pH, dissolved oxygen, turbidity, and ammonia were important determinants of fish abundance and community structure in Deepor Beel.

Wetlands of Jorhat district, particularly Nahotia and Potiasola, have been studied for their limnological characteristics, fish diversity and fishery potential; however, integrated information on aquatic fauna, including insects, molluscs and annelids, in relation to seasonal water-quality variations remains limited (Bordoloi et al., 2012; Bordoloi, 2014). Therefore, the present investigation was undertaken in 2 No. Puronigohain Gaon Wetland and Potiasola Wetland of Jorhat district, Assam, to assess aquatic faunal diversity in relation to selected physicochemical characteristics of water. The present findings contribute to a better understanding of seasonal habitat–community relationships in these floodplain wetlands.

Objectives of the Study

The present study aims to assess the diversity, abundance and distribution patterns of fishes and other aquatic fauna in the selected wetlands, and to evaluate the physicochemical characteristics of the two wetlands and determine their relationships with the distribution and diversity of aquatic fauna.

Materials and Methods

1. Study Wetlands and Sampling Design

Two wetlands, 2 No. Puronigohain Gaon Wetland and Potiasola Wetland, in Jorhat district, Assam, were selected for the study. Each wetland was divided into five sampling stations based on fish landing points, habitat characteristics and accessibility, resulting in ten sampling stations in total. Sampling was conducted systematically on a monthly/seasonal basis to capture spatial and seasonal variations during the monsoon and post-monsoon periods.

2. Collection and Identification of Aquatic Fauna

Fish and other aquatic fauna were collected using locally available fishing gears and traps appropriate to the respective habitats. Specimens were sorted, labelled and preserved in 10% formalin for subsequent identification. Fish identification was carried out using standard taxonomic keys and literature, with nomenclature verified through FishBase (Froese & Pauly, 2024). Non-fish aquatic organisms were identified to the lowest practicable taxonomic level using relevant taxonomic literature.

3. Physicochemical Analysis of Water

Water-quality assessment was conducted twice monthly from March, 2025 to February, 2026, covering the pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February) periods. Water samples were collected from all ten stations in clean, labelled 1000-mL sampling bottles and transported to the laboratory under appropriate conditions. Samples requiring laboratory analysis were stored at approximately 4°C until processing.

The following parameters were analysed:

- Atmospheric temperature
- Water temperature
- pH
- Transparency
- Dissolved oxygen (DO)
- Free carbon dioxide (CO_2)
- Total alkalinity
- Total dissolved solids (TDS)

Analytical procedures followed established protocols described in APHA, AWWA and WEF (2017), Standard Methods for the Examination of Water and Wastewater, supplemented where necessary by standard limnological procedures (Wetzel & Likens, 2000).

Results

1. Aquatic Fish Diversity

The two wetlands collectively supported a rich fish assemblage comprising 56 recorded species, including 43 small indigenous fishes and 13 large fishes. The small indigenous fish community represented diverse freshwater taxa, including Cyprinidae, Ambassidae, Channidae, Bagridae, Cobitidae and Mastacembelidae. Species such as *Amblypharyngodon mola, Anabas testudineus, Badis badis, Heteropneustes fossilis, Macrognathus pancalus* and *Salmophasia bacaila* showed relatively wider distribution, whereas several species exhibited restricted occurrence at particular sampling stations or wetlands. The large-fish assemblage included ecologically and commercially important species such as *Sperata seenghala, Wallago attu, Channa striata, Labeo rohita, L. calbasu, L. gonius, Silonia silondia, Catla catla* and *Ctenopharyngodon idella*. The occurrence of species belonging to different feeding guilds indicates the availability of diverse trophic niches and habitat conditions within the wetlands.

2. Diversity of Other Aquatic Fauna

In addition to fishes, 19 aquatic invertebrate taxa were recorded, representing the phyla Annelida, Arthropoda and Mollusca. The assemblage comprised aquatic bugs, beetles, dragonflies, damselflies, crustaceans, molluscs and aquatic annelids. Representative taxa included *Anisops, Corixa, Lethocerus, Dytiscus, Gyrinus, Libellula, Pseudagrion, Ranatra, Gerris* and *Hydrophilus*. These organisms constitute important components of aquatic food webs and their occurrence and distribution provide useful ecological information regarding habitat characteristics and environmental conditions.

3. Spatial Distribution of Aquatic Fauna

The distribution of aquatic fauna showed considerable spatial variation among the sampling stations of the two wetlands. While some stations supported relatively higher species richness, others showed comparatively restricted species occurrence. Such variation may be associated with differences in water depth, aquatic vegetation, substrate, water movement, hydrological connectivity, nutrient availability, physicochemical conditions and fishing intensity. The observed spatial heterogeneity indicates that individual stations provide distinct microhabitats, including shallow vegetated margins, open-water areas and deeper zones, which support different components of the aquatic community. Overall, the distribution and diversity of aquatic fauna appear to be influenced by the combined effects of habitat structure, hydrological characteristics and water-quality conditions.

4. Physicochemical Characteristics of the Wetlands

- **Temperature**

Both wetlands exhibited seasonal variation in atmospheric and water temperature. Atmospheric temperature ranged from approximately 25–29°C, while water temperature varied between 22–25°C. Temperature was generally higher during the pre-monsoon and monsoon seasons and lower during post-monsoon and winter. Such variation can influence metabolic activity, growth, reproduction and oxygen availability in aquatic organisms.

- **pH**

The pH of both wetlands remained neutral to slightly alkaline (7.0–7.9) throughout the study period. The relatively stable pH indicates generally favourable acid–base conditions for aquatic biota, with minor fluctuations potentially associated with rainfall, photosynthesis, respiration and decomposition.

- **Transparency**

Transparency ranged from 135–170 cm in 2 No. Puronigohain Gaon Wetland and 113–121 cm in Potiasola Wetland. Values were generally lower during the monsoon, probably due to runoff and suspended sediments, and increased during the post-monsoon period. Reduced transparency may limit light penetration and aquatic productivity.

- **Dissolved Oxygen**

DO ranged from 4.62–9.43 mg L^{-1} in 2 No. Puronigohain Gaon Wetland and 3.82–9.70 mg L^{-1} in Potiasola Wetland. DO was generally lower during the monsoon and higher during the post-monsoon period, reflecting seasonal changes in temperature, organic decomposition and oxygen exchange. The observed concentrations generally provided suitable conditions for aquatic fauna.

Table 1. Seasonal variation in physicochemical characteristics of the studied wetlands of Jorhat, Assam.

Physicochemical parameter	Pre-monsoon (March–May)	Monsoon (June–September)	Post-monsoon (October–November)	Winter (December–February)
Water temperature (°C)	Increasing with rising atmospheric temperature	Relatively high	Declining	Lowest
pH	Neutral–slightly alkaline	7.0–7.9; neutral–slightly alkaline	Generally stable/slightly higher	Generally stable
Transparency (cm)	Moderate–high	Lower	Higher; 135–170 in 2 No. Puronigohain Gaon and 113–121 in Potiasola	Generally high
Dissolved oxygen (mg L^{-1})	Moderate/variable	Lower; 4.62–9.43 in 2 No. Puronigohain Gaon and 3.82–9.70 in Potiasola	Higher	Generally favourable
Free CO_2 (mg L^{-1})	Variable	Higher; maximum 11.91 ± 0.43 in Potiasola (August)	Lower; minimum 4.10 ± 0.56 in 2 No. Puronigohain Gaon (November)	Generally low–moderate
Total alkalinity (mg L^{-1})	Moderate/increasing	Relatively lower	Higher; approximately 67–91	Moderate–high
Total dissolved solids (mg L^{-1})	Increasing	Variable	Generally higher; 168.22–365.63 in 2 No. Puronigohain Gaon and 169.47–309.55 in Potiasola	Moderate–high
Overall water-quality condition	Transitional	Strongly influenced by rainfall and runoff	Relatively stable/favourable	Relatively stable

Expected influence on aquatic fauna	Increasing environmental stress may occur with warming and declining water levels	Increased connectivity but greater turbidity and variable oxygen conditions	Generally favourable conditions for aquatic fauna	Relatively stable.

- **Free Carbon Dioxide**

Free CO_2 showed marked seasonal variation, with generally higher concentrations during the monsoon. The maximum value (11.91 ± 0.43 mg L^{-1}) was recorded in Potiasola Wetland during August, whereas the minimum (4.10 ± 0.56 mg L^{-1}) occurred in 2 No. Puronigohain Gaon Wetland during November. These variations may reflect changes in respiration, decomposition and photosynthetic activity.

- **Total Alkalinity**

Total alkalinity ranged approximately from 67–91 mg L^{-1} and generally increased during the post-monsoon period. Seasonal variation may be associated with mineral dissolution, rainfall and hydrological changes.

- **Total Dissolved Solids**

TDS ranged from 168.22–365.63 mg L^{-1} in 2 No. Puronigohain Gaon Wetland and 169.47–309.55 mg L^{-1} in Potiasola Wetland. Higher values during the post-monsoon period may reflect reduced dilution and concentration of dissolved ions and mineral inputs.

Overall, the wetlands exhibited distinct seasonal variability in physicochemical conditions. Monsoon was characterised by relatively higher temperature and free CO_2, but lower transparency and DO, whereas post-monsoon showed improved transparency and DO, reduced free CO_2, and increased alkalinity and TDS. These variations were primarily associated with rainfall, runoff, water depth, evaporation, decomposition and biological activity.

- **Relationship with Aquatic Faunal Diversity**

Aquatic faunal diversity showed seasonal and spatial variation in relation to changes in physicochemical conditions. Higher dissolved oxygen and transparency, particularly during the post-monsoon period, generally coincided with more favourable conditions for aquatic fauna. In contrast, the monsoon period, characterised by increased runoff, suspended sediments, reduced transparency and comparatively lower DO, may temporarily limit the occurrence of some sensitive organisms. Elevated free CO_2 during the monsoon may further reflect increased respiration and decomposition. Overall, aquatic faunal diversity appears to be governed by the combined influence of water quality and habitat characteristics, including DO, temperature, transparency, pH, TDS, aquatic vegetation, water depth,

substrate and hydrological connectivity. Local anthropogenic pressures may also contribute to spatial differences in faunal composition. Thus, no single physicochemical parameter can adequately explain the observed diversity patterns.

Discussion

The present study revealed considerable aquatic biodiversity in 2 No. Puronigohain Gaon and Potiasola wetlands, comprising 56 fish species and 19 aquatic invertebrate taxa. The relatively high faunal richness highlights the ecological significance of these wetlands as heterogeneous aquatic habitats supporting diverse assemblages. This finding agrees with broader assessments identifying Assam's wetlands as important reservoirs of aquatic biodiversity and ecosystem services (Duarah et al., 2025). Differences in aquatic vegetation, water depth, habitat complexity and hydrological connectivity may further contribute to spatial variation in faunal richness.

The physicochemical environment exhibited pronounced seasonal variability, largely reflecting monsoonal hydrology. Higher temperature and reduced transparency during the monsoon indicate the influence of rainfall, surface runoff and sediment influx, which increase suspended matter and reduce light penetration, thereby modifying aquatic habitat conditions. Conversely, increased transparency and dissolved oxygen during the post-monsoon period suggest improved water clarity and oxygenation following reduced runoff. Seasonal variation in dissolved oxygen may also be influenced by temperature, organic matter decomposition, photosynthetic activity and atmospheric gas exchange (Wetzel & Likens, 2000). Comparable seasonal patterns have been documented in other wetlands of Assam (Hazarika, 2013; Das et al., 2021), emphasizing the role of monsoonal hydrology in regulating wetland environmental dynamics. The neutral to slightly alkaline pH (7.0–7.9) indicates relatively stable conditions favourable for aquatic organisms. Higher alkalinity and TDS during the post-monsoon period may reflect reduced dilution and increased concentration of dissolved ions following the monsoon. Higher dissolved oxygen generally coincided with greater fish occurrence, whereas increased turbidity and TDS appeared to coincide with reduced occurrence at some sites. Similar relationships between environmental gradients and fish assemblage structure have been reported in Indian aquatic ecosystems (Lianthuamluaia et al., 2019).

Overall, aquatic faunal diversity appears to be regulated by interacting physicochemical and habitat factors rather than by any single variable. Water depth, aquatic vegetation, substrate, habitat complexity, hydrological connectivity and anthropogenic pressures may collectively influence faunal composition. Thus, the observed associations should be interpreted as ecological patterns rather than direct causal relationships.

Conclusion

The present study demonstrates that 2 No. Puronigohain Gaon Wetland and Potiasola Wetland support considerable aquatic biodiversity, comprising 56 fish species and 19 aquatic invertebrate taxa. The wetlands exhibited clear seasonal and spatial variations in physicochemical conditions, particularly in temperature, transparency, dissolved oxygen, free CO_2, alkalinity and TDS. The observed patterns indicate that water quality, seasonality and habitat characteristics collectively influence aquatic faunal distribution and diversity. The relatively favourable pH and dissolved-oxygen conditions suggest that both wetlands continue to provide suitable habitats for diverse aquatic organisms. However, increasing anthropogenic pressures, hydrological alteration and deterioration of water quality may pose risks to their ecological integrity. Overall, the findings highlight the ecological and biodiversity value of these wetlands and emphasise the need for regular water-quality monitoring, biodiversity assessment, sustainable fisheries management and conservation of wetland habitats. Further long-term studies incorporating statistical and multivariate analyses are recommended to identify the principal environmental factors governing aquatic faunal diversity and to support effective conservation and management of these important floodplain ecosystems.

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Avian Ecosystem Services: Ecological Roles and Contribution to Ecosystem Functioning

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Abstract

Birds are among the most ecologically diverse and functionally important components of terrestrial, freshwater, coastal, and agricultural ecosystems. Beyond their intrinsic conservation value, avian communities provide a wide range of ecosystem services that support ecosystem functioning and human well-being. These services include seed dispersal, pollination, regulation of insect and vertebrate populations, carrion removal, nutrient cycling, soil modification, and the transport of organisms and nutrients across landscapes. Birds also contribute indirectly through ecological interactions that influence plant regeneration, food-web structure, decomposition, and ecosystem resilience. In agricultural landscapes, insectivorous and predatory birds can suppress pest populations and potentially reduce dependence on chemical pesticides, while scavenging species contribute to sanitation by rapidly removing animal carcasses. Frugivorous birds facilitate forest regeneration by transporting seeds across fragmented landscapes, and nectar-feeding species contribute to pollination of numerous plant taxa. However, habitat loss, agricultural intensification, pollution, climate change, invasive species, hunting, and other anthropogenic pressures are reducing avian populations and thereby threatening the ecological functions they perform. Understanding birds as providers of ecosystem services provides an important framework for integrating biodiversity conservation with ecosystem management and sustainable development. This chapter reviews the major ecological roles of birds, examines their direct and indirect contributions to ecosystem services, and discusses threats, conservation implications, and research priorities.

Keywords: birds, ecosystem services, pollination, seed dispersal, pest regulation, scavenging, nutrient cycling, biodiversity, ecosystem functioning, conservation

Introduction

Birds occupy almost every major ecosystem on Earth, ranging from deserts, grasslands, forests, wetlands, mountains, and agricultural landscapes to coastal and marine environments. Their high mobility, diverse feeding strategies, varied habitat requirements, and participation in complex food webs allow them to influence ecological processes at multiple spatial and temporal scales. Consequently, birds should not be viewed only as indicators of environmental quality or as objects of conservation interest; they are also active agents of ecosystem functioning.

The ecosystem-service perspective emphasizes the benefits that ecosystems and their constituent organisms provide to human societies. These benefits are commonly classified into provisioning, regulating, cultural, and supporting services. Birds contribute to all four categories, although their contributions are particularly prominent among regulating, supporting, and cultural services. For example, insectivorous birds regulate herbivorous arthropod populations, frugivorous birds disperse seeds, nectar-feeding birds pollinate plants, scavenging birds remove carrion, and migratory species transfer nutrients between geographically separated ecosystems.

The ecological importance of birds is frequently underestimated because many of their services are indirect or difficult to quantify economically. A bird dispersing a seed may contribute to forest regeneration decades before the resulting tree provides a measurable benefit. Similarly, the removal of a carcass by scavengers may prevent the accumulation of organic waste and reduce opportunities for pathogen proliferation. These processes illustrate that the value of avian ecosystem services often extends beyond immediately observable outputs.

The decline of bird populations therefore has consequences that extend beyond biodiversity loss. Reductions in abundance or functional diversity can weaken ecological interactions and alter the delivery of ecosystem services. Conserving birds is consequently relevant not only to wildlife protection but also to ecosystem stability, agricultural sustainability, forest regeneration, public health, and human cultural well-being.

Conceptual Framework of Avian Ecosystem Services

Bird-mediated ecosystem services arise from interactions between birds, other organisms, and their physical environment. A useful conceptual framework connects four components: avian diversity, ecological functions, ecosystem processes, and human benefits.

Avian diversity determines the range of ecological functions available within an ecosystem. Different species possess different morphological and behavioral characteristics, including feeding guild, body size, habitat preference, foraging

height, migration strategy, and reproductive behavior. These traits influence how birds interact with plants, prey, decomposers, competitors, and other organisms.

Ecological functions become ecosystem processes when they influence energy flow, nutrient cycling, population dynamics, regeneration, or other characteristics of ecological systems. For example, consumption of herbivorous insects by insectivorous birds can influence plant productivity, while seed consumption and dispersal can affect plant recruitment and vegetation structure.

Human benefits emerge when these ecosystem processes contribute to outcomes valued by society. Pest suppression may reduce crop damage; seed dispersal may support forest restoration; scavenging may contribute to sanitation; and bird diversity may generate recreational, educational, aesthetic, and spiritual benefits.

Thus, the relationship can be summarized as:

Avian diversity → ecological interactions → ecosystem processes → ecosystem services → human well-being.

This framework also highlights why conserving functional diversity can be as important as conserving species richness. Loss of a species with a unique ecological function may have disproportionately large effects even when overall species richness changes only slightly.

Major Ecological Roles of Birds

1. Seed Dispersal

Seed dispersal is one of the most important ecosystem services provided by birds. Many plants produce fleshy fruits that attract frugivorous birds. Birds consume these fruits and subsequently transport viable seeds away from the parent plant, frequently depositing them in locations suitable for germination.

Avian seed dispersal can influence plant distribution, forest regeneration, genetic connectivity, and succession. Birds are particularly important in fragmented landscapes because their ability to move across habitat patches allows seeds to cross otherwise difficult barriers. Some species travel considerable distances between feeding and roosting sites, thereby facilitating long-distance dispersal.

Birds can also influence seed germination through endozoochory, in which seeds pass through the digestive tract. Passage through the gut may alter the seed coat and affect germination probability. Furthermore, fecal deposits provide nutrients that can enhance establishment.

The decline of frugivorous birds can therefore have cascading consequences for vegetation. Plants that depend strongly on particular dispersers may experience reduced recruitment, while changes in seed dispersal networks can alter forest composition and regeneration trajectories.

2. Pollination

Although insects are generally recognized as the principal animal pollinators, birds play important pollination roles in many ecosystems. Nectar-feeding birds, particularly hummingbirds in the Americas and sunbirds in Africa and Asia, visit flowers to obtain energy-rich nectar. During these visits, pollen may be transferred between flowers.

Avian pollination is particularly important for plants with floral characteristics adapted to birds, such as tubular flowers, bright colors, abundant nectar, and relatively sturdy floral structures. Bird pollination contributes to reproductive success, genetic exchange, and maintenance of plant diversity.

Changes in bird abundance can therefore influence plant reproductive systems. In regions where specialized plant–bird relationships occur, conservation of both partners is essential for maintaining ecosystem function.

3. Regulation of Insect Populations

Insectivorous birds consume large quantities of arthropods and can exert substantial top-down effects on insect populations. This ecological function is especially important in forests, grasslands, wetlands, and agricultural landscapes.

Bird predation may reduce populations of herbivorous insects and consequently decrease damage to plants. In agricultural systems, birds can consume caterpillars, beetles, grasshoppers, moths, aphids, and other potential crop pests. Such biological control may complement integrated pest management and reduce reliance on synthetic pesticides.

The magnitude of pest-control services depends on bird species, landscape structure, prey availability, crop type, season, and interactions with other predators.

4. Regulation of Vertebrate Populations

Some predatory birds regulate populations of rodents, reptiles, amphibians, fish, and other vertebrates. Raptors such as eagles, hawks, kites, falcons, and owls can influence prey abundance and behavior.

In agricultural landscapes, rodent predation can potentially reduce crop losses. In natural ecosystems, raptors contribute to food-web regulation and may influence prey distribution and behavior. These effects can extend through trophic cascades, in which changes in predator abundance indirectly influence vegetation and other ecosystem components.

5. Scavenging and Carcass Removal

Scavenging birds perform a critical sanitation function by consuming dead animals. Vultures are particularly efficient scavengers because their physiological and behavioral adaptations allow them to locate and rapidly consume carcasses.

Carcass removal accelerates decomposition and nutrient recycling while reducing the persistence of organic material in the environment. In some situations,

scavengers can also limit opportunities for proliferation or transmission of pathogens associated with carcasses.

The ecological consequences of losing scavengers can be substantial. Declines in vulture populations in parts of South Asia have demonstrated how changes in scavenger communities can disrupt traditional carcass-removal systems and produce wider ecological and socioeconomic consequences.

6. Nutrient Cycling

Birds contribute to nutrient cycling through feeding, excretion, mortality, and movement among habitats. Guano can contain substantial quantities of nitrogen, phosphorus, and other nutrients and may enhance productivity in nutrient-limited environments.

Colonial seabirds provide a particularly important example. Their movements between marine feeding grounds and terrestrial breeding sites transport marine-derived nutrients onto islands and coastal ecosystems. Similar nutrient-transfer processes occur when waterbirds move between wetlands, agricultural fields, grasslands, and other habitats.

Bird-mediated nutrient movement can therefore connect ecosystems that would otherwise be relatively isolated from one another.

7. Soil Modification and Ecosystem Engineering

Some birds influence physical habitat conditions through their feeding, nesting, and foraging activities. Ground-foraging species can disturb soil and litter, while species that excavate nesting cavities may modify trees and create resources subsequently used by other organisms.

Woodpeckers are an important example of avian ecosystem engineers. Their excavation of cavities creates nesting and roosting sites that may later be used by secondary cavity-nesting birds, mammals, reptiles, and invertebrates.

Through such activities, birds can modify habitat structure and increase the availability of ecological niches.

8. Food-Web Regulation

Birds occupy multiple trophic positions. They may function as primary consumers, secondary consumers, predators, scavengers, or omnivores. Their activities can therefore influence food-web structure.

The removal or decline of a bird species may affect multiple trophic levels. For instance, reducing populations of insectivorous birds may allow herbivorous insects to increase, potentially affecting plant communities. Conversely, reductions in large predators can alter prey behavior and abundance.

9. Long-Distance Transport and Connectivity

Migratory birds connect geographically distant ecosystems. A single species may depend on breeding habitats in one region, stopover sites in another, and wintering habitats thousands of kilometers away.

During migration, birds transport nutrients, seeds, parasites, microorganisms, and genetic material between ecosystems. They can also connect ecological communities across national and continental boundaries.

Consequently, conservation of migratory birds requires international cooperation and protection of interconnected habitats along migration routes.

Avian Contributions to Agricultural Ecosystems

Agricultural landscapes are increasingly recognized as multifunctional ecosystems rather than purely production-oriented systems. Birds can contribute to agricultural sustainability through pest control, seed dispersal, scavenging, and nutrient movement.

Insectivorous birds can reduce populations of crop-damaging arthropods, particularly when agricultural fields contain suitable nesting and refuge habitats. Raptors and owls may contribute to rodent control. However, the relationship between birds and agriculture is complex because some species can also consume crops, fruits, seeds, or livestock feed.

Effective agricultural management should therefore focus on functional diversity and ecological context rather than assuming that all birds provide beneficial services in every situation. Landscape heterogeneity, maintenance of natural vegetation, reduced pesticide exposure, and provision of nesting sites can support beneficial bird communities.

Agroforestry systems are especially relevant because trees provide nesting, roosting, and foraging opportunities while crops provide additional food resources. Such systems can simultaneously support biodiversity and agricultural production.

Birds and Forest Ecosystem Function

Forests support diverse avian communities that participate in nearly every major ecological process. Frugivores disperse seeds, nectarivores pollinate plants, insectivores regulate arthropods, raptors regulate prey, and cavity excavators modify habitat structure.

Bird-mediated seed dispersal is particularly important during forest regeneration. Birds may transport seeds into disturbed areas, abandoned agricultural fields, and fragmented forest patches. By moving seeds away from parent plants, they can reduce density-dependent mortality and facilitate colonization.

Bird diversity can also serve as an indicator of forest condition. Changes in the abundance of habitat specialists, insectivores, understory species, and canopy-associated species can reveal alterations in vegetation structure and habitat quality.

Birds in Wetland and Aquatic Ecosystems

Wetlands support large numbers of resident and migratory birds and are important sites for feeding, breeding, and seasonal congregation. Waterbirds influence aquatic and terrestrial ecosystems through predation, nutrient transfer, disturbance, and movement between habitats.

Birds feeding in wetlands can influence aquatic invertebrate and fish populations. Their excreta contribute nutrients to water bodies and surrounding soils, while their movements transport organic material between aquatic and terrestrial environments.

Wetlands also provide important cultural and recreational services through birdwatching, photography, education, and tourism. Maintaining wetland bird diversity therefore provides both ecological and socioeconomic benefits.

Cultural and Educational Services

Birds provide ecosystem services that extend beyond ecological regulation. Their songs, colors, migration behavior, and diversity have influenced human cultures, literature, art, folklore, religion, and scientific inquiry.

Birdwatching and wildlife tourism generate economic benefits in many regions. Protected areas that support large concentrations of birds can attract visitors and create employment opportunities in guiding, accommodation, transportation, photography, and associated services.

Birds are also effective tools for environmental education because they are relatively visible, diverse, and widely distributed. Citizen-science programs based on bird observations can generate large datasets while increasing public engagement with biodiversity conservation.

Birds as Indicators of Environmental Change

Birds are widely used as ecological indicators because many species respond rapidly to changes in habitat structure, food availability, pollution, climate, and land-use patterns.

Changes in bird abundance, species composition, breeding success, migration timing, or distribution can provide evidence of environmental change. Long-term bird monitoring can therefore help identify ecosystem degradation and assess the effectiveness of conservation interventions.

However, indicator value varies among species. Effective monitoring should select species or functional groups with well-understood relationships to specific environmental conditions.

Threats to Avian Ecosystem Services

The delivery of avian ecosystem services is threatened by multiple interacting pressures.

Habitat Loss and Fragmentation

Conversion of forests, grasslands, wetlands, and natural habitats to agriculture, infrastructure, and urban areas reduces habitat availability. Fragmentation can isolate populations and disrupt movement between feeding, nesting, and roosting sites.

Agricultural Intensification

Intensive agriculture can reduce bird diversity through removal of hedgerows and trees, simplification of landscapes, pesticide use, and reduction of natural food resources.

Pesticides and Chemical Contamination

Pesticides can directly poison birds or indirectly reduce their food supply by eliminating insects. Persistent contaminants may accumulate through food webs and affect reproduction, behavior, survival, and population dynamics.

Climate Change

Climate change can alter migration timing, breeding phenology, prey availability, geographic ranges, and habitat suitability. Mismatches between bird migration and seasonal food availability may reduce reproductive success.

Hunting, Trapping, and Illegal Trade

Unsustainable exploitation can reduce bird populations and remove individuals from ecologically important functional groups. Losses of large-bodied predators and scavengers can be particularly consequential because these species often have slow population growth.

Collision and Infrastructure

Buildings, communication towers, power lines, roads, and wind-energy infrastructure can cause mortality or disrupt movement. Appropriate design and placement of infrastructure can reduce these risks.

Conservation of Birds for Ecosystem-Service Maintenance

Conservation strategies should move beyond species protection and explicitly recognize the ecological functions performed by birds. Important approaches include:

- **Protection and Restoration of Natural Habitats:** Forests, wetlands, grasslands, riparian zones, and coastal habitats should be conserved and restored.
- **Maintenance of Landscape Connectivity:** Wildlife corridors and habitat networks can facilitate movement and gene flow.

- **Bird-Friendly Agricultural Practices:** Reduced pesticide use, integrated pest management, agroforestry, hedgerows, and retention of native vegetation can enhance bird diversity.
- **Protection of Scavengers and Predators:** Conservation of vultures, raptors, owls, and other high-trophic-level species can maintain food-web regulation and sanitation functions.
- **Protection of Migratory Routes:** Internationally coordinated conservation is essential for species that depend on multiple habitats throughout their annual cycle.
- **Reduction of Anthropogenic Mortality:** Measures such as bird-safe building designs and appropriate infrastructure planning can reduce collisions.
- **Long-Term Monitoring:** Population and functional monitoring should be integrated into ecosystem-management programs.
- **Community Participation:** Local communities should be involved in habitat conservation, sustainable land management, and citizen-science initiatives.

Valuation of Avian Ecosystem Services

Quantifying the economic value of avian ecosystem services can strengthen conservation arguments. However, valuation should not be limited to direct monetary benefits.

A comprehensive assessment can combine:

- Ecological indicators, such as pest abundance, seed dispersal rates, pollination success, or carcass removal rates.
- Economic indicators, such as avoided crop losses, reduced pesticide expenditure, tourism revenue, and restoration costs.
- Social indicators, including recreational value, educational benefits, cultural significance, and public preferences.
- Functional indicators, including abundance and diversity of species representing particular ecological roles.

Conclusion

Birds are integral components of functioning ecosystems and provide a diverse portfolio of ecosystem services. Through seed dispersal, pollination, pest regulation, predation, scavenging, nutrient cycling, habitat modification, and long-distance ecological connectivity, birds influence ecological processes across terrestrial, aquatic, agricultural, and urban environments.

Maintaining diverse and abundant bird communities can support ecological resilience, sustainable agriculture, forest regeneration, nutrient cycling, and environmental health. Conversely, the loss of functional bird groups may generate cascading effects that are difficult and costly to reverse.

Future conservation and research programs should consequently adopt an ecosystem-service perspective while retaining species-centered conservation approaches. Protecting habitats, maintaining landscape connectivity, reducing chemical and infrastructure-related threats, conserving migratory routes, and promoting bird-friendly agricultural practices are essential for sustaining both avian populations and the ecological services they provide. Recognizing birds as active contributors to ecosystem functioning can strengthen the scientific, economic, and societal case for their long-term conservation.

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Human-Tiger Conflict at Kultali Block of South 24 Parganas

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Abstract

The Kultali block in the South 24 Parganas district forms a crucial part of the mangrove forest region of Sundarban, the largest delta in the world. The primary activities for generating income among the local population include fisheries, wage labor, agriculture, honey harvesting from the forests, and the collection of crabs and seed shrimp from the area. The fragile ecosystem of Kultali is home to a diverse array of wildlife, including the Royal Bengal tiger, snakes, crocodiles, and sharks. According to data from the Sundarban Tiger Reserve (STR) and Wildlife Trust of India (WTI), the Gosaba administration block has the largest number of recorded human-animal or human-tiger conflicts (HTC) in the Sundarbans, with Kultali coming in second. Some parts of the Kultali block, like Deulbari, Dongajora, Ajmalmari, Maipith and Bhuvaneswari, have a higher risk of human-tiger conflict than other areas due to their proximity to the closest buffer region. These areas lie at, near forest boundaries, or along river/creek channels. The boundary between "forest" and "human habitation" is porous. Therefore, tigers often swim across creeks, especially at low tide, which makes human–tiger interactions more likely. Economic dependence on forest resources (fishing, crab hunting, firewood, and honey) raises the risk. Broken or incomplete fences are also a major cause of the conflict. Association for Protection of Democratic Rights (APDR) and WTI were recorded several recent human tiger conflicts at Kultali block. Managing human–tiger conflict needs the West Bengal Forest Department to work with Civil Society

Organizations (CSOs) so that the community can take part. Projects such as Bagh Bondhu and Primary Response Teams (PRTs) that belong to IUCN's Integrated Tiger Habitat Conservation Programme (ITHCP) help, with crowd control, communication, tiger rescue and relocation and the setting up of safety nets and fences. Local Tiger-Scout groups and Prakritishala institutes run awareness programmes that encourage people to live with tigers. Still fencing, new jobs, community awareness and teaching children are needed for lasting conflict mitigation.

Keywords: Kultali, Sundarban, Human tiger conflict, forest resource, Bagh-Bondhu, alternative livelihood.

Introduction

The Kultali Block of South 24 Parganas, located adjacent to the Sundarbans mangrove forest, represents a critical interface between human settlements and the natural habitat of the Bengal tiger (*Panthera tigris tigris*). The Bengal tiger inhabiting the Sundarbans has adapted to the mangrove environment, exhibiting unique behavioral and ecological traits. Tigers here rely on dense vegetation for cover, and their prey primarily consists of deer, wild boar, and other forest animals. The fragmented nature of tiger habitats, combined with tidal influences, shapes their movement patterns and territoriality (Naha et al., 2016; Rahman et al., 2025). This region is characterized by its rich biodiversity and the presence of one of the largest tiger populations in the world. However, the close proximity of human populations to tiger habitats has led to increasing incidences of human-tiger conflict, posing significant challenges to both conservation efforts and local livelihoods (Naha et al., 2016; Rahman et al., 2025). The Sundarbans mangrove ecosystem is a UNESCO World Heritage Site and serves as a vital refuge for the Bengal tiger, a species listed as endangered. Conservation of this habitat is essential not only for maintaining biodiversity but also for ensuring ecological balance in the region. Protecting the Bengal tiger contributes to preserving the broader environmental health of the Sundarbans, which supports millions of people through ecosystem services such as fisheries, storm protection, and carbon sequestration (UNESCO, 2026; WTI, 2025).

One thing that really stands out about this area is how many people live close to the forest core and buffer zones. It is quite a situation. Lately I have noticed that fights between people and wildlife are happening much more often. These fights, between people and wildlife are growing fast especially when Royal Bengal tigers are involved (Chatterjee, 2023). The present study aims to analyze the human–tiger conflict in the Kultali Block of the Indian Sundarbans by identifying its major causes, patterns, and socioeconomic impacts on local communities. It evaluates the effectiveness of existing mitigation measures, compensation schemes, and institutional frameworks adopted by the Forest Department and other stakeholders. The study also documents recent incidences of human–tiger conflict in the region,

including tiger intrusions into villages, livestock depredation, and human casualties reported from Kultali and adjoining areas. Recent records indicate repeated tiger incursions in Deulbari village of Kultali, the installation of early-warning systems (ANIDERS) in conflict-prone areas, and fatal tiger attacks on local resource collectors in the Sundarbans landscape, highlighting the continuing severity of the conflict (WTI, 2025a; WTI, 2025b). To manage this conflict, apart from their own mechanism, the West Bengal Forest Department often takes the support of Civil Society Organizations (CSOs) for community engagement and participation. 'Bagh Bondhu' and 'Primary Response Team' are examples of such community initiatives by the Integrated Tiger Habitat Conservation Programme (ITHCP) of IUCN for crowd control during straying, communicating with the Forest Department, extending local support to the Forest Department in capturing and relocating stray tigers, installing safety nets/fences around villages, etc.(WTI, 2025a; WTI, 2025c). Additionally, there are continuous educational initiatives. Local "Tiger-Scout" organisations and "Prakritishala" institutes run awareness campaigns to educate locals about living in harmony with wildlife. However, there is an urgent need for continued maintenance and expansion of fencing/nylon-net barriers along village perimeters, promoting alternative livelihood options, raising community awareness about tiger behaviour and safe practices, children's education and community outreach to nurture coexistence and respect for wildlife while ensuring safety (WTI, 2025b; WTI, 2025c). The study further seeks to propose practical recommendations for conflict mitigation and sustainable coexistence between humans and tigers. Ultimately, it aims to provide a comprehensive understanding of the conflict scenario that can assist policymakers, conservationists, forest managers, and local stakeholders in developing effective long-term conservation and livelihood strategies.

Materials and Methods

Study Areas

Kultali Block (22°05′12″ N & 88°35′37″ E) is situated in the South 24 Parganas district of West Bengal, India, bordering the Sundarbans mangrove forest. The Kultali Community Development (CD) Block covers a total geographical area of 306.18 square kilometer. The block is bounded by Jaynagar I and Canning I CD Blocks to the north, Basanti CD Block and the Sundarbans National Park to the east, the Sundarbans National Park to the south, and Jaynagar II CD Block to the west. The southern and eastern boundaries are characterized by dense mangrove forests, numerous tidal creeks, and estuarine waterways that form part of the Sundarbans Biosphere Reserve, making the region highly vulnerable to human–wildlife conflicts, particularly with the Bengal tiger (Dhar and Mandal, 2023). Human settlements are dispersed throughout the block, often located near forest

fringes due to historical dependence on forest resources (Naha et al., 2016; Islam et al., 2023).

Kultali Block is traversed by an intricate network of tidal rivers, creeks, and canals that form part of the lower Gangetic delta and the Indian Sundarbans. The principal rivers include the Matla, Thakuran, Piyali, Bidyadhari, Kankalmari, and Nimania rivers. Among the important canals are Gurakhal (Gura Khal) and Nabipukur Khal, along with numerous natural tidal creeks that connect villages with the surrounding mangrove forests. These waterways are strongly influenced by semidiurnal tides and serve as the primary routes for fishing, transportation, agriculture, and forest access. However, they also facilitate the movement of wildlife, particularly Bengal tigers, thereby increasing the risk of human–tiger conflict in fringe villages bordering the Sundarbans (Naha et al., 2016). GPS base map of the study areas along with recent incidents (Tiger human conflict) zone represented on fig.1.

Methodology

The present study was conducted in the Kultali Community Development (CD) Block of South 24 Parganas district, West Bengal, located along the northern fringe of the Indian Sundarbans. A mixed-methods research approach combining quantitative and qualitative techniques was adopted to assess the causes, patterns, socio-economic impacts, and mitigation measures of human–tiger conflict (Das, 2012). The study area was selected purposively because of its high incidence of human–wildlife interactions. Primary data were collected through field surveys, direct observations, household questionnaire surveys, key informant interviews (KIIs), and focus group discussions (FGDs). A total of 125 households from 5 conflict-prone villages (Deulbari, Dongajora, Ajmalmari, Maipith and Bhuvaneswari) were selected using stratified random sampling. Respondents included farmers, fishermen, crab collectors, honey collectors, livestock owners, and other forest-dependent communities. Semi-structured questionnaires were used to gather information on household socio-economic characteristics, frequency and causes of conflict, human casualties, livestock depredation, crop damage, economic losses, compensation received, community perceptions, and existing mitigation practices. Key informant interviews were conducted with Forest Department officials, Panchayat representatives, local leaders, and members of Eco-Development Committees to obtain institutional perspectives on conflict management. Field observations were carried out to identify conflict hotspots, forest entry points, embankments, rivers, canals, and other landscape features associated with tiger movement, while the geographic coordinates of major conflict sites were recorded using a handheld GPS. Secondary data on conflict incidents, compensation records, tiger rescue operations, and demographic information were collected from the West Bengal Forest Department, Sundarban Tiger Reserve authorities, government reports, Census of India, and published scientific literature. Spatial data

were integrated and analyzed using Geographic Information System (GIS) software to prepare conflict distribution maps and identify high-risk zones.. Data also collected from ADPR, WTI and Lokmata Rani Rasmani Mission. This integrated methodological framework provided a comprehensive understanding of the spatial, ecological, and socio-economic dimensions of human–tiger conflict in Kultali Block and supported the development of appropriate conservation and conflict mitigation strategies (Naha et al., 2016; Islam et al., 2023; WTI, 2025a).

Results and Discussions

Causes of Human-Tiger Conflict

Human–tiger conflict in Kultali Block is driven by a combination of ecological, socio-economic, and anthropogenic factors. The close proximity of villages to the Sundarbans mangrove forests and the high dependence of local communities on forest resources create frequent opportunities for encounters between humans and tigers. The common cause of conflict is as follows:

Habitat Encroachment and Land Use Changes

The expansion of agricultural land and human settlements into the natural territories of Bengal tigers has significantly reduced available habitat. This encroachment fragments tiger habitats, limiting their movement and forcing them into closer contact with human populations. As a result, tigers increasingly venture into human-dominated landscapes in search of food and territory. Habitat fragmentation and degradation mainly caused by mangrove clearing for settlements, agriculture and shrimp aquaculture, construction of embankments and roads, tourism-related development, resource extraction, and pollution. Cyclones, tidal erosion and sea-level rise further degrade mangrove habitats. These changes reduce suitable tiger habitat and increase contact between wildlife and human settlements, thereby intensifying human–tiger conflict.

Livelihood Dependence on Forest Resources

Local communities in Kultali Block rely heavily on forest resources for their daily needs, including fishing, honey collection, fuelwood gathering, and small-scale agriculture. Frequent human presence within tiger habitats elevates the risk of encounters and conflicts, as these activities often overlap spatially and temporally with tiger movements.

Prey Base Depletion and Its Effects

Overfishing, poaching, and habitat degradation have led to a decline in the natural prey populations of tigers, such as deer and wild boar. This depletion compels tigers to seek alternative food sources, often targeting livestock in nearby villages, thereby escalating human-tiger conflicts.

Human Activities Increasing Encounter Risks

Activities such as honey harvesting, fuelwood collection, and fishing involve entering dense forest areas or riverine habitats that are also tiger territories. These routine activities increase the probability of sudden encounters, sometimes resulting in attacks on humans or livestock.

Types of Human Tiger conflict

The major types of human–tiger conflict occurring in Kultali Block are closely linked to the proximity of villages to the Sundarbans mangrove forests, dependence on forest resources, and the movement of tigers across rivers and embankments. The common forms of conflict are as follows:

- **Human Attacks and Fatalities:** Tigers occasionally enter villages or encounter people inside the forest, resulting in injuries or deaths of fishermen, crab collectors, honey collectors, fuelwood collectors, and farmers.
- **Livestock Depredation:** Tigers prey on domestic animals such as cattle, goats, calves, and pigs, particularly when livestock graze or are kept in poorly protected sheds near forest fringes.
- **Tiger Straying into Villages:** Tigers frequently enter human settlements by crossing tidal rivers, canals, or damaged embankments, causing fear, panic, and disruption of daily activities. Such incidents often require rescue operations by the Forest Department.
- **Retaliatory Responses:** Although less common due to strict legal protection and awareness programmes, frightened villagers may surround, injure, or occasionally kill tigers in self-defence or to protect their livestock and property.
- **Economic Losses and Livelihood Disruption:** Conflict results in loss of income due to human casualties, livestock predation, restrictions on fishing and forest resource collection, crop damage caused during tiger movement, and reduced access to forests for livelihood activities.
- **Psychological and Social Impacts:** Continuous fear of tiger attacks creates stress, anxiety, school absenteeism among children, and reduced participation in livelihood activities, particularly among forest-dependent households.
- **Property Damage:** During village incursions, tigers may damage fences, livestock enclosures, doors, and temporary structures while attempting to capture livestock or escape from crowds.

Recent Data

Based on a database of WTI, 29 tiger-related incidents have been officially recorded from 2019 to June 2025 from the Kultali block (WTI, 2025a). A horrible tiger incident occurred recently on 23rd November 2025, a 21-year-old fisherman from Kultali, Tapas Haldar, was killed in a tiger attack when he was crab hunting near a creek. Sambhu Sardar, Kantamari, Kultali was killed by tiger on November, 2025

(The Times of India, 2025). Association for Protection of Democratic Rights (APDR) claiming that 12 people had been attacked by tigers in the region during 2026, with 9 of those attacks fatal. During 2026, Kultali Block experienced a series of severe human–tiger conflict incidents. The first fatality occurred on 24 April, when honey collector Gobinda Gayen was killed by a tiger. A serious injury was reported on 21 May involving Sabir Dhali. The highest number of incidents occurred during June, when Gosto Jana, Bandana Das, and an unidentified person from Deulbar lost their lives, while Sekesh Datta sustained injuries. The unidentified victim's body could not be recovered. In July, Mannan Laskar was seriously injured and admitted to P.G. (SSKM) Hospital after a tiger attack on 5 July, and Krishna Sardar (44 years) was killed on 24 July. In addition, Abur Ali Molla and Ramprasad Baghani remained missing after tiger attacks, with their bodies never recovered, while Gopal Chakrabarti of Deulbari also died in a tiger attack. These incidents indicate that the conflict was concentrated in villages adjoining the Sundarban forest fringe, particularly the Maipith and Deulbari areas, emphasizing the need for improved early-warning systems, rapid-response teams, and community-based conflict mitigation strategies (Telegraph India, 2026; WTI, 2025a).

Impact

Human–tiger conflict is a problem for both conservation and the way people live in the Kultali Block of the Sundarbans. Many families use the forests, creeks and rivers to fish, catch crabs, collect honey and do other forest jobs. When a tiger attacks it can kill a person hurt someone badly or wipe out a person’s ability to earn money. This puts pressure on families who already struggle. If the main earner dies or is hurt suddenly the family can end up in debt make money and find it hard to pay for food, school and health care. When people see tigers times, they feel scared, worried and stressed, especially those who live near the forest edges.

Human–tiger conflict also makes people stay away from forests and fishing spots so they lose access to the resources they need. Damage to the habitat breaking up mangrove areas more people working close, to the forest border and tigers accidentally wandering into villages can raise the number of encounters. Long term conflict can also make people hate tiger protection and could lead to people hurting tigers back. Human–tiger conflict therefore hurts not people’s safety and ways of earning but also the future of tiger protection and living together peacefully.

Mitigation

Effective mitigation in Kultali requires an approach that involves the West Bengal Forest Department, local communities, Civil Society Organizations and conservation agencies. Strengthening and regularly maintaining nylon net fencing, protective barriers and village boundary structures can reduce tiger movement into populated areas. Rapid response mechanisms such as Bagh Bondhu and Primary

Response Teams can assist with crowd control, communication, monitoring, rescue and safe relocation of straying tiger. The Sundarbans Tiger Project by WTI gets help from KfW, IUCN and the West Bengal Forest Department under ITHCP. This Sundarbans Tiger Project works hard to fix conflict-management systems and get people involved. There are other important steps being taken too. People are using nylon-net fencing and running awareness programmes. There is also help, with ways to earn money, quick compensation and habitat protection. All of these steps aim to help humans and tigers live together in peace.

Community awareness and education are equally important. Regular awareness programmes should educate villagers about tiger behaviour, forest entry precautions, group movement, use of equipment and appropriate responses during tiger sightings. Special attention should be given to fishermen, crab collectors, honey collectors and other forest dependent people, who face exposure to tiger habitats. School based programmes can also educate children about wildlife conservation and safe behaviour around forest areas.

Economic measures are also necessary. Timely compensation for deaths and injuries livelihood diversification, alternative employment opportunities and community-based income generating programmes can reduce dependence on high-risk forest activities. Improved communication between villagers and the Forest Department reporting of tiger sightings, community participation in monitoring and appropriate early warning systems can further reduce risk. The GPS-enabled SOS alarm system and speed-boat community support initiative launched in Kultali further demonstrates the importance of rapid emergency response for forest-dependent communities (WTI, 2025d).

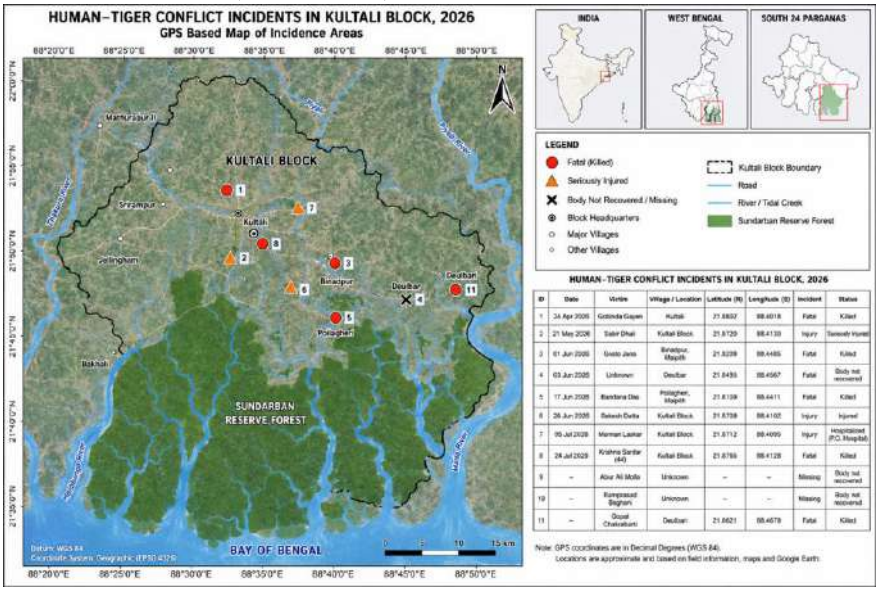


Fig. 1. GPS base map of the study areas along with recent incidents (Tiger human conflict) zone

Finally long-term conflict mitigation requires habitat protection and restoration the conservation of mangroves, tidal channels and natural forest corridors. Reducing habitat degradation and human encroachment can help maintain tiger habitat away from settlements. A combination of fencing, rapid response, community awareness, livelihood support, compensation, habitat conservation and participatory management is therefore essential for reducing human–tiger conflict and promoting sustainable human–tiger coexistence, in Kultali Block.

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Ecological Approaches to Sustainable Pest and Disease Management

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Abstract

Agricultural intensification has substantially increased food production, but it has also contributed to pest outbreaks, plant diseases, pesticide resistance, biodiversity loss, soil degradation and contamination of environmental resources. Conventional pest management based heavily on synthetic pesticides can provide rapid suppression of target organisms but may disrupt ecological interactions and impose risks to non-target organisms, human health and ecosystem services. An ecological approach to pest and disease management seeks to regulate harmful organisms by strengthening the natural processes operating within agroecosystems. It integrates crop diversification, soil health management, biological control, conservation of natural enemies, host resistance, cultural practices, ecological engineering, precision monitoring and judicious use of pesticides within an integrated pest management framework. Recent research emphasizes that plant diversity and soil microbial ecology can act synergistically to improve plant health and suppress pests and pathogens. Advances in microbial biopesticides, semiochemicals, resistant cultivars, remote sensing, artificial intelligence and climate-informed surveillance are further expanding the possibilities for sustainable crop protection. Climate change, however, is altering pest distributions, pathogen epidemiology and the effectiveness of established management practices. Therefore, future pest management must move from reactive pest eradication toward preventive, ecosystem-based and knowledge-intensive crop health management. This chapter reviews the principles, components, recent advances, constraints and future prospects of ecological pest

and disease management and proposes an integrated framework for resilient and sustainable agricultural production.

Keywords: Agroecology; Biological control; Biodiversity; Integrated Pest Management; Microbial Biocontrol; Plant disease; Pest Management; Soil health; Sustainable agriculture; Ecological intensification.

Introduction

Pests and plant diseases remain major constraints to agricultural productivity, food quality and farm profitability. Insect pests, mites, nematodes, weeds, plant-pathogenic fungi, oomycetes, bacteria, viruses and phytoplasmas interact with crops within complex agroecosystems. Globally, plant pests are estimated to cause substantial crop losses, creating major economic and food-security challenges. The International Plant Protection Convention emphasizes that protecting plant health requires coordinated prevention, surveillance, preparedness and sustainable management rather than dependence on a single control technology.

The conventional approach to crop protection has historically emphasized direct suppression of pest populations through synthetic pesticides. Although chemical pesticides remain important tools when appropriately selected and applied, their excessive or poorly targeted use may result in pesticide resistance, pest resurgence, secondary pest outbreaks, residues, contamination of soil and water, and adverse effects on pollinators and other beneficial organisms. Recent reviews continue to identify environmental contamination and risks to non-target organisms as important reasons for reducing unnecessary pesticide dependence.

Ecological pest and disease management provides an alternative paradigm. Instead of viewing pests and pathogens as organisms that must always be eradicated, it considers them components of an agroecosystem whose populations can often be maintained below economically damaging levels through ecological processes. This approach is closely related to agroecology, ecological intensification and integrated pest management (IPM).

A recent perspective by Altieri et al. (2024) argues for an agroecological approach in which plant diversity and soil microbial ecology are deliberately managed to improve crop health. Their framework emphasizes diversified cropping systems, organic matter management and beneficial interactions among plants, microorganisms and arthropods.

The modern concept of sustainable pest management therefore involves a transition from input substitution—simply replacing synthetic pesticides with individual biological products—to agroecosystem redesign, in which ecological processes are strengthened to provide durable pest and disease regulation.

Concept and Principles of the Ecological Approach

The ecological approach is based on the premise that pest and disease outbreaks are influenced not only by the presence of the harmful organism but also by crop genotype, soil conditions, surrounding vegetation, natural enemies, climate, farming practices and landscape structure.

The major principles are:

- Prevention rather than eradication
- Maintenance of ecological balance
- Conservation of biodiversity
- Enhancement of natural enemies and beneficial microorganisms
- Improvement of soil health
- Use of resistant or tolerant crop varieties
- Crop diversification and habitat management
- Regular monitoring and early detection
- Use of pesticides only when economically and ecologically justified
- Integration of multiple compatible management tactics

Thus, ecological management does not necessarily mean eliminating pesticides completely. Rather, pesticides become one component of a broader decision-making system and should be selected and applied in ways that minimize effects on beneficial organisms and delay resistance.

The Food and Agriculture Organization (FAO) describes IPM as an approach that builds on ecosystem services such as pest predation while protecting other ecosystem services, including pollination. It also recognizes the contribution of IPM to reducing pesticide residues and crop losses.

Agroecosystem Biodiversity and Pest Regulation

Biodiversity is one of the central foundations of ecological pest management. Agricultural monocultures generally provide large areas of a uniform and highly accessible food resource for specialized pests. Diversification can disrupt pest host-finding, reduce resource continuity and create habitats for predators and parasitoids.

1. Crop Diversification

Crop rotation, intercropping, mixed cropping and cultivar mixtures can reduce pest and disease pressure by disrupting pest life cycles and reducing the spatial continuity of host plants.

Important diversification practices include:

- cereal–legume rotations;
- intercropping;
- strip cropping;
- cultivar mixtures;
- cover crops;

- trap crops;
- flowering border crops; and
- agroforestry systems.

Evidence summarized by Altieri et al. (2024) indicates that greater plant diversity can increase natural-enemy abundance and pest mortality while reducing crop damage in comparison with simplified cropping systems.

2. Habitat Manipulation

Vegetation surrounding crop fields can provide nectar, pollen, shelter and alternative prey for natural enemies. Flower strips, hedgerows, field margins and agroforestry components can therefore function as biological-control infrastructure.

However, habitat manipulation should be designed according to the ecology of the target crop and pest. Simply increasing plant diversity does not guarantee pest suppression; the selected plants should provide resources to beneficial organisms without becoming reservoirs for important pests or pathogens.

3. Landscape-Scale Management

Pest management increasingly needs to be considered beyond individual fields. Semi-natural habitats, hedgerows, woodlots and flowering vegetation can influence the movement and persistence of natural enemies across agricultural landscapes. Ecological pest management therefore benefits from cooperation among neighboring farmers and landscape-level planning.

4. Soil Health as a Foundation of Plant Disease Management

The soil is not merely a physical substrate for plant growth; it is a biologically active ecosystem containing bacteria, fungi, archaea, nematodes, protozoa and other organisms that influence nutrient cycling and plant health.

Healthy soils can contribute to disease suppression through:

competition between beneficial and pathogenic microorganisms;

- antibiosis;
- parasitism;
- predation;
- production of antimicrobial metabolites;
- induced systemic resistance;
- improved nutrient availability; and
- improved plant physiological vigor.

Biological Control

Biological control is a major component of ecological pest management. It involves the use or conservation of living organisms to suppress pests and pathogens.

1. Predators and Parasitoids

Important arthropod natural enemies include ladybird beetles, lacewings, predatory bugs, spiders and parasitoid wasps. Their conservation can be promoted by:

- minimizing broad-spectrum insecticides;
- providing flowering resources;
- maintaining refuges;
- reducing unnecessary disturbance; and
- using selective pesticides when chemical intervention is required.

2. Microbial Biocontrol

Microbial biological-control agents include bacteria, fungi and other microorganisms. Examples include *Bacillus thuringiensis, Beauveria bassiana, Metarhizium anisopliae, Trichoderma spp.* and *Bacillus spp*.

Microbial inoculants may suppress pests and pathogens through antibiosis, parasitism, competition, lytic enzymes, toxins or induction of plant defense responses. Recent literature highlights microbial biocontrol agents and biofertilizers as important components of sustainable crop protection.

FAO has also emphasized biological control as an environmentally favorable component of sustainable pest management and highlighted its increasing importance under climate-change conditions.

3. Conservation Biological Control

Conservation biological control is particularly compatible with agroecology because it focuses on protecting naturally occurring beneficial organisms rather than repeatedly introducing control agents.

The strategy is based on the principle:

"Protect and strengthen the natural enemy community before attempting to suppress the pest directly."

Cultural and Agronomic Practices

Cultural practices can prevent pest and disease establishment before chemical intervention becomes necessary.

Important measures include:

1. Crop Rotation

Rotation interrupts pest and pathogen life cycles, particularly for organisms with limited host ranges. Rotating crops from different botanical families can reduce the accumulation of soilborne pathogens and pests.

2. Sanitation

Removal and destruction of infected plant material can reduce pathogen inoculum. Proper disposal of crop residues is particularly important for diseases in which infected residues serve as major sources of primary inoculum.

3. Optimized Planting

Planting date, plant density, row spacing and irrigation can influence microclimate and disease development. Dense canopies may increase humidity and leaf wetness, creating favorable conditions for several fungal and bacterial diseases.

4. Weed Management

Weeds may compete with crops and also act as alternative hosts for insect pests and pathogens. Ecological weed management should therefore combine preventive, cultural, mechanical and biological approaches rather than depend entirely on herbicides.

5. Nutrient Management

Excessive nitrogen can increase susceptibility to some insect pests and pathogens by promoting succulent vegetative growth, whereas balanced nutrition can improve crop vigor and resistance. Nutrient management should therefore be integrated with plant-health management.

Host Plant Resistance

Host resistance is among the most environmentally compatible approaches to pest and disease management. Resistant cultivars can reduce pest establishment or pathogen infection without requiring repeated pesticide applications.

Resistance mechanisms may include:

- antibiosis;
- antixenosis;
- tolerance;
- physical barriers;
- biochemical defense;
- constitutive resistance; and
- induced systemic resistance.

However, resistance is rarely permanent. Pest and pathogen populations can evolve in response to resistant cultivars. Consequently, resistance should be integrated with crop rotation, cultivar diversification, biological control and other tactics to delay resistance breakdown.

Botanical Pesticides and Biopesticides

Plant-derived compounds and microbial biopesticides provide alternatives to some conventional chemical pesticides. Botanical products may act through repellency, feeding deterrence, toxicity, growth regulation or oviposition disruption.

Biopesticides are particularly valuable when they have:

- target specificity;
- short environmental persistence;
- compatible effects on natural enemies;

- diverse modes of action; and
- relatively low toxicity to non-target organisms.

Nevertheless, "biological" does not automatically mean "risk-free." Their environmental safety, efficacy, formulation, persistence and compatibility with other IPM components must be scientifically evaluated before widespread use.

Recent reviews emphasize the potential of biopesticides as components of sustainable IPM while also identifying formulation, field efficacy, regulatory and adoption challenges.

Ecological Engineering for Pest Management

Ecological engineering involves deliberate modification of the agricultural environment to enhance ecosystem services such as natural pest regulation.

Examples include:

- flowering strips;
- insectary plants;
- trap crops;
- banker plants;
- refuge habitats;
- hedgerows;
- agroforestry;
- conservation of field margins; and
- diversified cropping patterns.

The objective is to create an agricultural environment in which beneficial organisms can survive, reproduce and regulate pest populations.

Ecological engineering is especially attractive because it attempts to make pest management a property of the farming system rather than an activity performed only after pest populations have reached damaging levels.

Monitoring, Decision Support and Economic Thresholds

Effective ecological pest management depends on accurate monitoring. Farmers need information on pest abundance, disease incidence, crop growth stage, weather conditions and natural-enemy populations before selecting control measures.

Monitoring methods include:

- field scouting;
- pheromone traps;
- sticky traps;
- light traps;
- disease forecasting;
- remote sensing;
- molecular diagnostics;
- automated imaging; and

- digital decision-support systems.

Economic thresholds help determine when intervention is justified. This prevents unnecessary pesticide applications and allows natural enemies and other ecological processes to suppress low pest populations.

Precision Agriculture and Digital Ecological Management

Precision agriculture provides an opportunity to combine ecological principles with advanced technologies.

Sensors, drones, satellite imagery, machine learning and geographic information systems can identify spatial and temporal variation in pest and disease pressure. Instead of treating an entire field uniformly, farmers can potentially apply management measures only where they are needed.

- Emerging systems include:
- AI-based disease diagnosis;
- automated insect recognition;
- disease-risk forecasting;
- variable-rate pesticide application;
- robotic weed control;
- digital scouting;
- climate-based pest prediction; and
- spatial decision-support systems.

These technologies should not replace ecological knowledge. Rather, they can improve the timing, precision and efficiency of ecological management.

Climate Change and Ecological Pest Management

Climate change is becoming an important factor in plant health. Increasing temperatures, altered precipitation, extreme weather events and changes in seasonality can modify pest development, pathogen survival, crop susceptibility and geographic distributions.

The IPPC reports that warmer temperatures and milder winters can allow pests and diseases to survive and spread into areas previously unsuitable for them.

Climate change can also affect biological control. Temperature, humidity and resource availability influence the activity of both pests and their natural enemies. Consequently, ecological management systems must be climate-resilient.

Future strategies should include:

- climate-informed pest forecasting;
- early-warning systems;
- diversification of crops and varieties;
- conservation of functional biodiversity;
- improved surveillance of invasive species;
- resilient soil management; and

- adaptive IPM recommendations.

The IPPC has specifically identified climate change as an emerging challenge for plant-health surveillance and phytosanitary risk management.

Integration of Ecological Approaches into IPM

The ecological approach should be implemented as a hierarchy rather than as a collection of unrelated techniques.

Ecological IPM hierarchy

- **Step 1 – Prevention:** Use resistant cultivars, healthy planting material, crop rotation and appropriate agronomic practices.
- **Step 2 – Ecological Strengthening:** Increase biodiversity, improve soil health and conserve natural enemies.
- **Step 3 – Monitoring:** Regularly monitor pests, diseases, natural enemies and environmental conditions.
- **Step 4 – Biological and Physical Control:** Use predators, parasitoids, microbial agents, traps, barriers and mechanical methods when required.
- **Step 5 – Selective Chemical Intervention:** Apply pesticides only when economically justified and select products compatible with natural enemies and resistance-management principles.
- **Step 6 – Evaluation:** Assess pest suppression, crop yield, economic return, pesticide use and ecological effects.

FAO's 2025 guidance on IPM for major crop pests and diseases reinforces the use of integrated "bundles" of management measures rather than dependence on a single intervention. The guidance covers major pest and pathogen threats affecting cereals, potato, fruits and vegetables.

Resistance Management

The repeated use of the same pesticide or mode of action can select resistant pest populations. Resistance is therefore both an economic and ecological problem.

Resistance management should include:

- rotation of pesticide modes of action;
- avoiding unnecessary applications;
- using recommended doses;
- integrating biological control;
- maintaining refuges where appropriate;
- monitoring resistance;
- using mixtures only when scientifically justified; and
- prioritizing preventive ecological measures.

The ecological approach is particularly valuable because it reduces the selection pressure created by continuous reliance on a single chemical mode of action.

Advantages of Ecological Pest and Disease Management

The major benefits include:

- reduced dependence on synthetic pesticides;
- conservation of biodiversity;
- protection of pollinators and natural enemies;
- reduced pesticide residues;
- improved soil biological activity;
- improved ecosystem services;
- reduced risk of pest resurgence;
- improved long-term resistance management;
- greater system resilience;
- potential reduction in production costs; and
- improved environmental sustainability.

FAO recognizes IPM as an approach that can reduce pesticide residues and strengthen ecosystem services while contributing to crop productivity and food security.

Limitations and Challenges

Despite its advantages, ecological pest management has several limitations.

- **Knowledge Intensity:** Ecological management requires knowledge of pest biology, natural enemies, crop physiology, soil ecology and local environmental conditions.
- **Variable Field Performance:** Biological-control agents and ecological interventions can perform differently under different environmental conditions.
- **Slow Action:** Some ecological interventions may act more slowly than conventional pesticides. This can be problematic when crops face rapidly increasing pest populations.
- **Farmer Adoption:** Farmers may hesitate to adopt unfamiliar techniques if benefits are uncertain or delayed.
- **Market and Policy Constraints:** Agricultural policies, pesticide subsidies, input supply chains and market standards can influence adoption.
- **Need For Local Adaptation:** A pest-management strategy successful in one agroecological region may not produce the same results elsewhere.

Therefore, ecological pest management should be supported through farmer training, extension systems, participatory research, local experimentation and enabling agricultural policies.

Future Perspectives

The future of sustainable pest and disease management lies in combining ecological principles with modern technologies.

Several emerging areas deserve particular attention:

- **Microbiome-Based Crop Protection:** Understanding plant and soil microbiomes may allow the development of microbial consortia capable of enhancing disease resistance and plant growth.
- **Precision Biological Control:** Digital monitoring can help determine where and when biological control agents should be released or conserved.
- **AI-Supported Diagnosis:** Artificial intelligence may enable rapid recognition of insect pests and disease symptoms from field images, although field validation remains essential.
- **Semi Chemical Technologies:** Pheromones, attractants, repellents and herbivore-induced plant volatiles may provide increasingly precise methods of manipulating pest behavior. Emerging research is exploring plant-signaling mechanisms and controlled release of volatile compounds as nature-inspired pest-management technologies.
- **Climate-smart IPM:** Pest models increasingly need to incorporate climate projections, extreme weather and changing pest distributions.
- **Landscape-Scale Ecological Management:** Future IPM programs should increasingly address farms as components of interconnected landscapes rather than isolated production units.
- **Farmer-Centered Innovation:** Technological solutions will be successful only when they are affordable, understandable, locally appropriate and compatible with farmers' production objectives.

A Proposed Framework for Sustainable Ecological Pest Management

A practical framework can be summarized as:

Healthy soil → diverse crops → resilient plants → functional biodiversity → natural pest regulation → regular monitoring → targeted intervention → reduced pesticide dependence → improved ecosystem health

This represents a shift from the traditional model:

Pest outbreak → pesticide application → temporary suppression → resurgence/resistance → repeated application

toward:

Prevention → ecological regulation → monitoring → threshold-based intervention → evaluation → adaptation

Such a transition is consistent with current thinking on agroecology and sustainable IPM. Recent research emphasizes that diversified plant communities and biologically active soils can work together to generate stronger ecological regulation of pests and pathogens.

Conclusion

Ecological pest and disease management represents a fundamental shift in the philosophy of crop protection. Its objective is not simply to replace synthetic pesticides with biological products but to redesign agricultural systems so that natural ecological processes contribute substantially to pest and disease regulation.

Crop diversification, soil health, biological control, resistant cultivars, habitat management, ecological engineering, monitoring and selective pesticide use can be combined within an integrated framework. Recent evidence indicates that plant diversity and soil microbial activity can generate complementary mechanisms of pest and disease suppression, providing an important scientific basis for agroecological crop protection.

Climate change and biological invasions further strengthen the need for resilient crop-protection systems. The increasing availability of digital surveillance, artificial intelligence, precision agriculture and advanced microbial technologies creates new opportunities to make ecological management more accurate and scalable.

The central principle for future agriculture should therefore be "prevention through ecological design, supported by monitoring and targeted intervention." Sustainable crop protection will depend not on a single technology but on the intelligent integration of ecological processes, biological resources, farmer knowledge and modern scientific tools.

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The Urban Jungle: Physiological and Behavioral Evolution in City-Dwelling Species

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Abstract

This chapter examines how urbanization acts as a selective pressure driving evolutionary, physiological, and behavioral shifts in city-dwelling animals. Factors such as artificial light at night (ALAN), noise, heat islands, and human food force species to diverge from rural populations. Animals adapt through modified wing shapes, smaller body sizes, nocturnal shifts (Diel Activity Shift), altered mating calls, and heightened problem-solving abilities to navigate urban infrastructure.

Keywords: Sensory Recalibration, Diel Activity Shift, Cognitive Buffer Hypothesis, Synanthropic Species, Acoustic Adaptation Hypothesis

Introduction

In 2026, cities are recognized as rapidly expanding ecosystems presenting novel biological challenges. Unlike traditional zoological studies focused on wild habitats, modern urban environments require animals to constantly adapt. Species encounter human-induced pressures, leading to phenotypic changes, genomic modifications, and sensory recalibration required to exploit urban resources while avoiding human conflicts.

In the past, zoologists concentrated generally on "clean" wild residences like rainforests or grasslands. However, in 2026, the city is acknowledged all at once of the fastest-developing ecosystems on Earth. Urbanization designs a singular set of discriminating pressures: pretended light, perpetual noise, "heat isles," and a diet of human treated cookings. This branch survey by virtue of what animals are not just "indulging" downtowns but are literally developing new characteristics to thrive in bureaucracy. Animals reside places frequently look and function otherwise than

their rural cousins. For example, many city fowls have grown smaller, straightforward wings. These extensions are not planned for long-distance exodus except for speedy maneuvering to prevent trucks and cup constructions. Additionally, we visualize changes in Anthropogenic Selection. In some city spiders, analysts have famous a change in color to better camouflage against actual. In animals, the "Urban Heat Island" effect—place cities are 2°C to 5°C hotter than the countryside—is superior to tinier carcass sizes in few class to help them discard heat more capably. Perhaps ultimate spellbinding change is in animal judgment. City life is a "baffle" that rewards logical. Urban raccoons and squirrels have proved considerably taller "innovation scores" in workshop tests distinguished to country one. They have well-informed to understand traffic signal patterns, open complex latch devices on garbage cans, and even use "desirous" acts specifically proposed at persons to catch meat. This is a shift from idea-driven management to well-informed, bendable understanding. To prevent humans, many occurring every day (epoch-alive) mammals are suitable nightly (night-alive). This is popular as the "Diel Activity Shift." By switching their peak endeavor to the middle of the midnight, animals like coyotes and foxes can move through city streets harmlessly. This change influences their whole physical science, from their eye awareness to their mating calls, that must immediately equate the depressed-commonness hum of city tool. Understanding city compliance is essential for governmental biodiversity planning. If we ability mammals use "green hallways" (parks and flowers), we can design municipalities that support wildlife alternatively demolish it. Zoology in 2026 is about judgment a balance place person and "urban-suitable" class can live as man and wife but unmarried in a working environment.

While phenotypic changes like organ shape are seeable to the evident eye, the deepest shifts in city development are happening at the genomic level. Urban environments serve as speedy developmental workshops where draft pressure is considerably more forceful than in the "pure" wild. Research in 2026 has rooted that city cultures are frequently fragmented by tangible obstructions like highways, superior to unique groups that experience swift ancestral drift. Surprisingly, this seclusion frequently accelerates the rise of advantageous mutations, specifically those had connection with detoxifying city pollutants. Recent studies have emphasized the part of epigenetic indicating, place environmental stressors like burdensome metals in city soil cause synthetic tags on DNA. These tags turn particular genes on or off without changeful the latent rule, admitting species like the White-add Mouse to fit to extreme-fat human diets in just any generations. Furthermore, maritime city class like the Atlantic Killifish have grown a specialized hereditary fighting to mechanical PCBs in city harbors, a achievement of rapid progress that would usually take happiness in a constant, rural atmosphere.

Sensory Recalibration in the Neon Night

Cities are never truly dark or quiet, and this "sensory trap" has forced a radical recalibration of animal perception. The Acoustic Adaptation Hypothesis explains how urban birds, such as the Great Tit, have evolved to sing at a higher pitch to ensure their mating calls are not drowned out by the low-frequency rumble of traffic. This is not merely a behavioral change but a physiological shift in how these birds process and produce sound. Similarly, the "ALAN" (Artificial Light at Night) effect has altered the visual systems of urban insects; many city-dwelling moths have evolved a reduced "flight-to-light" response, making them less likely to die of exhaustion around streetlamps than their rural cousins.

In addition to sight and sound, the sense of smell has become a critical tool for survival in the urban jungle. For urban mammals, the ability to distinguish between toxic industrial waste and nutritious human leftovers has sharpened olfactory precision. Urban foxes, for instance, show an increased density of olfactory receptors geared specifically toward detecting the high-sugar and high-fat scents associated with processed foods. This sensory specialization allows them to navigate the "invisible landscape" of city scents, avoiding danger while maximizing caloric intake in a landscape dominated by human activity.

The Rise of the Urban Generalist-Specialist

The urban ecosystem of 2026 favors species that are "generalists" in their diet but "specialists" in their navigation of human infrastructure. This paradox defines the winners of the modern biodiversity landscape, often referred to as synanthropic—species that live near and benefit from humans. The common Pigeon is perhaps the ultimate example, having evolved the biological ability to sequester toxic lead into its feathers, effectively "cleaning" its bloodstream as it grows. This physiological adaptation allows it to thrive in environments that would be lethal to most other avian species.

The Cognitive Buffer Hypothesis suggests that animals with larger brains relative to their body size are the most successful urbanites. This is why corvids, such as crows and ravens, have become the dominant "intellectuals" of the city; they don't just react to the environment, they anticipate human behavior. They have been observed utilizing subway tunnels as wildlife highways and timing their movements to coincide with commuter schedules to scavenge food. As we look toward the 2030s, the distinction between "nature" and "city" continues to blur, proving that life is a relentless process of recalibration where humans and urban-adapted species must find a functional, shared ecosystem.

Conclusion

Urban ecosystems demonstrate rapid ongoing adaptation at phenotypic, sensory, and genomic levels. Animals utilizing larger brains (Cognitive Buffer Hypothesis) and behavioral flexibility become successful synanthropic species. Understanding

these dynamics is essential for urban planners to construct green corridors and develop sustainable infrastructure where humans and urban wildlife functional coexist.

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