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SUSTAINABLE APPROACHES IN AQUATIC SCIENCE

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PREFACE

Aquatic science, encompassing the study of freshwater and marine ecosystems, plays a vital role in understanding and preserving one of Earth's most valuable resources—water. As global challenges such as climate change, pollution, overexploitation of aquatic resources, and biodiversity loss intensify, the need for sustainable management and conservation of aquatic systems has become more urgent than ever. The present volume, *Sustainable Approaches in Aquatic Science*, aims to highlight contemporary research and innovative strategies that contribute to the sustainability and resilience of aquatic environments.

This book brings together diverse perspectives from researchers, academicians, and practitioners working in the fields of limnology, aquaculture, fisheries, aquatic ecology, and environmental management. It explores a range of topics including sustainable aquaculture practices, conservation of aquatic biodiversity, pollution mitigation, water quality assessment, and the impact of anthropogenic activities on aquatic ecosystems. Each chapter emphasizes the integration of traditional ecological knowledge with modern scientific tools to develop adaptive and eco-friendly approaches for the management of aquatic resources.

The compilation also underscores the importance of community involvement, policy frameworks, and technological innovations in achieving long-term sustainability goals. By addressing both fundamental and applied aspects, this volume provides valuable insights for students, researchers, policymakers, and professionals engaged in aquatic and environmental sciences.

It is hoped that *Sustainable Approaches in Aquatic Science* will serve as a significant contribution to ongoing efforts toward maintaining the ecological balance of aquatic habitats and ensuring their sustainable utilization. The editors extend heartfelt thanks to all contributors and reviewers whose scholarly input and dedication have made this book possible. We also express gratitude to the publishing team for their cooperation and commitment in bringing this volume to fruition.

- Editors

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BY-CATCH AND DISCARDS IN FISHERIES: EXTENT, UTILISATION AND MEASURES FOR REDUCTION

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Abstract:

Bycatch and discards represent one of the most persistent challenges in global fisheries management. Bycatch refers to the capture of non-target organisms during fishing, while discards are the portion of catch that is returned to the sea, often dead or dying. Globally, an estimated 20–27 million tonnes of fish are discarded annually, resulting in ecological, economic, and ethical concerns. However, advances in selective fishing technology, improved utilisation of low-value catches, and adaptive management strategies are helping mitigate this issue. This chapter reviews the current understanding of fish bycatch and discards, summarises modern methods for utilisation, and outlines harvesting measures designed to reduce discards, with specific references to recent research and case studies from India and abroad.

1. Introduction:

Fisheries provide a vital source of food, income, and employment worldwide. However, non-selective fishing practices result in substantial capture of non-target species, a phenomenon known as bycatch. When part of the bycatch is discarded—often due to low economic value, legal restrictions, or poor quality—it becomes a discard (FAO, 1994).

Bycatch and discards lead to resource wastage, alteration of marine ecosystems, and reduced fishery productivity. As fisheries move toward sustainability, reducing discards and optimising bycatch utilisation are key strategies. Understanding the magnitude of the issue and implementing targeted mitigation measures are essential for ecological and economic resilience in fisheries systems.

2. Global Overview of Bycatch and Discards

2.1 Extent and Trends

FAO's global assessment (FAO 1994; Kelleher 2005) estimated that about 8–25% of total marine catches are discarded annually—equivalent to 20–27 million tonnes. Shrimp trawl fisheries, especially in tropical regions, contribute disproportionately, with bycatch-to-target ratios exceeding 5:1 in some cases (FAO, 2020).

Recent studies indicate that discard rates are declining in many industrialised fisheries due to stricter regulation, improved gear selectivity, and discard bans (Lively & McKenzie, 2023). Nevertheless, high discard levels persist in small-scale, multispecies, and tropical fisheries (Mendo *et al.*, 2022).

2.2 Case Studies

- **Peru (Artisanal Shrimp Trawls):** A 2022 study found that bycatch constituted 82% of total catch, with 50.6% discarded. Over 270 species were caught incidentally, demonstrating extreme biodiversity impact (Mendo *et al.*, 2022).
- **India (Midwater Trawl, NW Coast):** Bycatch accounted for 53% of total catch, but only 6% was discarded, due to local use of bycatch for fishmeal and animal feed (Abdul Azeez *et al.*, 2024).
- **Australian Prawn Trawl Fishery:** Use of exclusion devices reduced bycatch by over 80%, demonstrating success of technological interventions (Broadhurst *et al.*, 2015).

3. Causes of Bycatch and Discards

1. **Non-target capture:** Occurs when fishing gears catch species outside the target assemblage.
2. **Size selectivity:** Juveniles and undersized individuals are often discarded due to regulations or lack of market.
3. **Market constraints:** Low-value or damaged fish may not be worth landing.
4. **Regulatory discards:** Quota restrictions or banned species must be returned.
5. **Operational constraints:** Limited storage or sorting time on vessels encourages discarding (FAO, 2020).

4. Utilisation of Fish Bycatch and Discards

4.1 Overview

Traditionally, bycatch and discards were regarded as waste. However, increasing pressure on global fish stocks and sustainability concerns have motivated the development of methods to utilise these resources efficiently. The guiding idea is to transform what was once discarded into valuable products for human consumption, aquaculture feed, pharmaceuticals, and other industries.

The degree of utilisation varies greatly among regions and fisheries.

- **Industrialised nations** often have strict landing regulations but limited markets for low-value fish.
- **Developing nations**, particularly in Asia, make higher use of bycatch for reduction (fishmeal/fish oil) and direct consumption (dried, fermented, or salted fish).

Proper utilisation of bycatch can:

1. Reduce waste and environmental impact.
2. Increase fishers' income.
3. Support food security.
4. Create secondary industries (processing, feed, fertiliser, etc.).

4.2 Processing Pathways for Utilisation

There are several key utilisation routes, each depending on species composition, freshness, and market access.

4.2.1 Reduction into Fishmeal and Fish Oil

This is the most common utilisation pathway for bycatch globally.

Process overview:

1. **Raw Material:** Small, low-value fish or trawl bycatch unsuitable for direct consumption.
2. **Cooking and Pressing:** Fish are cooked to denature proteins, pressed to remove liquid.
3. **Separation:** Liquids are centrifuged to separate oil and stickwater.
4. **Drying:** The solid fraction is dried and ground into fishmeal.
5. **By-products:** Fish oil and condensed stickwater are recovered for use in feed.

Applications:

- **Fishmeal** → Aquaculture, poultry, and livestock feed.
- **Fish oil** → Nutritional supplements (omega-3 fatty acids), aquafeed enrichment.

Examples:

- In India, **coastal fishmeal plants** in Kerala, Karnataka, and Tamil Nadu process trawl bycatch (small pelagics, anchovies, juvenile threadfin breams) into feed-grade meal.
- **Thailand and Vietnam** have established integrated trawl and fishmeal systems where nearly 90% of trawl bycatch is utilised in reduction (FAO, 2020).

Advantages:

- Large-scale, economically viable.
- Reduces organic waste at landing centres.

Limitations:

- Quality deterioration from delayed processing.
- Low nutritional quality if high in non-fish components.
- High energy requirement for processing plants.

4.2.2 Human Consumption — Direct and Value-Added Products

Many bycatch species are edible but not preferred in fresh form due to small size, bony texture, or poor market familiarity. Processing technologies can make them acceptable to consumers.

1. Traditional utilisation:

- **Drying, salting, smoking, fermenting** — practiced widely in coastal Asia and Africa.
 - Example: In Kerala and Gujarat, small non-target fishes (ponyfish, croakers, ribbonfish juveniles) are dried and sold in local markets or exported to Sri Lanka and Southeast Asia.

2. Modern value-added processing:

- **Surimi and fish mince products:** Mechanically separated meat from small fish is used to make surimi, fish balls, and sausages.
- **Fish protein hydrolysates (FPH):** Enzymatic hydrolysis of bycatch proteins produces peptides for nutraceuticals, feed additives, and flavour enhancers.
- **Fish silage:** Acid or enzymatic treatment of minced bycatch produces a liquid feed used in aquaculture and livestock.

3. Nutraceuticals and bioactive compounds: Recent research shows that bycatch (especially pelagic species and shark by-products) is rich in collagen, gelatin, chitosan, enzymes, and omega-3 fatty acids that can be extracted for cosmetics and pharmaceuticals (D'Souza *et al.*, 2025).

4.2.3 Ornamental and Aquarium Trade

Some small colourful reef-associated species incidentally captured in trawl and trap fisheries have ornamental value. Example: Juvenile butterflyfish, damselfish, and wrasses captured off Kerala are occasionally sold to the aquarium trade. While this provides income, it must be regulated to avoid overexploitation of reef species.

4.2.4 Bait and Livestock Feed

- **Bait:** Bycatch of small pelagics, squids, and cuttlefish are frozen and sold as bait in longline and trap fisheries (for tuna, lobster).
- **Direct feed:** Minced or chopped bycatch is used directly in shrimp farms or as pig/poultry feed in rural coastal areas.
- **Silage feed:** Fish silage from bycatch is gaining attention as a sustainable alternative to fishmeal due to its low cost and ease of preparation.

4.2.5 Organic Fertiliser and Compost

Low-quality or decomposed bycatch unsuitable for food or feed is processed into fish fertiliser. Fish waste is mixed with organic matter (e.g., cow dung, sawdust) and composted for 30–45 days. It provides nitrogen, phosphorus, and trace minerals beneficial for crop production. In India, some small-scale cooperatives along the west coast produce “fish compost” from unsorted bycatch, reducing waste disposal at harbours.

4.3 Economic and Social Dimensions

- **Employment:** Processing of bycatch provides jobs for women in coastal communities (sorting, drying, packing).
- **Value chains:** Utilisation converts low-value fish into higher-value products, improving fisher income.
- **Circular economy:** By integrating bycatch utilisation, fisheries approach a “zero-waste” production model.

However, caution is needed. Excessive demand for bycatch as raw material for fishmeal plants can encourage deliberate capture of small or juvenile fish — a practice that undermines resource sustainability (FAO, 2020). Hence, utilisation must complement, not replace, bycatch reduction.

4.4 Constraints and Challenges in Utilisation

1. **Quality deterioration:** Bycatch is often mixed, un-iced, or stored long hours on deck → reduces suitability for consumption.
2. **Infrastructure gaps:** Lack of cold storage, processing units, and transport in artisanal sectors.
3. **Market barriers:** Consumer unfamiliarity with low-value species.
4. **Regulatory restrictions:** Some countries prohibit landing of certain protected or non-target species.
5. **Health and safety:** Mixed bycatch can contain toxic or contaminated species requiring monitoring.

4.5 Recent Technological Developments

1. **Mobile fishmeal and silage units:** Portable plants for onboard or near-shore processing of small catches.
2. **High-pressure processing (HPP) and freeze-drying** to preserve protein quality in bycatch products.
3. **Enzymatic valorisation:** Using proteases to recover high-value peptides and oils from discarded biomass.
4. **Biorefinery concept:** Integrated processing of bycatch into multiple co-products (protein, oil, collagen, chitin).

Research from Norway, Japan, and India has demonstrated that a biorefinery approach could increase total recovery from bycatch biomass by over 60%, drastically reducing waste (Lively & McKenzie, 2023).

4.6 Sustainability Considerations

Utilisation should not justify unsustainable fishing. FAO (2020) recommends a three-step approach:

1. **Avoid** bycatch through selective fishing.
2. **Reduce** unavoidable bycatch and discards.
3. **Utilise** unavoidable discards efficiently and safely.

Thus, utilisation complements — but never replaces — preventive bycatch reduction measures.

Table 1: Summary of utilisation techniques of fish bycatch

Utilisation Method	Main Products	Advantages	Limitations
Fishmeal & Fish oil	Feed, nutraceuticals	Large-scale, profitable	High capital cost
Value-added food	Surimi, hydrolysates	Expands food availability	Requires technology
Silage & Feed	Aquaculture/livestock feed	Low-cost, simple	Limited shelf-life
Ornamental/Bait	Aquarium, longline bait	Immediate income	Risk to reef species
Fertiliser	Organic manure	Environmental benefit	Low market value

5. Harvesting and Management Measures to Reduce Discards

5.1 Gear-based Modifications

Selective gears are the most effective physical interventions for bycatch reduction.

- **Bycatch Reduction Devices (BRDs):** Mechanical grids or escape panels allow non-target species to escape before capture.
- **Turtle Excluder Devices (TEDs):** Successfully reduce sea turtle mortality in shrimp trawls by 90% or more.
- **T90-mesh codends:** Rotated mesh configuration improving selectivity and reducing bycatch of small fish (Broadhurst *et al.*, 2015).
- **Square-mesh windows** and **circle hooks** are also used for size and species selectivity.

5.2 Temporal and Spatial Management

Implementing seasonal closures during peak juvenile abundance or area restrictions in nursery habitats helps reduce discards. Example: seasonal closures in the Peruvian shrimp trawl fishery reduced juvenile capture by 30% (Mendo *et al.*, 2022).

5.3 Real-Time and Electronic Monitoring

Electronic logbooks, onboard cameras, and real-time bycatch alerts allow dynamic management. Such systems are increasingly used in EU and Australian fisheries to monitor compliance with discard bans.

5.4 Market and Policy Instruments

- **Discard bans (Landing Obligations):** Enforce landing of all catch, incentivising full utilisation (EU CFP 2013).
- **Eco-labelling and certification:** Promote selective and responsible fishing practices.
- **Quota flexibility:** Allows substitution between species quotas, reducing discard pressure.

5.5 Education and Stakeholder Engagement

Fishers' participation is crucial. Co-management, gear trials, and awareness programs have been successful in Indian trawl fisheries. Fisher-driven adoption of BRDs often leads to long-term compliance.

6. Case Study: India

India's multi-species trawl fisheries exhibit moderate to high bycatch levels. Studies along the west coast show that bycatch comprises 30–55% of trawl catches (Abdul Azeez *et al.*, 2024). However, only 5–10% is discarded because of widespread use in fishmeal plants and poultry feed industries.

The **Central Institute of Fisheries Technology (CIFT)** has advocated for:

- Square-mesh codends to prevent juvenile capture.
- Mesh size regulation.
- Seasonal trawl bans (e.g., monsoon trawl ban).
- Awareness programs for fishers on bycatch management.

Utilisation of bycatch in India supports a secondary industry that supplies raw material to fishmeal factories, indirectly enhancing employment and reducing waste.

7. Challenges

1. **Data deficiency:** Small-scale fisheries lack consistent bycatch reporting.
2. **Economic trade-offs:** Gear modifications can reduce target catch.
3. **Ecosystem-level effects:** Mortality of keystone or endangered species remains a concern.
4. **Technological barriers:** High costs of selective gears and monitoring systems.
5. **Policy enforcement:** Limited surveillance and weak governance in many developing nations.

Emerging Research and Future Directions

- **Artificial Intelligence and Smart Gear:** Smart gear and AI-assisted video monitoring hold promise for adaptive bycatch management.
- **Community-Based Solutions:** Co-management and stakeholder workshops enhance compliance and innovation.
- **Circular Economy Opportunities:** Integration with global food systems and animal nutrition industries

Conclusion:

The reduction and utilisation of bycatch and discards are central to sustainable fisheries. Technological innovations such as BRDs, TEDs, and selective meshes, coupled with management measures like closed seasons and market-based incentives, have proven effective in multiple contexts. In developing regions such as India, economic utilisation of bycatch for fishmeal, feed, and value-added products has reduced discards while supporting livelihoods. However, sustainable progress depends on balancing ecological protection with socio-economic realities. Integrated policies, participatory management, and continuous monitoring are critical for achieving the FAO's goal of zero waste fisheries.

References:

1. Abdul Azeez, P., *et al.* (2024). Analysis of bycatches from mid-water trawl fishery targeting ribbonfish (*Trichiurus lepturus*) on the north-west coast of India. *Indian Journal of Fisheries*, 71(1), 95–104.
2. Broadhurst, M. K., *et al.* (2015). Reducing discards through gear modification in the South Australian prawn trawl fishery. *ICES Journal of Marine Science*, 72(9), 2609–2619.
3. D'Souza, S., *et al.* (2025). Utilisation of bycatch and low-value fish in Indian marine fisheries. *All Scientific Journal*, 10(3), 41–48.
4. Food and Agriculture Organization (FAO). (1994). *A global assessment of fisheries bycatch and discards* (FAO Fisheries Technical Paper No. 339). Rome: FAO.
5. Food and Agriculture Organization (FAO). (2020). *State of world fisheries and aquaculture (SOFIA)*. Rome: FAO.
6. Lively, J. A., & McKenzie, J. (2023). Bycatch and discards: A review of wasted fishing. *Advances in Marine Biology*, 95, 1–26.
7. Mendo, J., *et al.* (2022). Bycatch and discards in the artisanal shrimp trawl fishery in Northern Peru. *PLOS ONE*, 17(6), e0268128.
8. Food and Agriculture Organization (FAO). (2024). *Options for utilization of bycatch and discards*. Rome: FAO.

ECOLOGICAL IMPORTANCE OF THE PONNANI–THRISSUR (KOLE)

WETLANDS: A SCIENTIFIC REVIEW

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Abstract:

The Thrissur–Ponnani “Kole” wetlands are a low-lying, seasonally inundated wetland–agro ecosystem on Kerala’s coastal plain that combines high biodiversity with intense agricultural production. Spanning roughly 13,600 ha across Thrissur and Malappuram districts, the Kole lands are recognized for their role in rice production, flood buffering, and groundwater recharge and as habitat for many freshwater and avifaunal species. This review synthesises recent limnological, hydro geochemical, biodiversity and socio-economic studies to summarise the wetlands’ ecological functions, the services they provide to local communities, and the principal threats and management implications for conservation and sustainable use.

Keywords: Wetlands, Biodiversity, Habitat, Flood Buffering, Ground Water

1. Introduction:

“Kole” (a Malayalam term loosely translated as “bumper yield”) denotes a particular wetland–agriculture system in central Kerala where post-monsoon dewatering and carefully timed paddy cultivation occurs on sub-sea-level floodplains. The Kole wetlands extend from the lower reaches of the Chalakudy–Bharathapuzha river systems and are embedded within the larger Vembanad–Kole complex; their hydrology is dominantly monsoon-driven and interacts strongly with tidal and estuarine dynamics near the coast. The region is notable both as an ecological hotspot (supporting waterbirds, fishes, odonates and diverse benthic and planktonic communities) and as one of Kerala’s important rice-producing tracts.

2. Biodiversity Value and Habitat Provision

The Kole wetlands support a remarkable suite of freshwater and wetland taxa. Systematic surveys demonstrate that the landscape sustains abundant odonate diversity (44 species documented in a year-long study), significant fish assemblages (multiple ichthyofaunal surveys report dozens of resident and seasonal species), and numerous waterbird species, including several species of conservation concern recorded in regional red-data lists. The mosaic of

habitats — shallow open water, seasonal ponds, paddy fields, reedbeds and riparian corridors — creates structural heterogeneity that supports both resident and migratory fauna, and offers breeding and foraging grounds for amphibians, macroinvertebrates and waterfowl. Odonates and ornamental/food fishes have been used as bioindicators in multiple studies that confirm the wetlands' ecological integrity in many subunits while also highlighting spatial variation in habitat quality.

3. Hydrological Functions and Landscape Services

Kole wetlands perform key hydrological roles at landscape scale. Seasonal inundation during the southwest monsoon allows the wetlands to act as temporary reservoirs and natural drainage basins, attenuating flood peaks in adjacent settlements and farmland. The cyclical flooding–drying regime enhances lateral connectivity between rivers, shallow aquifers and surface water bodies; this facilitates groundwater recharge during recession and helps maintain baseflows in dry months. Hydrogeochemical studies show spatial heterogeneity in water chemistry — including areas influenced by freshwater–seawater mixing near estuaries and variable salinity facies — which has implications for irrigation suitability and aquatic ecology. The wetlands therefore function as hydrological buffers and as regulators of water quality through sedimentation and nutrient retention processes.

4. Provisioning Services — Rice, Fisheries and Livelihoods

The Kole lands are an agro-wetland system adapted for high-yield paddy cultivation on inundated soils; traditional drainage practices, bunding and communal coordination enable cultivation once monsoon waters recede. These areas are among the region's important rice suppliers and also sustain fish production (both wild and culture-based) that contributes to local food security and income. Socio-economic analyses and stakeholder valuation studies demonstrate that households derive multiple direct benefits — rice, fish, fodder and, in some places, ecotourism opportunities — and that many farmers express strong willingness to invest in conservation-oriented measures when livelihoods and ecosystem services are acknowledged. Such provisioning services are tightly coupled to the wetlands' hydrological regime, making farming practices and ecosystem conservation interdependent.

5. Supporting and Regulating Services

Beyond direct provisioning, Kole wetlands deliver regulating services: they sequester and cycle nutrients, trap sediments carried by rivers, and moderate local microclimates. Their vegetated margins and paddy soils contribute to carbon storage relative to drained cropping systems. The seasonal inundation supports primary productivity and nutrient turnover that underpin higher trophic levels (zooplankton, fishes, birds). By acting as nutrient sinks and diluting pollutant

pulses during floods, the wetlands provide an important water-treatment function for downstream estuarine and coastal systems. These regulating and supporting services have been quantified qualitatively and in some localized studies but remain under-valued in conventional economic accounting.

6. Threats to Ecological Integrity

Multiple anthropogenic pressures threaten the Kole wetlands' ecological functions. Major drivers include: (a) land-use change and reclamation for built infrastructure and permanent agriculture, (b) alterations to hydrological connectivity (canalisation, embankments and poorly designed drainage works), (c) salinity intrusion in lower reaches due to tidal influence and reduced freshwater flushing, (d) nutrient and pesticide runoff from intensified agriculture, and (e) uncoordinated urban expansion and waste discharge. Remote-sensing and change-detection studies document loss and fragmentation of wetland cover over recent decades, while field surveys report declines in some bird populations and shifts in fish community structure in impacted subunits. The convergence of ecological sensitivity (shallow, low-turnover waters) with intense human use renders the system particularly vulnerable to regime shifts such as persistent eutrophication or conversion away from wetland functions.

7. Management Implications and Conservation Strategies

Sustaining the Kole wetlands requires integrated interventions that recognise the coupled human-environment system. Key actions supported by the literature include:

- **Protecting Hydrological Connectivity:** maintain natural flow paths and avoid infrastructure that severs river–wetland exchange; implement controlled sluice operations where needed.
- **Promoting Wetland-Sensitive Agriculture:** retain traditional timed-dewatering paddy cycles, promote organic or low-input practices to reduce nutrient/pesticide loading, and incentivise farmers through payments for ecosystem services.
- **Monitoring and Research:** expand systematic limnological and biodiversity monitoring (water quality, fish catches, bird counts, odonate indexes) to track ecological health and detect early warning signals. Recent theses and hydrochemical studies provide baselines that should be periodically updated.
- **Community engagement and governance:** leverage existing farmer institutions and local knowledge for coordinated water management, and institutionalise local stakeholder participation in planning. Studies show community willingness to support conservation when benefits are transparent.

- **Landscape Planning and Legal Protection:** identify ecologically sensitive subunits for protected status, regulate reclamation, and integrate Kole wetlands into district-level land-use plans and climate adaptation strategies.

Conclusions:

The Ponnani–Thrissur Kole wetlands are an ecologically and socio-economically valuable wetland–agroecosystem that provides high biodiversity, critical hydrological regulation, and substantial provisioning services for local communities. Scientific studies over the past decade have documented the wetlands’ biodiversity richness, hydrogeochemical heterogeneity and the strong links between traditional agricultural practice and wetland health. However, mounting anthropogenic pressures place the system at risk. Conservation and sustainable use require integrated management that balances local livelihoods with ecological constraints, backed by targeted monitoring, hydrological safeguards and participatory governance. Protecting the Kole wetlands will conserve both a unique coastal wetland landscape and the multiple ecosystem services on which thousands of people depend.

References:

1. Chandran, A. V., Jose, S., & Subin, J. (2021). The dragonflies and damselflies (Insecta: Odonata) of the Kole Wetlands, central Kerala, India. *Journal of Threatened Taxa*.
2. Srinivasan, J. T. (2010). *Understanding the Kole lands in Kerala as a multiple-use wetland ecosystem* (CESS Working Paper No. 89).
3. Parvathy, C. A. (2024). *Limnological study of Thrissur–Ponnani Kole wetlands (2018–2022)* [Doctoral thesis, University of Calicut]. University of Calicut Repository.
4. Vidya, P. V., Rajathy, S., & Ratheesh Kumar, C. S. (2024). Hydrogeochemical characteristics of Thrissur Kole Wetland, Southwest India. *International Journal of River Basin Management*.
5. Rose, A., & Prema, P. (2024). Evaluating stakeholder preferences and willingness to pay for Kole wetlands conservation. *Asian Journal of Agricultural Extension, Economics & Sociology*.
6. Harilal, C. C., *et al.* (2021). Change detection in land cover using remote sensing and GIS — a case study of Ponnani Kole Wetland, Kerala. *ResearchGate Monograph Collection*.

IMPACTS OF PLASTIC POLLUTION ON MARINE MICROALGAE POPULATIONS: A CRITICAL REVIEW

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Abstract:

Microalgae form the foundational primary producers of marine ecosystems, driving global biogeochemical cycles and supporting food webs. The ubiquity of plastic debris — including macro-, micro- and nanoplastics — in aquatic environments poses multiple, interacting threats to microalgae. Experimental and field observations report a spectrum of effects from neutral or stimulatory (biofilm substrate/colonization) to inhibitory and toxic (growth reduction, photosynthetic impairment, oxidative stress), depending on particle size, polymer type, surface properties, concentration, and co-contaminants. Microplastics also alter community composition by providing novel substrates for fouling and by selectively favoring opportunistic or harmful taxa, with potential consequences for bloom dynamics and ecosystem functioning. The mechanistic pathways include physical shading and light scattering, sorption and transport of hydrophobic pollutants and metals, disruption of nutrient uptake and cell membranes, oxidative stress induction, and the formation of eco-coronas that change particle–cell interactions. Major knowledge gaps remain in (i) environmentally realistic exposure scenarios (concentration, aging, and mixture complexity), (ii) long-term and community-level consequences in situ, and (iii) interactions between plastics and other stressors such as warming and eutrophication. We synthesize current evidence, identify methodological challenges, and propose priorities for future research and policy to reduce risks to marine primary production and coastal ecosystem services.

Keywords: Microplastics, Nano Plastics, Photosynthesis, Biofilm and Hydrophobic Pollutants

1. Introduction:

Marine microalgae — including eukaryotic phytoplankton and cyanobacteria — are central to oceanic primary production, global carbon sequestration, and the base of aquatic food webs (Li *et al.*, 2021). In recent decades, synthetic plastics have accumulated across marine realms, fragmenting into microplastics (MPs, <5 mm) and nanoplastics (NPs, <1 µm), which become widely bioavailable to planktonic organisms (Barari *et al.*, 2024; Slaveykova *et al.*, 2023). The interaction between marine microalgae and plastic particles is multifaceted: plastics can act as surfaces for biofilm growth, vectors for contaminants and microbes, and direct stressors that

influence cell physiology and community composition (Nava *et al.*, 2021; Binda *et al.*, 2024). This review critically examines evidence on how plastic pollution impacts marine microalgae at cellular, population, and community scales, synthesizing mechanistic insights, methodological limitations, and knowledge gaps for future research and management.

2. Scope and Methods of the Review

This review integrates peer-reviewed experimental studies, mesocosm experiments, field surveys, and recent syntheses (2019–2025), with emphasis on studies that examine direct effects of MPs/NPs on microalgal growth, photosynthesis and community dynamics, and those exploring mechanisms (e.g., oxidative stress, adsorption of pollutants). Representative, high-impact, and methodologically rigorous studies were prioritized to highlight consistent patterns and uncertainties. Where possible, we emphasize studies with environmentally relevant particle types, aging/weathering treatments, and concentrations measured in surface waters.

3. Types of Plastic Particles and Exposure Realism

Plastics encountered by microalgae range from fragments of polyethylene (PE), polypropylene (PP), and polystyrene (PS) to engineered nanoplastics and aged weathered particles bearing surface oxidation and sorbed substances. Laboratory experiments frequently use manufactured polystyrene spheres (PS beads) for reproducibility, but these do not capture the heterogeneity of environmental plastics (shape, roughness, eco-corona) and often occur at concentrations higher than ambient measurements (Nava *et al.*, 2021; Shukla *et al.*, 2024). Weathering changes particle surface chemistry and increases attachment of natural organic matter (forming eco-coronas), which strongly influences interactions with microalgal cells (Slaveykova *et al.*, 2023). Consequently, extrapolating from pristine PS bead tests to real-world impacts requires caution.

4. Direct Physiological Effects on Microalgae

4.1 Growth and Reproduction

A substantial body of laboratory research reports concentration- and size-dependent growth inhibition in microalgae exposed to MPs/NPs (e.g., *Chlorella* spp., *Tetraselmis* spp., *Scenedesmus* spp.). Li *et al.* (2021) and subsequent experiments demonstrate that nanoplastics can more potently inhibit algal growth than larger microplastics, likely due to enhanced cellular uptake and surface-area-to-volume effects that increase reactivity (Li *et al.*, 2021; Barari *et al.*, 2024). However, effects are not universal — some studies report no effect or even stimulatory growth when plastics serve as substrates for attached growth or when particle concentrations are low relative to ambient nutrient levels.

4.2 Photosynthesis and Photophysiology

Microplastics can interfere with photosynthesis via shading, light scattering, and direct disruption of photosynthetic machinery. Meta-analyses and targeted studies show decreases in

chlorophyll-a content, maximum quantum yield (F_v/F_m), and photosynthetic electron transport under MP/NP exposure, often accompanied by increased non-photochemical quenching and reduced carbon fixation (Li *et al.*, 2021; Zhu *et al.*, 2025). Such changes can reduce primary productivity and alter diel carbon fluxes, though the magnitude depends on particle optical properties, concentration, and the depth-light environment.

4.3 Oxidative Stress and Cellular Damage

Oxidative stress indicators (e.g., increased reactive oxygen species, lipid peroxidation, altered antioxidant enzyme activities) are widely reported in microalgae exposed to MPs/NPs, suggesting membrane and metabolic damage (Zhao *et al.*, 2024). Nanoplastics, due to their small size, may penetrate cell walls or membranes leading to intracellular ROS generation, DNA damage, and impaired nutrient assimilation (Barari *et al.*, 2024; Das *et al.*, 2024).

5. Indirect and Community-Level Effects

5.1 Plastics as Substrates: Biofilms and Species Sorting

Plastics provide novel floating and sinking substrates for microbial biofilms (the “plastisphere”), facilitating colonization by bacteria, diatoms, and microalgae (Nava *et al.*, 2021). This can increase local microalgal biomass on particles and potentially aid dispersal of terrestrial or invasive taxa into pelagic zones, altering community assembly and potentially seeding harmful algal blooms (HABs) in new regions (Binda *et al.*, 2024; Malinowski *et al.*, 2023). The taxonomic composition of plastisphere communities appears to be driven more by local species pools and nutrient regimes than polymer type per se, though aging and fouling state modulate colonization patterns.

5.2 Food Web and Ecosystem Consequences

Microalgae exposed to micro/nanoplastics may be less nutritious or contaminated with sorbed pollutants, affecting grazers and higher trophic levels through reduced growth or bioaccumulation (Malinowski *et al.*, 2023; Zhu *et al.*, 2025). Changes in microalgal community composition (e.g., shifts toward smaller cells or tolerant taxa) can alter carbon export efficiency and biogeochemical cycling, with potential feedbacks to climate-relevant processes. Evidence from mesocosms suggests that MPs can influence planktonic interactions and marine productivity, but field-level demonstrations of ecosystem-scale impacts remain limited.

6. Interactions with co-Contaminants and Multiple Stressors

Microplastics can sorb hydrophobic organic pollutants and metals, acting as vectors that concentrate and transport contaminants to microalgae and other plankton (Das *et al.*, 2023; Liu *et al.*, 2022). Co-exposure experiments show additive, antagonistic, or synergistic effects depending on chemical mixtures and particle properties: polystyrene nanoplastics have been shown to modulate metal nanoparticle toxicity in algae, sometimes mitigating and sometimes

enhancing harm (Liu *et al.*, 2022; Huang *et al.*, 2019). Interactions with global-change stressors — particularly warming, acidification, and eutrophication — are an active research frontier; emerging studies indicate that combined stressors can amplify negative impacts on phytoplankton physiology and community stability (Cousins *et al.*, 2025; Yadav *et al.*, 2023).

7. Mechanistic Synthesis

Synthesis of experimental and field data suggests several recurring mechanisms by which plastics influence microalgae:

- **Physical interference:** shading and light scattering by suspended particles reduce photon flux to cells (Li *et al.*, 2021).
- **Surface interactions:** adhesion of particles to cell surfaces can impair nutrient exchange or cause heteroaggregation and sedimentation of cells (Nava *et al.*, 2021).
- **Chemical vectoring:** plastics concentrate hydrophobic contaminants and metals, modifying exposure profiles to microalgae (Das *et al.*, 2023).
- **Oxidative and cellular damage:** NPs can induce ROS-mediated damage and membrane disruption (Barari *et al.*, 2024).
- **Microbial community shifts:** plastisphere formation alters local microbe-algae interactions, sometimes favoring opportunistic or harmful species (Binda *et al.*, 2024).

8. Methodological Challenges and Biases

A major challenge in synthesizing the literature is variability in experimental design: particle type (pristine vs. aged), size distribution, concentration, exposure duration, and assay endpoints vary widely, complicating comparability and environmental relevance (Shukla *et al.*, 2024; Nava *et al.*, 2021). Many lab studies employ high, short-term exposures to pristine PS beads, which can overestimate risks relative to environmentally realistic, aged particle scenarios. Detection and quantification methods for nanoplastics and aged fragments in natural waters are still developing, making it difficult to establish realistic exposure baselines for experiments (Slaveykova *et al.*, 2023; Shukla *et al.*, 2024). Additionally, planktonic communities in nature experience multiple concurrent stressors, which single-factor laboratory tests cannot capture.

9. Knowledge Gaps and Research Priorities

To improve ecological realism and predictive power, we recommend the following priorities:

1. **Environmentally anchored exposures** — conduct experiments with particle types, sizes, and concentrations informed by field measurements (including aged/weathered particles and eco-coronas).
2. **Long-term and community-level studies** — expand mesocosm and in situ studies to track chronic exposure, recovery, and trophic transfer.

3. **Multi-stressor experiments** — examine interactions between plastics, warming, acidification, and eutrophication to assess realistic cumulative impacts.
4. **Mechanistic molecular studies** — deploy omics approaches to identify biomarkers of plastic exposure, eco-corona composition, and pathways of cellular disruption.
5. **Improved detection** — develop robust, standardized methods for quantifying nanoplastics and aged fragments in the field to constrain exposure scenarios.

10. Policy and Management Implications

While scientific uncertainties remain, the evidence that plastics can impair key physiological processes in microalgae and restructure communities supports precautionary measures to reduce plastic inputs into coastal and marine systems. Management options include improved waste handling, reduction of single-use plastics, stormwater controls to limit run-off of degraded plastics, and support for remediation technologies. Importantly, policy should prioritize actions that reduce sources (prevention) while funding research into ecological impacts and detection capacity. Additionally, environmental monitoring programs should routinely include microplastic and nanoplastic assessments alongside biological indicators of phytoplankton health.

Conclusions:

Micro- and nanoplastic pollution poses multi-dimensional risks to marine microalgae, ranging from altered photosynthesis and oxidative stress at the cellular level to shifts in community composition with potential ecosystem-scale consequences. The literature reveals consistent patterns — particularly the greater reactivity of nanoscale plastics and the importance of particle aging and eco-coronas — but also highlights substantial methodological heterogeneity and gaps in environmental realism. Addressing these gaps through targeted, interdisciplinary research and coupling science to preventative policy can reduce uncertainty and better protect the foundational productivity of marine ecosystems.

References:

1. Barari F, Gabrabad E, Bonyadi Z, (2024). Recent progress on the toxic effects of microplastics and their influence on aquatic organisms. *Environmental Pollution*. 10 (12): 321-332.
2. Binda G, Allan J, Hurley R. (2024). The interaction between plastics and microalgae affects dispersal and community assembly. *Communications (Earth & Environment)*. 2024; 5(1):545.
3. Cousins IT, Johansson JH, Salter ME. (2025). Combined effects of ocean warming and microplastics on marine phytoplankton. *Marine Environmental Research* 45(2): 331-342.

4. Das S, Kumari S, Mc Knight V, Redwing JM, Yang Y, (2024). Fluorescent nanoplastics increase the toxic effects of graphene oxide on freshwater algae *Scenedesmus obliquus*. *Science of the Total Environment*. 13: 231-235.
5. Huang B, Wei ZB, Yang LY, Pan K, Miao AJ (2019). Combined toxicity of silver nanoparticles with polystyrene toward freshwater algae. *Environmental Science & Technology*, 53(20): 12000–12011.
6. Li Y, Liu X, Shinde S, Wang J, Zhang P (2021). Impacts of micro- and nanoplastics on photosynthesis and phytoplankton physiology: a review. *Frontiers in Marine Science* 9(1): 12-18.
7. Liu F, Gao Z, Chu W, Wang S (2022). Polystyrene nanoplastics alleviate or modulate the toxicity of CuO nanoparticles in marine microalgae. *Frontiers in Marine Science* (12) 4: 34-44.
8. Nava V, Chandra S, Aherne J 2021 Microalgae colonization of different microplastic polymers: diversity and community structure. *Science of the Total Environment*. 21(1): 244-250.
9. Shukla S, Khanna S, Khanna K (2024). Unveiling the toxicity of micro-nanoplastics: a systematic review of detection and ecotoxicology. *Environmental Toxicology and Chemistry* (10) 4: 37-45.
10. Slaveykova I, Berge-Lefranc D, Chaspoul F (2023). Progress in research on the bioavailability and toxicity of nanoplastics to plankton. *MDPI Environmental Sciences* (11) 2: 355-360.
11. Yadav D, Babu S, Yadav K, Kumawat A, Singh D (2023). Microplastic effects in aquatic ecosystems with special reference to marine systems. *Frontiers in Ecology and Evolution* (13) 1: 555-560.
12. Zhao W, An W, Liu W, Liang W, Gao W (2025) Adverse effects of microplastics on growth and oxidative stress in *Haematococcus pluvialis*. *Science of the Total Environment* (8) 2: 122-129.
13. Zhu R, Ye X, Lu X, Xiao L, Yuan M, Zhao H (2025) A global estimate of multiecosystem photosynthesis losses due to microplastics. *PNAS*. (9) 1: 111-120.

GREENHOUSE AQUACULTURE FOR FUTURE SUSTAINABILITY

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Abstract:

Greenhouse aquaculture offers a sustainable solution to the challenges of maintaining optimal water temperatures for fish growth, particularly in regions with adverse climates. Unlike traditional open pond systems, which face temperature fluctuations and heat loss, greenhouses provide a controlled environment that ensures stable water temperatures year-round. This system integrates technologies like Recirculating Aquaculture Systems (RAS) and aquaponics, along with renewable energy sources and automation, to optimize resource use and enhance productivity. Greenhouses also enable off-season fish production, broodstock maturation, and effective fry rearing, benefiting rural fishing communities economically. By leveraging the natural greenhouse effect, transparent structures trap solar energy to create favorable conditions for aquaculture. Thermal analysis and automation are crucial in managing micro-climatic factors like temperature, humidity, and solar radiation. This study underscores the potential of greenhouse aquaculture to meet the growing demand for seafood while promoting sustainability and food security, particularly for rural communities.

1. Introduction:

Aquaculture is rapidly expanding in India, attracting a growing number of farmers with limited technical expertise. The success of fish farming is influenced not only by nutritional needs but also by water temperature, which plays a crucial role in the growth and survival of fish species (Corey *et al.*, 1983). While growth rates tend to improve with rising water temperatures, they may decline or even become negative if temperatures exceed the optimal range (Jobling, 1993). During winter, many regions in India experience water temperatures below 20°C, which significantly hampers fish growth due to decreased metabolic activity. As a result, colder climates necessitate additional or supplemental heating to raise water temperatures (Brett & Groves, 1979).

Sources of heat for aquaculture often include waste heat from power plants, geothermal hot water, and greenhouses, which can employ either passive or active heating methods. For

instance, Zhu *et al.* (1998) demonstrated that greenhouse pond systems can increase water temperatures by approximately 5.2°C in a 1-meter-deep pond compared to the outside air temperature. Greenhouse systems help maintain consistent water temperatures, facilitating year-round fish growth, accelerating broodstock maturation, and creating favorable conditions for rearing fry or fingerlings in controlled environments. Furthermore, heat loss from pond surfaces is influenced by factors such as wind velocity and the temperature gradient between the pond and surrounding air. Greenhouses provide an effective solution to reduce heat loss while simultaneously enhancing water temperature (Corey *et al.*, 1983).

1.1 Importance of Aquaculture

Aquaculture is one of the fastest-growing industries in India, attracting many fish farmers with limited exposure to advanced technologies. However, during winter, water temperatures in several parts of India fall below 20°C. In such low-temperature conditions, fish experience reduced metabolic activity, which negatively impacts their growth. Since water temperature is a critical factor for fish growth, introducing greenhouse fish pond systems can help mitigate this challenge. These systems can raise water temperatures during winter, maintaining levels necessary for optimal fish growth, even when open-air pond temperatures drop below the required range. By adopting greenhouse fish pond technology, year-round fish growth can be achieved within a controlled environment. Maintaining optimal water temperature is particularly vital for aquatic species, emphasizing the need for innovative and alternative technologies to enhance water temperature for sustainable fish production (Sarkar & Tiwari, 2005).

In this context, greenhouse ponds offer an excellent alternative for maintaining water temperature and ensuring optimal fish growth compared to traditional open pond systems. This technology holds significant potential, particularly for meeting the year-round demand for off-season broodstock maturation. Additionally, greenhouse systems provide a controlled environment ideal for raising fish seed, including fry and fingerlings, ensuring consistent production and growth (Tribeni *et al.*, 2006).

1.2 Present Scenario of Aquaculture

India ranks as the second-largest aquaculture-producing nation in the world, following China. In 2022, the total global production of aquatic animals reached 185.4 million metric tons (MT), with aquaculture contributing 94.4 MT to this figure. India made a significant contribution to aquaculture production, with its inland aquaculture accounting for 59.1 MT during the same year. Furthermore, the global annual per capita apparent consumption of aquatic products was estimated at 20.7 kg in 2022 (FAO, 2024).

2. Greenhouse Pond Management

2.1 Greenhouse and Greenhouse Aquaculture

A greenhouse is a structure with transparent walls and a roof, typically made of glass or plastic, designed to create a controlled environment conducive to plant growth. Sunlight passes through the transparent covering and is absorbed by the plants and the greenhouse structure, converting it into heat. This heat becomes trapped inside, creating a warm microclimate that supports plant cultivation, even in colder climates. By maintaining a stable temperature, greenhouses extend the growing season and enable year-round farming.

Greenhouse pond systems (GPS), used as hatchery, nursery, over-wintering and highly intensive aquaculture facilities, can provide a good alternative for the maintenance of water temperature. In aquaculture, greenhouses are increasingly used in colder regions to enhance fish production. These structures help maintain stable water temperatures, which promotes fish growth and minimizes the risk of diseases. Unlike horticultural greenhouses, aquaculture greenhouses require careful monitoring of water quality parameters, such as dissolved oxygen, carbon dioxide levels, and pH, to ensure the health and well-being of the aquatic species. Additionally, aquaculture greenhouses are designed with adequate height and sufficient side walking space to facilitate easy fish sampling and harvesting (Zhu *et al.*, 1998).

2.2 Concept of Greenhouse

The concept of a greenhouse is rooted in the natural greenhouse effect, which occurs within Earth's atmosphere. This phenomenon traps heat, enabling life to thrive on the planet. The atmosphere absorbs ultraviolet (UV) and infrared (IR) radiation from the sun while allowing shortwave solar radiation to reach Earth's surface. The trapped heat warms the air between the surface and the atmosphere, maintaining a suitable temperature for life. A greenhouse, inspired by this natural process, is a sealed structure with transparent walls and a roof, typically made of glass or plastic. It is designed to trap heat, creating optimal growing conditions for plants. By controlling factors such as light intensity, temperature, humidity, and air composition, greenhouses allow for enhanced productivity and year-round cultivation (Cengel, 1998).

2.3 History of the Greenhouse

The history of greenhouse cultivation dates back to the 4th century B.C. The earliest recorded use of glass for this purpose appeared in France in 1385 (Crockett, 1977). Between the 15th and 18th centuries, greenhouse farming spread across Europe and eventually reached the United States in the early 1900s (Von *et al.*, 2000). Significant advancements were made in the 1960s with the development of wide-span greenhouses, which improved light transmission and enhanced productivity (Taft, 1962). During the 1960s and 1970s, greenhouse technology was

widely adopted in Japan and China, contributing to its expansion across more than 50 countries (Alexander, 1981). Greenhouses have become a global agricultural practice, adapted to various climates and constructed using diverse materials to meet modern farming needs.

Table 1. Uses of Greenhouses in India

Type of Greenhouse	Heating	Cooling	References
U-shaped/ Quonset shape	Direct gain	Natural ventilated	Pillai <i>et al.</i> , 1999; Bandyopadhyay <i>et al.</i> , 2000; Mohapatra <i>et al.</i> , 2002
Quonset shape (IARI model)	Direct gain	Natural and forced ventilation	Sarkar and Tiwari, 2006; Tiwari and Sarkar, 2006
Even span	Direct with north brick wall	Natural and forced ventilation	Sarkar and Tiwari, 2005; Tiwari <i>et al.</i> , 2006
Quonset shape (IARI model)	Direct and indirect gain (flat plate collector)	Natural and forced ventilation	Tribeni <i>et al.</i> , 2006
Even span	Direct gain	Natural	Sarkar and Tiwari, 2006
Even span	Direct gain	Natural	Jain 2007

2.4 Importance of Greenhouse in Aquaculture

Greenhouse technology plays a crucial role in advancing aquaculture by providing a controlled environment that enhances fish production. As fish growth is highly influenced by environmental factors like water temperature, greenhouses create a favorable microclimate that supports optimal conditions for year-round or seasonal fish farming. Transparent structures are built over ponds to partially or fully regulate environmental parameters, ensuring consistent and improved fish yields. This approach is particularly beneficial in addressing the challenges posed by the growing global population and limited resources. Greenhouse aquaculture allows for greater control over water temperature and other critical factors, which are essential for maximizing fish growth and productivity. Unlike traditional aquaculture practices that primarily focus on management, greenhouse technology integrates environmental control, making it a sustainable and commercially viable option. By combining advancements in biotechnology with precise environmental regulation, greenhouse aquaculture represents an innovative solution for boosting fish production and meeting future demands (Zhang *et al.*, 2022).

2.5 Advantages of Greenhouse

The advantages of greenhouse are discussed as follows (Tiwari, 2007):

1. Heat Loss Reduction

Greenhouses help minimize heat loss, leading to an increase in water temperature. The key benefits include:

- Lower air velocity.
- Decreased temperature difference between the pond water and the surrounding air.
- Reduced vapor pressure difference between the pond water and the air by enhancing relative humidity.

These advantages collectively minimize heat loss caused by evaporation, convection, and radiation.

2. Off-Season Fish Production

By providing a controlled environment, greenhouses support year-round fish growth, enabling off-season seed rearing. This approach meets the demand for broodstock and fish seed, especially in temperate climates.

3. Cost Effectiveness

The productivity of a greenhouse can be increased through practices like multiple cropping and intensive culture. While controlling the environment inside the greenhouse adds to the overall cost, the higher yield of high-value crops during the off-season makes greenhouse cultivation a cost-effective option, despite the increased per-unit production costs.

4. Length of Growing Season

Water temperature is a key factor influencing fish growth, as the growth period depends on it. Cold temperatures in winter cause warm-water fish species to become less active, eat less, and grow slower. As the water warms in summer, their metabolism and overall activity increase. Warmer water not only boosts growth rate and metabolism but also enhances survival, swimming speed, feeding, digestion, spawning, and the survival of eggs and larvae.

2.6 Thermal Analysis of Greenhouse

To analyze greenhouse systems, thermal assessments are carried out using steady-state, quasi-steady-state, and periodic models.

(a) Steady State Model

The steady-state model asserts that the total energy within a system remains constant, with the energy entering the system, such as heat, work, or material movement, exactly balancing the energy leaving the system (Arinze *et al.*, 1984).

(b) Transient Model (Quasi-steady State)

The transient model describes a system where the total energy changes over time. In a quasi-steady state, a special case of the transient state, the energy remains constant for short periods before undergoing further changes (Singh & Tiwari, 2000).

2.7 Steady State Analysis of Cooling Concepts

Cooling is essential to maintain optimal oxygen levels inside a greenhouse. The need for thermal cooling arises when excess heat builds up, which is mainly influenced by the time of year. Cooling requirements fluctuate with the seasons. For example, in North Indian climates, excess heat in March can be effectively vented through the roof using natural convection. However, during the hotter months from April to June, natural convection alone is inadequate, and forced convection is the more effective method for heat removal (Sharan, 2013).

3. Greenhouse Construction

3.1 Introduction

A greenhouse provides a controlled micro-climate that supports the optimal growth conditions for fish. The structure should be lightweight yet durable enough to withstand environmental forces like wind and snow. Greenhouses are semi-permanent structures designed to last for around 25 years, with a focus on maximizing light transmission and resisting various loads.

3.2 Classification

Based on working principles, shape, utility and cost, greenhouses are classified into the following categories:

3.2.1 Working Principles

Greenhouses are categorized into passive and active types based on their operational principles:

(i) Passive Greenhouse

A passive greenhouse operates without the use of machines, relying on natural processes such as convection and sunlight (radiation) to regulate its internal environment. The glass walls and roof collect, store, and distribute sunlight throughout the structure. Its design is optimized to maximize solar gain during the winter while minimizing it in the summer, helping to reduce heating and cooling demands. This type of greenhouse is highly efficient for energy conservation, as it operates without any ongoing energy costs for operation (Duffie and Beckman, 1991).

(ii) Active Greenhouse

An active greenhouse uses mechanical systems, such as fans and pumps, to transfer heat or fluids, allowing for better environmental control. It can also incorporate solar panels or conventional fuels to provide thermal energy. This type of greenhouse offers precise temperature

regulation, making it ideal for regions that require additional heating or cooling to maintain optimal growing conditions (Aldrich & Bartok, 1994).

3.2.2 Shape

Greenhouses come in various shapes, each offering unique benefits. A single-span greenhouse is a simple structure with a single roof span, while a multi-span greenhouse consists of connected single-span units, covering larger areas. Other shapes include the spherical dome, which provides efficient light distribution, and the hyperbolic paraboloid, known for its modern aesthetic and strong wind resistance. The Quonset and modified Quonset designs are economical and widely used, offering cost-effective solutions. The Gothic arch design improves light diffusion and aids in snow runoff, while the mansard roof combines steep and flat slopes to increase headroom. Finally, the Gabic even and uneven span designs are tailored for specific landscapes or slopes, offering versatility in various environments (Tiwari & Goyal, 1998).

3.2.3 Cost of Construction or Extent of Environment Control

Greenhouses are categorized based on the cost per square meter of the constructed area. Broadly, they are divided into three main categories, depending on the level of environmental control required (Tiwari & Goyal, 1998; Sirohi & Behera, 2000).

(i) Low Cost or Low-Tech Greenhouses

A low-cost or low-tech greenhouse is a basic structure built with a 150-200 μ m-thick polythene sheet and locally sourced materials such as bamboo and timber. The internal temperature is 6-10°C higher than the outside, which makes it ideal for colder regions. While it requires minimal investment, it lacks advanced control systems, making it an affordable and practical solution for simple farming needs in resource-limited areas (Tiwari & Goyal, 1998).

(ii) Medium-Tech Greenhouses

A medium-tech greenhouse features a strong, permanent frame constructed from galvanized iron (GI) pipes and is covered with UV-stabilized polythene sheets (200-250 μ). It includes exhaust fans and thermostats for efficient temperature regulation. The frame lasts for 25 years, and the glazing material has a lifespan of around 3 years. Designed for dry and warm climates, this greenhouse is widely used in vegetable farming (Kumar *et al.*, 2018).

(iii) Hi-Tech Greenhouses

A high-tech greenhouse incorporates automated systems that manage temperature, humidity, and other environmental conditions to create ideal growth environments. These systems prevent issues, like heating and fan operation happening at the same time. It is adaptable to all climates, making it especially well-suited for fish farming, where stable temperatures are essential (Shamshiri *et al.*, 2018).

3.2.4 Greenhouse Cover Material

Prior to World War II, greenhouses were predominantly built with glass as the glazing material. However, with advancements in material technology, various alternatives such as plastic film, rigid sheets and polyvinyl chloride (PVC) have been introduced for greenhouse construction (Castellano *et al.*, 2008). Materials like polyethylene, PVC, ethyl vinyl acetate (EVA), acrylic, polycarbonate, fiberglass, polyester and polyvinyl fluoride (PVF) are now commonly used. The classification of greenhouses also depends on the material used for constructing the frame, which can be made of wood, bamboo, steel, aluminum, or reinforced concrete (Von & Von, 2011).

3.2.5 Utility

Greenhouses serve various purposes depending on their utility. Retail and wholesale greenhouses are used commercially for producing and selling plants, fish, and other goods. Institutional greenhouses are intended for academic studies, as well as public gardens and parks. Overwintering greenhouses generally rely on insulation to keep temperatures near freezing without the need for heaters, though minimal heating may be used if temperatures fall significantly below freezing.

3.3 Glazing properties

The term glazing refers to the use of transparent plastic or glass to cover a greenhouse frame. UV-stabilized polyethylene is commonly used because of its low cost and durability. Over time, glazing materials experience light transmissivity loss, known as degradation or weatherability. There are various glazing materials available: Glass, a traditional choice, remains effective for about seven years. Plastic glazing, on the other hand, has a shorter lifespan, with ordinary plastic lasting just 3-4 months due to UV damage, whereas UV-stabilized plastic can last more than two years because it resists UV deterioration (Both, 2002).

3.4 Ventilation

3.4.1 Natural Convection

Natural Convection utilizes temperature differences to promote air movement naturally, where hot air rises and exits through roof vents, drawing in cooler air from outside. This method is effective in maintaining air circulation with 25-50 air changes per hour, making it a cost-effective solution that does not require advanced equipment. However, its efficiency is limited in very hot or dry climates, making it best suited for moderate climates, such as in North India during March or April (Teitel & Tanny, 1999).

3.4.2 Forced Convection

Forced Convection relies on fans to actively circulate air by removing hot air from the space. The efficiency of this system depends on the number and capacity of the fans used, making it

more costly due to the need for equipment and energy consumption. Forced convection is particularly beneficial in hotter climates, where natural ventilation may not provide adequate cooling, and is commonly used during the peak summer months, such as April in North India (Teitel *et al.*, 2008).

3.5 Shading

Shading is essential in controlling solar radiation entering a greenhouse, which is the main source of heat. Techniques like using shade cloth on the roof can reduce excessive radiation, especially during summer. Additionally, lime-based shading compounds can lower infrared radiation, and caustic compounds are used to clean the cover and restore light transmittance (ASHRAE, 1978). Bailey (1981) found that an aluminum-plated mesh reduced internal temperature by 6°C compared to an unshaded greenhouse at 33°C. Feuermann *et al.* (1998) developed a model to study the thermal performance of liquid radiation filter greenhouses in different climates. Shamim and McDonald (1995) demonstrated that a 25 mm foam layer reduced thermal radiation by transmitting only 50% of solar radiation, lowering greenhouse temperatures in hot-arid climates.

3.6 Heating Arrangements

Several heating methods are employed to enhance the heat gain from solar radiation entering the greenhouse, as outlined below:

3.6.1 Direct Gain

In the Direct Gain system, sunlight enters the greenhouse through the walls and roof, which are strategically positioned to maximize solar radiation. This system relies on large glazed areas and thermal storage materials like water and soil to capture and store heat. To minimize heat loss at night, movable insulation is used to cover the glazing surfaces. While this method increases the internal heated area and raises the water temperature, it can lead to issues such as heat loss during winter or overheating in the summer. To address this, various controls, including reflectors, roof overhangs, and vents, are used to regulate solar heat gain and maintain a stable temperature.

3.6.2 Movable Insulation

Movable Insulation primarily focuses on reducing heat loss during cold winter nights. Night curtains or thermal screens are placed inside or outside the greenhouse cover to conserve heat by preventing radiation loss to the cold night sky. These insulations are removed during the day to allow sunlight to enter and heat the greenhouse. This system has been shown to save significant energy, with studies indicating up to 70% reduction in heating load and approximately 20% reduction in energy consumption (Chandra and Albright, 1980). Movable insulation is

particularly effective in maintaining optimal temperatures for plant growth, such as tomatoes and peppers, during winter (Barral *et al.*, 1999).

4. Difference Between the Greenhouse Aquaculture and Open Pond Culture

Aspect	Greenhouse Aquaculture	Open Pond Culture
Environmental Control	Fully controlled (temperature, light, humidity, water quality).	Relies on natural environmental conditions.
Seasonality	Year-round production.	Seasonal production.
Productivity	High productivity with minimal losses.	Lower productivity, vulnerable to diseases and predators.
Species Suitability	Ideal for species needing specific conditions (e.g., tilapia, shrimp).	Best for species adapted to local environments.
Sustainability	Environmentally friendly with minimal water and waste (RAS systems).	Faces issues like water pollution and habitat loss.
Initial Cost	High due to infrastructure and technology requirements.	Low, as it relies on natural resources.
Operational Costs	High, due to energy for climate control and monitoring.	Low, minimal dependence on external systems.
Risk Factors	Low risk (diseases, predators, and extreme weather controlled).	High risk of losses from natural challenges.
Location Flexibility	Can be established in urban or arid regions with controlled systems.	Requires natural water bodies or land, limiting flexibility.

4.1 Case Studies on Greenhouse Aquaculture

Several studies have confirmed the benefits of greenhouse aquaculture on growth, survival, and reproduction of different fish species. In Kenya, Nile tilapia (*Oreochromis niloticus*) broodstock reared under greenhouse conditions showed significantly higher weight gain (799.7% vs. 647.1%), specific growth rate, fecundity and spawning frequency compared to open ponds (Musal *et al.*, 2012). Similarly, African catfish (*Clarias gariepinus*) fry reared in greenhouses at lower stocking densities attained greater final weight (148.6 ± 3.59 mg vs. 96.6 ± 2.4 mg) and survival (97.3% vs. 54.7%) than those outside, demonstrating the role of controlled environments in high-altitude regions (Josiah *et al.*, 2012). In India, common carp (*Cyprinus carpio*) fry reared in greenhouses during winter achieved significantly higher growth (116.4 g vs. 90.2 g) and better feed conversion efficiency due to a 3.5–6.7 °C rise in water temperature compared to open tanks (Tiwari *et al.*, 2006). Collectively, these case studies highlight that greenhouse aquaculture

ensures thermal regulation, enhances growth and survival, improves reproductive efficiency and supports sustainable fish production in diverse climatic conditions.

5. Current Trends in Greenhouse Aquaculture

Greenhouse aquaculture is advancing with a focus on sustainability and efficiency through energy-efficient technologies, sustainable water management and advanced monitoring systems. These innovations reduce fossil fuel dependence, conserve water and enhance productivity. Solar-powered smart greenhouses help regulate temperatures while optimizing energy use and renewable energy integration in aquaponics supports sustainable infrastructure (Wahyu *et al.*, 2024). Aquaponics creates a closed-loop system that conserves water, making it ideal for arid regions, while Recirculating Aquaculture Systems (RAS) enhance sustainability by filtering and reusing water (Chandramenon *et al.*, 2024). Automation and climate adaptation technologies, such as IoT and AI, enable real-time monitoring, improving efficiency and reducing labor costs (Bin *et al.*, 2024). Advanced monitoring systems further optimize resource management, ensuring ideal growth conditions and fostering innovation in small-scale aquaculture (Malabadi *et al.*, 2024). These advancements highlight greenhouse aquaculture's role in promoting sustainability and global food security.

6. Future Prospects in Greenhouse Aquaculture

The future of greenhouse aquaculture is promising, driven by advancements in sustainability, energy efficiency and technology. Solar energy integration reduces reliance on fossil fuels and lowers operational costs (Prasetyo *et al.*, 2023), while Recirculating Aquaculture Systems (RAS) enhance sustainability by reducing water usage by up to 99% (Lal *et al.*, 2024). Species diversification, including shrimp and tilapia, can boost profitability by meeting market demand. Additionally, aquaponics maximizes resource efficiency by integrating fish farming with plant cultivation, utilizing nutrient-rich water. Automation and AI further improve efficiency by enabling real-time monitoring of environmental conditions, optimizing water quality, temperature and feeding schedules (Lal *et al.*, 2024). These innovations make greenhouse aquaculture a sustainable solution for future food production while addressing environmental challenges (Martinell, 2024).

Conclusion:

Aquaculture faces challenges from harsh climatic conditions that affect traditional open pond systems, limiting fish production and sustainability. Greenhouse aquaculture provides a solution by creating a controlled environment with stable water temperatures, enabling year-round fish growth, faster broodstock maturity, and effective fry or fingerling rearing. This method uses energy-efficient technologies, renewable energy, and sustainable practices like Recirculating

Aquaculture Systems (RAS) and aquaponics to optimize resources and reduce environmental impact. Automation and smart technologies further lower labor costs and enhance efficiency. With rising demand for seafood, greenhouse aquaculture offers a sustainable and reliable way to meet global food needs and support food security.

References:

1. Aldrich, R. A., & Bartok, J. W. (1994). *Greenhouse Engineering* (NRAES 33).
2. Alexander, A.C. (1981), "Note on the Application of Plastic Sheets for Agricultural Use", A Report Prepared from Chinese Pamphlets, Embassy of the Republic of India in Beijing, China.
3. Arinze, E. A., Schoenau, G. J., & Besant, R. W. (1984). A dynamic thermal performance simulation model of an energy conserving greenhouse with thermal storage. *Transactions of the ASAE*, 27(2), 508-0519.
4. ASHRAE (1978), Application Hand Book: Environmental Control for Animals and Plants, Chapter 2, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, p. 16.
5. Bailey, B. J. (1981). The reduction of thermal radiation in glasshouses by thermal screens. *Journal of Agricultural Engineering Research*, 26(3), 215-224.
6. Bandyopadhyay, M. K., Tripathi, S. D., Aravindakshan, P. K., Singh, S. K., Sarkar, B., Majhi, D., & Ayyappan, S. (2000, January). Fish culture in polyhouse ponds-a new approach for increasing fish production in low temperature areas. In *The Fifth Indian Fisheries Forum*, p. 7.
7. Barral, J. R., Galimberti, P. D., Barone, A., & Lara, M. A. (1999). Integrated thermal improvements for greenhouse cultivation in the central part of Argentina. *Solar Energy*, 67(1-3), 111-118.
8. Bin Zamnuri, M. A. H., Qiu, S., bin Rizalmy, M. A. A., He, W., Yusoff, S., Roeroe, K. A., ... & Loh, K. H. (2024). Integration of IoT in Small-Scale Aquaponics to Enhance Efficiency and Profitability: A Systematic Review. *Animals: an Open Access Journal from MDPI*, 14(17), 2555.
9. Both, A. J. (2002). Greenhouse glazing. *Horticultural Engineering Newsletter. Rutgers Cooperative Extension*, 17, 5-6.
10. Brett, J.R. and Groves, T.D.D. (1979), "Physiological Energetics", In *Fish Physiology, Vol. III, Bioenergetics and Growth*, W.S. Hoar, D.J. Randall and J.R. Brett (Eds.), *Academic Press*, New York, pp. 279-352.

11. Castellano, S., Mugnozza, G. S., Russo, G., Briassoulis, D., Mistrotis, A., Hemming, S., & Waaijenberg, D. (2008). Design and use criteria of netting systems for agricultural production in Italy. *Journal of Agricultural Engineering*, 39(3), 31-42.
12. Cengel, Y.A. (1998), Heat Transfer: A Practical Approach, WCB/McGraw-Hill, New York, pp. 514, 666.
13. Chandra, P., & Albright, L. D. (1980). Analytical determination of the effect on greenhouse heating requirements of using night curtains. *Transactions of the ASAE*, 23(4), 994-1000.
14. Chandramenon, P., Gascoyne, A., Naughton, L., & Tchuenbou-Magaia, F. (2024). Making Aquaponics More Sustainable Using Worms and Water Replenishment Combined with a Sensing-and IoT-Based Monitoring System. *Applied Sciences*, 14(18), 8516.
15. Corey, P. D., Leith, D. A., & English, M. J. (1983). A growth model for coho salmon including effects of varying ration allotments and temperature. *Aquaculture*, 30(1-4), 125-143.
16. Crockett, J.U. (1977), Greenhouse Gardening. *Time Life Books, Virginia*, p. 56.
17. Duffie, J.A. and Beckman, W.A. (1991), Solar Engineering of Thermal Processes, John Wiley & Sons, Inc., New York.
18. FAO. 2024. *The State of World Fisheries and Aquaculture 2024. Blue Transformation in action*. Rome. <https://doi.org/10.4060/cd0683en>
19. Feuermann, D., Kopel, R., Zeroni, M., Levi, S., & Gale, J. (1998). Evaluation of a liquid radiation filter greenhouse in a desert environment. *Transactions of the ASAE*, 41(6), 1781-1788.
20. Jain, D. (2007). Modeling the thermal performance of an aquaculture pond heating with greenhouse. *Building and environment*, 42(2), 557-565.
21. Jobling, M. (1993), "Bioenergetics, Feed Intake and Energy Partitioning", In *Fish Eco-Physiology*, J.C. Rankin and F.B. Jensen, Chapman & Hall, London, pp. 1-44.
22. Josiah, A. S., Mwatete, M. C., & Njiru, J. (2012). Effects of greenhouse and stocking density on growth and survival of African catfish (*Clarias gariepinus* Burchell 1822) fry reared in high altitude Kenya regions.
23. Kumar, P., Tiwari, K. N., & Jha, M. K. (2018). *Greenhouse technology for controlled environment farming*. Springer.
24. Lal, J., Vaishnav, A., Deb, S., Gautam, P., Pavankalyan, M., Kumari, K., & Verma, D. K. Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming. *Archives of Current Research International*, 24, 799-810.
25. Malabadi, R. B., Kolkar, K. P., Chalannavar, R. K., Castaño-Coronado, K., Mammadova, S. S., Baijnath, H., ... & Abdi, G. (2024). Greenhouse farming: Hydroponic vertical

- farming-Internet of Things (IOT) Technologies: An updated review. *World Journal of Advanced Research and Reviews*, 23(02), 2634-2686.
26. Martinell, D. P. (2024). New technologies as a means to achieve sustainability. In *An Introduction to Sustainable Aquaculture* (pp. 286-314). Routledge.
 27. Mohapatra, B. C., Singh, S. K., Sarkar, B., Majhi, D., Maharathi, C., & Pani, K. C. (2002). Common carp, *Cyprinus carpio* (L.) seed rearing in polyhouse pond environment during low temperature periods. *Journal of Aquaculture*, 37-41.
 28. Musal, S., Orina, P. S., Aura, C. M., Kundu, R., Ogello, E. O., & Munguti, J. M. (2012). The effects of dietary levels of protein and greenhouse on growth, behaviour and fecundity of Nile tilapia (*Oreochromis niloticus* L.) broodstock.
 29. Pillai, B. R., Tripathy, A. P., & Rao, K. J. (1999). Observations on the growth of postlarvae of *Macrohrachium rosenhergii* in polythene sheet covered earthen nursery ponds during winter. *Indian Journal of Fisheries*, 46(1), 57-59.
 30. Prasetyo, A., Rahman, J., Elfiano, E., Saragih, S. A., & Lazrisyah, S. (2023). Integration of Solar Energy Technology in Improving Energy Sustainability and Efficiency in the Fisheries Sector (Case Study of Rokan Hilir Regency, Riau Province). *International Journal of Regional Innovation*, 3(3).
 31. Sarkar, B. and Tiwari, G.N. (2005), "Thermal Modeling of a Greenhouse Fish Pond System", *Agricultural Engineering International: The CIGR E-journal*, BC 05 015, Vol. VII.
 32. Sarkar, B., & Tiwari, G. N. (2006). Study of thermal aspects in open and greenhouse ponds. *International journal of energy research*, 30(14), 1228-1241.
 33. Shamim, T. and McDonald, T.W. (1995), "Experimental Study of Heat Transfer Through Liquid Foam", *Proceedings of ASHRAE*, Atlanta, USA, Transaction No. 1, pp. 150- 157.
 34. Shamshiri, R. R., Kalantari, F., Ting, K. C., & Thorp, K. R. (2018). *Advances in greenhouse automation and climate control systems*. Elsevier.
 35. Sharan, G. (2013, February). Cooling need of greenhouses in semi-arid hot water-scarce Kutch region of North-West India. In *International Conference on Agricultural Engineering: New Technologies for Sustainable Agricultural Production and Food Security 1054* (pp. 31-38).
 36. Singh, R. D., & Tiwari, G. N. (2000). Thermal heating of controlled environment greenhouse: a transient analysis. *Energy conversion and management*, 41(5), 505-522.
 37. Sirohi, P. S., & Behera, T. K. (2000). Protected cultivation and seed production in vegetables. *Indian Horticulture*, 45(1), 23-25.
 38. Taft, L.R. (1962), *Greenhouse Construction*, Orange Judd Co., New York, p. 256.

39. Teitel, M., & Tanny, J. (1999). Natural ventilation of greenhouses: experiments and model. *Agricultural and Forest Meteorology*, 96(1-3), 59-70.
40. Teitel, M., Ziskind, G., Liran, O., Dubovsky, V., & Letan, R. (2008). Effect of wind direction on greenhouse ventilation rate, airflow patterns and temperature distributions. *Biosystems Engineering*, 101(3), 351-369.
41. Tiwari, G. N. (2007). Fundamentals of aquaculture greenhouse. *New Delhi Anamaya publishers*. 225p.
42. Tiwari, G. N., Das, T., & Sarkar, B. (2006). Experimental study of greenhouse Prawn drying under natural convection. *Agricultural Engineering International: CIGR Journal*, Vol. VIII.
43. Tiwari, G., Sarkar, B., & Ghosh, L. (2006). Observation of common carp (*Cyprinus carpio*) fry-fingerlings rearing in a greenhouse during winter period.
44. Tiwari, G.N. and Goyal, R.K. (1998), Greenhouse Technology, *Narosa Publishing House*, New Delhi, pp. 252-311.
45. Tiwari, G.N. and Sarkar, B. (2006) "Energy Inputs and Fish Yield Relationship for Open and Greenhouse Pond", *Journal of Fisheries and Aquatic Science*, 1(2), pp. 171- 180.
46. Tribeni Das, T. D., Tiwari, G. N., & Bikash Sarkar, B. S. (2006). Thermal performance of a greenhouse fish pond integrated with Flat Plate Collector.
47. Von Elsner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., Von Zabeltitz, C., Gratraud, J., & Suay-Cortes, R. (2000). Review of structural and functional characteristics of greenhouses in European Union countries: Part I, design requirements. *Journal of Agricultural Engineering Research*, 75(1), 1–16.
48. Von Zabeltitz, C., & von Zabeltitz, C. (2011). Greenhouse structures. *Integrated Greenhouse Systems for Mild Climates: Climate Conditions, Design, Construction, Maintenance, Climate Control*, 59-135.
49. Wahyu, S., Purwalaksana, A. Z., Ritonga, A. F., Suharmanto, P., Kusumadjati, A., Akbar, A. M., & Sujadi, T. (2024, October). Optimization of a Smart Greenhouse with a Solar Energy System for Floating Raft Hydroponic Cultivation: Implementation and Performance Evaluation. In *Journal of Physics: Conference Series* (Vol. 2866, No. 1, p. 012098). IOP Publishing.
50. Zhang, S., Guo, Y., Li, S., Ke, Z., Zhao, H., Yang, J., ... & Zhang, Z. (2022). Investigation on environment monitoring system for a combination of hydroponics and aquaculture in greenhouse. *Information Processing in Agriculture*, 9(1), 123-134.
51. Zhu, S., Deltour, J., & Wang, S. (1998). Modeling the thermal characteristics of greenhouse pond systems. *Aquacultural Engineering*, 18(3), 201-217.

FISHING CRAFTS AND GEARS IN THE WETLANDS OF KERALA: SCIENTIFIC OVERVIEW

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Abstract:

Kerala's wetlands—comprising backwaters, lagoons, estuaries, and floodplains—form one of India's most productive inland fishery systems, supporting thousands of artisanal fishers who rely on traditional crafts such as dugout canoes, catamarans, and plank-built boats. These crafts, evolved through centuries of ecological adaptation, operate a variety of small-scale gears including gillnets, cast nets, seines, and traps that are finely tuned to the hydrological and ecological settings of the region. While these artisanal systems exemplify sustainable, low-impact fishing traditions, increasing fishing pressure, habitat degradation, and the use of non-selective or fine-meshed nets have led to juvenile overfishing and ecosystem disturbance. The sustainability of Kerala's wetland fisheries therefore depends on integrated management strategies that combine scientific gear regulation, spatial and seasonal closures, community-based co-management, and livelihood diversification. Such adaptive and participatory approaches are crucial to maintaining the ecological integrity, productivity, and socioeconomic resilience of Kerala's wetland-dependent fishing communities.

Keywords: Wetlands, Crafts, Gears, Artisanal Fisheries

1. Wetland Types of Kerala in Fisheries Context

The state of Kerala, situated along the southwestern coast of India, possesses one of the most intricate and ecologically diverse wetland systems in the country. These wetlands form a continuum of aquatic habitats encompassing backwaters, lagoons, estuaries, riverine floodplains, mangrove swamps, and marshes, each characterized by distinct hydrological and salinity regimes (Radhakrishnan *et al.*, 2021). The largest of these systems include the Vembanad–Kol, Ashtamudi, and Kayamkulam estuaries, which collectively represent over 40 % of Kerala's inland water spread area (Biju & Nair, 2020). Hydrologically, these wetlands are influenced by the southwest monsoon, tidal exchange with the Arabian Sea, and seasonal river inflows, resulting in a dynamic freshwater–brackish water gradient that supports diverse aquatic communities and high primary productivity (Rasheed *et al.*, 2019).

From a fisheries perspective, these wetlands function as critical nursery and feeding grounds for numerous finfish and shellfish species, including commercially important taxa such as *Etroplus suratensis* (pearlspot), *Lates calcarifer* (barramundi), *Mugil cephalus* (mullet), and various penaeid shrimps (Remesan, 2006). The shallow depth, abundant detritus, and macrophyte cover enhance nutrient recycling, supporting dense planktonic and benthic assemblages that underpin fishery productivity (Joseph *et al.*, 2018). Consequently, the wetlands sustain a vibrant artisanal fishery sector, providing livelihood security to thousands of traditional fishers and women engaged in postharvest processing.

However, the fisheries potential of these wetlands is not fully realized due to several interacting factors. Habitat modification through reclamation, pollution, and hydrological alterations has reduced effective spawning and nursery areas (Sreedevi *et al.*, 2022). Additionally, overfishing and inappropriate gear use—such as fine-meshed gillnets or drag nets in nursery zones—have led to recruitment overfishing and a decline in catch per unit effort (CPUE) (Nair & Pillai, 2017). Seasonal hydrological fluctuations caused by the monsoon cycle further influence fish availability, catch composition, and fishing effort, making the wetland fishery highly seasonal and environmentally driven (Biju & Nair, 2020).

Overall, Kerala's wetland ecosystems act as biological and socio-economic keystones, linking inland and coastal fisheries through the migration and life-cycle completion of multiple species. Understanding their ecological functioning and the context of artisanal fishing practices is therefore essential for sustainable management and conservation of these productive yet vulnerable systems.

2. Principal Craft Types Used in Kerala Wetlands

The fishing crafts employed in the wetlands of Kerala are highly specialized and have evolved through centuries of local innovation and ecological adaptation. The physical and hydrological characteristics of these wetlands—such as shallow depth, fluctuating salinity, dense vegetation, and narrow waterways—have driven the development of lightweight, maneuverable, and shallow-draft crafts that can efficiently operate in confined aquatic environments (Remesan, 2006; Thomas & Nandan, 2019). These crafts are predominantly artisanal and constructed using indigenous materials, reflecting a strong link between traditional ecological knowledge and local craftsmanship.

2.1 Dugout Canoes (Vallam / Vanchi)

Dugout canoes, locally called *vallam* or *vanchi*, represent the most widely used traditional fishing craft in Kerala's inland and backwater fisheries. They are typically formed from a single log of locally available hardwood species such as *Artocarpus hirsutus* (anjili) or *Ailanthus triphysa* (matti), chosen for buoyancy and durability (Pillai *et al.*, 2018). The hull design is

narrow and shallow, with a flat or slightly rounded bottom that facilitates navigation through weed-choked or silted canals and floodplains.

These canoes are commonly used for cast netting, gillnetting, line fishing, and the setting of small traps. Some modern variants are plank-built and reinforced with fiberglass for greater longevity. Their small size allows operation by one or two fishers, making them ideal for subsistence and short-distance fishing (Remesan, 2006).

2.2 Catamarans (Kattumaram)

The *kattumaram* or catamaran is a traditional log-raft craft constructed by lashing together two or more logs, typically using coir ropes. While more common in coastal fisheries, smaller versions are employed in estuarine and lagoonal sectors of wetlands such as Ashtamudi and Kayamkulam (Biju & Nair, 2020). The catamaran's buoyant structure and open frame make it particularly suited to wave-exposed or tidally influenced zones where stability is required. Fishers operating these crafts mainly deploy gillnets, encircling nets, and small seines, targeting mullets (*Mugil cephalus*), anchovies, and shrimps. The design is simple yet robust, requiring minimal maintenance, and its light weight facilitates easy beaching or hauling across sandbars (Radhakrishnan *et al.*, 2021).

2.3 Plank-Built and Masula Boats

Plank-built boats and *masula* boats represent an intermediate category between small canoes and large mechanized vessels. Traditionally built with wooden planks fastened by coir ropes and wooden pegs (without nails), these crafts exhibit a flexible hull structure that withstands wave action and allows repairability (Joseph *et al.*, 2018). In many wetland fisheries, especially around the Vembanad–Kol and Ashtamudi systems, these crafts are semi-mechanized with small outboard motors for extended trips or operations in deeper sections of the backwater.

They are used to operate boat seines (vala), larger gillnets, and drag nets for capturing schooling fishes and prawns. Their enhanced carrying capacity also makes them suitable for multi-day fishing and transport of gear and catch to landing centers (Sreedevi *et al.*, 2022).

2.4 Kettuvallam and Larger Mechanized Boats

The *kettuvallam*—traditionally a large, plank-built barge used for transport of rice, coconut, and fish—has historical significance in Kerala's inland navigation and fish trade (Rasheed *et al.*, 2019). Constructed by joining planks with coir ropes and sealing with natural resins, the *kettuvallam* could traverse the extensive backwater networks linking fishing villages and markets.

Although many of these crafts have been repurposed for tourism (houseboats) today, their traditional forms were once essential for carrying bulk catches and fishing equipment across the Vembanad–Kol and adjacent wetland systems. In some regions, mechanized versions equipped

with diesel or outboard engines are still used for largescale fishing operations and fish transport (Biju & Nair, 2020).

2.5 Design and Functional Adaptations

Across all categories, Kerala's wetland fishing crafts share several engineering adaptations that reflect ecological constraints. These include:

- Low freeboard and shallow draft, allowing access to narrow, shallow, and vegetated channels.
- High maneuverability, essential for setting and retrieving nets in confined or obstructed waters.
- Lightweight construction materials, facilitating manual launching, hauling, and repair.
- Minimal wave resistance and high stability, optimized for still or slow-moving backwater environments (Radhakrishnan *et al.*, 2021).

The evolution of these crafts thus represents a co-adaptation between human technology and wetland ecology, ensuring efficient fishing with minimal disturbance to fragile habitats. Despite modernization, these traditional designs continue to dominate inland fisheries, underscoring their resilience and functional sustainability in Kerala's wetland ecosystem

3. Common Fishing Gears and Their Functional Selectivity in Kerala Wetlands

Fishing gears employed in Kerala's wetland ecosystems reflect centuries of adaptation to shallow hydrological conditions, fluctuating salinity, and species-specific behavior. The selection and deployment of these gears are determined by depth, substrate type, target species, seasonality, and local hydrodynamics (Remesan, 2006; Thomas & Nandan, 2019). Since these are artisanal and small-scale fisheries, gears are generally simple, cost-effective, and manually operated, with limited mechanization. The most frequently used categories include gillnets, cast nets, seines, traps, and hook-and-line systems, each differing in mode of operation, selectivity, and ecological impact.

3.1 Gillnets (Bottom-Set, Drift, and Wall Nets)

Gillnets, locally known as *vala* or *vala kambi*, are among the most common and economically important gears in Kerala's wetlands. These are passive entangling nets designed to capture fish by their gill covers or body parts as they attempt to swim through the mesh. Depending on the habitat, fishers use bottom-set gillnets (resting on the substrate) or drift/wall gillnets (suspended in the water column).

Mesh size selection varies according to the target taxa—for example, larger meshes (60–80 mm) are used for *Etroplus suratensis* (pearlspot) and *Lates calcarifer* (barramundi), while finer meshes (25–40 mm) target small cyprinids and prawns (Kurup *et al.*, 2018).

While gillnets are highly size-selective, their ecological drawback arises from the use of undersized meshes, which result in juvenile bycatch and recruitment overfishing (Nair & Pillai, 2017). Moreover, continuous night-time operation can entangle nontarget fauna such as crabs and shrimps, impacting biodiversity in sensitive wetland zones (Sreedevi *et al.*, 2022).

3.2 Cast Nets (Chakri / Thattavala)

Cast nets, locally referred to as *chakri vala* or *thattavala*, are circular, hand-operated nets fitted with lead weights along the periphery. These are active, single-operator gears primarily used in shallow and nearshore habitats such as canals, paddy fields, and floodplain margins. The fisher throws the net to form a spreading circle that sinks rapidly, enclosing the fish, which are then collected by drawing a central line (Radhakrishnan *et al.*, 2021).

Cast nets are highly selective by area, allowing minimal bycatch and negligible habitat damage due to their short contact with the substrate. They are ideal for capturing surface and mid-water species such as *Ambassis* spp., small *Mugil* spp., and shrimps in calm backwaters (Biju & Nair, 2020). Although effective, their operational range and catch volume are limited by manual strength and area of deployment.

3.3 Seines and Boat-Seines

Seine nets (*vala* or *thangu vala*) are long, encircling nets that capture schooling fishes by surrounding and then hauling them towards a confined area. Beach seines are operated manually along shallow shores, while boat seines are deployed from larger crafts in deeper wetland stretches such as Vembanad and Ashtamudi (Remesan, 2006). These gears are highly efficient for capturing pelagic and semi-pelagic species such as sardines, mullets, and anchovies. However, unregulated seine operations can be ecologically damaging, especially when operated in macrophyte-rich or breeding zones, where they can uproot vegetation and disturb benthic habitats (Joseph *et al.*, 2018).

Their selectivity depends largely on mesh configuration and hauling speed—slower hauling reduces juvenile mortality, while regulated mesh size improves sustainability.

3.4 Traps, Fyke Nets, and Bag Nets

Passive entrapment gears such as bamboo traps, fyke nets, and bag nets are extensively used in the inlet and outlet channels of wetlands, especially during tidal exchange or migratory periods. These gears exploit the directional movement of fish and crustaceans, guiding them into enclosed chambers through funnel-shaped entrances (Rasheed *et al.*, 2019).

Trap designs vary regionally: for example, cylindrical bamboo traps (*ottal vala*) are common in Kole wetlands, while stake nets (*koodu vala*) and bag nets (*paya vala*) are used in estuarine regions.

Trap selectivity depends primarily on entrance diameter, mesh size, and bait use. They are generally non-destructive and energy-efficient, making them ecologically sustainable if placed outside nursery areas (Thomas & Nandan, 2019).

Bag nets, which are anchored in tidal currents, are particularly efficient for harvesting juvenile prawns and crabs migrating between mangroves and open waters (Sreedevi *et al.*, 2022).

3.5 Hook-and-Line and Small Trawls

The hook-and-line method represents one of the most traditional and species-specific fishing techniques in Kerala's backwaters. Simple handlines are used from canoes to capture carnivorous species such as *Lates calcarifer*, *Mystus gulio*, and catfishes (Biju & Nair, 2020). The selectivity of this gear is high, governed by hook size, bait type, and depth of operation, resulting in minimal bycatch.

Conversely, mini trawl nets—though limited in scale—are occasionally used in the marginal zones of lagoons to capture benthic shrimps and small fishes. These, however, raise environmental concerns due to sediment disturbance and non-selective capture, and are discouraged in sensitive wetland areas (Radhakrishnan *et al.*, 2021).

3.6 Seasonal and Ecological Gear Choice

The deployment of fishing gears in Kerala's wetlands is strongly seasonal. Gillnet operations peak during post-monsoon and pre-summer months, coinciding with fish migration from estuaries into freshwater reaches, whereas cast-netting remains a yearround subsistence activity. Trap and bag net fisheries are more active during tidal influx periods, when juvenile prawns and crabs migrate through connecting channels (Kurup *et al.*, 2018). Thus, gear selection mirrors both hydrological cycles and species availability, emphasizing the dynamic interplay between human activity and wetland ecology.

4. Ecological and Socio-Economic Implications of Fishing Crafts and Gears in Kerala Wetlands

The structure and functioning of Kerala's wetland ecosystems are closely intertwined with artisanal fishing practices. While traditional crafts and gears have sustained local livelihoods for centuries, the increasing fishing pressure, modernization, and altered hydrological regimes have begun to influence both ecological stability and socioeconomic balance (Kurup *et al.*, 2018; Sreedevi *et al.*, 2022). The ecological implications primarily relate to gear selectivity, juvenile mortality, and habitat degradation, whereas socio-economic effects involve livelihood dependency, technological transitions, and equity in resource access.

4.1 Selectivity and Juvenile Catch

One of the most critical ecological challenges in Kerala's wetland fisheries arises from the use of non-selective and fine-meshed gears, particularly small-mesh gillnets and drag nets. These

gears indiscriminately capture juvenile and sub-adult stages of commercially valuable fishes such as *Etroplus suratensis*, *Mystus gulio*, and *Lates calcarifer*, leading to recruitment overfishing (Nair & Pillai, 2017).

Scientific assessments in the Vembanad–Kol and Ashtamudi wetlands have shown that catches often contain 40–60% immature individuals, reflecting the absence of mesh size regulation (Biju & Nair, 2020). Similarly, the placement of bamboo traps and bag nets in migratory channels during breeding seasons intercepts larval and juvenile prawns and fishes moving between nursery and feeding habitats (Thomas & Nandan, 2019).

Implementing mesh size standardization, temporal fishing bans, and spatial closures in nursery zones has been shown to significantly improve stock recruitment and longterm yield (Kurup *et al.*, 2018). Therefore, managing the selectivity of fishing gears is fundamental to achieving ecologically sustainable harvests in these sensitive wetland systems.

4.2 Habitat Impacts and Ecosystem Disturbance

Beyond direct exploitation, certain fishing operations cause physical disturbance to wetland habitats. The repeated use of drag or seine nets in vegetated shallows uproots submerged macrophytes, disturbs benthic sediments, and disrupts periphytic communities vital for nutrient cycling and larval shelter (Joseph *et al.*, 2018). Moreover, the increasing use of motorized crafts in confined waterways leads to wave-induced erosion, turbidity increase, and damage to marginal vegetation such as *Nymphaea*, *Typha*, and mangroves that function as breeding habitats (Rasheed *et al.*, 2019). The decline of macrophyte beds and benthic fauna directly reduces food availability for detritivorous and benthic-feeding fishes, altering community structure and decreasing overall productivity (Radhakrishnan *et al.*, 2021).

Mitigating these impacts requires spatial zoning of fishing areas, avoidance of heavy gear use in macrophyte-rich zones, and promotion of low-impact, non-motorized crafts in ecologically fragile stretches (Sreedevi *et al.*, 2022).

4.3 Livelihoods, Technoloical Transition, and Equity

Fishing in Kerala’s wetlands represents not only an ecological activity but also a critical socio-economic pillar supporting thousands of artisanal fishers, many belonging to traditional fishing communities. These fishers depend on low-cost, manually operated crafts and gears, which are accessible and adapted to local conditions (Remesan, 2006).

However, recent decades have witnessed a technological transition characterized by partial mechanization, fiberglass reinforcement of boats, and adoption of synthetic net materials. While these innovations have improved catch efficiency and durability, they have also exacerbated disparities between small-scale traditional fishers and larger mechanized operators (Radhakrishnan *et al.*, 2021).

Increased operational costs, declining fish stocks, and limited alternative employment have led to economic vulnerability and livelihood insecurity among artisanal communities (Biju & Nair, 2020). To ensure equitable and sustainable resource use, co-management models emphasizing community participation, regulated access, and income diversification (e.g., aquaculture and eco-tourism) are increasingly being recommended (Sreedevi *et al.*, 2022).

4.4 Integrated Ecological–Socioeconomic Perspective

The ecological and socio-economic dimensions of wetland fisheries are mutually reinforcing. Unsustainable gear practices not only degrade habitats but also reduce long-term catches, directly affecting household income and food security. Conversely, economic stress can drive overexploitation as fishers seek immediate returns.

Sustainable management, therefore, demands an integrated approach—combining scientific regulation (mesh size limits, spatial closures, seasonal bans) with community-driven governance and livelihood support mechanisms. Such adaptive management strategies have been shown to enhance both ecological resilience and socio-economic well-being in Kerala’s wetland landscapes (Kurup *et al.*, 2018; Sreedevi *et al.*, 2022).

5. Management Lessons and Recommendations for Sustainable Wetland Fisheries in Kerala

The management of wetland fisheries in Kerala requires an integrated framework that balances ecological sustainability with socio-economic welfare. Scientific studies across the Vembanad–Kol, Ashtamudi, and Ponnani Kole wetlands have demonstrated that unsustainable fishing intensity, habitat degradation, and lack of coordinated governance are major constraints to the long-term viability of these systems (Kurup *et al.*, 2018; Sreedevi *et al.*, 2022). Therefore, adaptive and participatory management strategies are essential to maintain productivity, biodiversity, and livelihood security.

5.1 Gear Regulations Tuned to Wetland Ecology

Effective management begins with gear-based regulations that align with the ecological characteristics of wetlands. The introduction of minimum legal mesh sizes for gillnets, seines, and traps is critical to prevent the capture of juvenile fishes and ensure adequate recruitment (Nair & Pillai, 2017). Studies have shown that implementing a 40–50 mm minimum mesh size for gillnets in backwaters significantly reduces juvenile bycatch without affecting total catch volume (Biju & Nair, 2020).

Equally important is the prohibition of destructive seine operations and small-scale trawling in shallow or vegetated habitats. Such activities disturb benthic sediments and uproot macrophytes, which serve as spawning and nursery grounds (Rasheed *et al.*, 2019). Seasonal monitoring should ensure that seine operations are limited to deeper, less sensitive zones of the wetland.

Establishing gear-specific spatial and temporal restrictions thus allows a balance between utilization and conservation of key habitats.

5.2 Spatial Zoning and Seasonal Closures

Spatial and temporal management tools provide a biologically sound mechanism to safeguard breeding populations and habitat integrity. The delineation of no-fishing zones around mangrove fringes, reedbeds, floodplain channels, and spawning shoals during critical breeding periods enhances recruitment success (Thomas & Nandan, 2019). For instance, protecting the Vembanad–Kol wetland’s reedbed margins during May–July, which coincide with the breeding period of *Etroplus suratensis* and *Mystus gulio*, has shown measurable increases in post-monsoon catch per unit effort (CPUE) (Joseph *et al.*, 2018).

Similarly, seasonal closures aligned with hydrological and migratory cycles (e.g., monsoon flooding) enable the regeneration of fish stocks and benthic communities (Sreedevi *et al.*, 2022). Integrating these closures within a legal and community-supported framework ensures both compliance and ecological recovery

5.3 Co-management and Fisher Participation

Kerala’s wetlands are characterized by a high degree of community dependence and fragmented institutional oversight. Evidence from pilot co-management initiatives in the Vembanad and Ashtamudi wetlands suggests that fisher-led governance significantly improves rule compliance, monitoring efficiency, and conflict resolution (Radhakrishnan *et al.*, 2021).

Establishing local gear committees and fisher cooperatives allows for participatory decision-making regarding mesh size enforcement, fishing schedules, and spatial zoning. The integration of traditional ecological knowledge (TEK) with scientific data has proven effective in identifying breeding grounds and predicting seasonal migrations (Kurup *et al.*, 2018). Moreover, community-based monitoring of catch and effort data, supported by local universities and fisheries departments, enhances transparency and adaptive management capacity (Sreedevi *et al.*, 2022). By fostering ownership and shared responsibility, co-management strengthens both ecological outcomes and social equity among resource users

5.4 Gear Innovation and Capacity Building

Technological improvements in fishing gear and craft design offer opportunities to enhance selectivity and sustainability. Introducing escape panels in gillnets and traps, modified funnel entrances, and raised footropes in seines can minimize bycatch of juveniles and non-target species (Biju & Nair, 2020). Lightweight and low-impact boat designs—including fiber-reinforced shallow-draft models—reduce habitat disturbance and fuel consumption.

Capacity building programs focusing on sustainable fishing methods, post-harvest processing, and market linkages empower local fishers to improve income without increasing fishing

pressure. Promoting livelihood diversification through community aquaculture, fish seed rearing, ornamental fish farming, and value addition reduces dependence on capture fisheries (Radhakrishnan *et al.*, 2021). Such integrated livelihood strategies are vital to strengthen economic resilience in the face of declining wild stocks and climate-driven variability in wetland hydrology.

5.5 Policy Integration and Long-Term Sustainability

For durable impact, management interventions must be integrated within state and national wetland policies. Kerala's Inland Fisheries Policy (2018) emphasizes ecosystem-based management, yet its implementation remains fragmented. Coordinated action between the Department of Fisheries, local panchayats, and research institutions is essential to harmonize ecological, economic, and social objectives (Sreedevi *et al.*, 2022). Long-term sustainability also depends on periodic stock assessments, habitat restoration (mangroves, macrophytes, floodplains), and climate adaptation planning. Restoring ecological connectivity between rivers and wetlands through sluice regulation and pollution control can rejuvenate migratory fish populations and wetland productivity (Thomas & Nandan, 2019). A science-based, participatory governance framework—combining regulation, education, and innovation—thus represents the most effective pathway for ensuring the ecological integrity and livelihood sustainability of Kerala's wetland fisheries.

Conclusion:

Kerala's wetland fisheries are sustained by a diverse assemblage of small, shallowdraft crafts—including dugout and plank-built canoes, catamarans, and limited mechanized boats—designed to navigate the narrow, vegetation-rich channels of the state's inland and estuarine systems. These traditional crafts support an array of artisanal gears such as gillnets, cast nets, seines, and traps that are finely tuned to the hydrological and ecological settings of backwaters. However, unsustainable fishing practices, particularly the use of undersized mesh nets, non-selective seines, and excessive fishing effort in nursery and breeding habitats, can disrupt recruitment processes and degrade ecosystem integrity.

Empirical research across the Vembanad–Kol, Ashtamudi, and Ponnani Kole wetlands highlights that the sustainability of these fisheries depends on ecologically informed management. The integration of science-based gear regulations, spatial zoning, seasonal fishing closures, and fisher-community co-management frameworks offers the most effective pathway to balance productivity, biodiversity conservation, and livelihood security. Such adaptive, participatory strategies are essential for ensuring the long-term resilience and ecological functionality of Kerala's wetland fisheries.

References:

1. Biju, A., & Nair, N. B. (2020). Hydrological dynamics and fisheries of the Vembanad–Kol Wetland System, Kerala, India. *Journal of Inland Fisheries Society of India*, 52(1), 45–56.
2. Joseph, S., Rasheed, K., & Sathianandan, T. V. (2018). Nutrient enrichment and biological productivity of Kerala backwaters. *Indian Journal of Fisheries*, 65(3), 12–20.
3. Kurup, B. M., Nandan, S. B., & Sreedevi, P. R. (2018). Fishing gear diversity and resource sustainability in Kerala's inland waters. *Fisheries Technology*, 55(2), 67–78.
4. Nair, S. M., & Pillai, V. N. (2017). Seasonal variation and catch dynamics of artisanal fisheries in Kerala wetlands. *Environmental Biology of Fishes*, 100(9), 1071–1085.
5. Pillai, V. N., Nair, S. M., & Kurup, B. M. (2018). Traditional fishing crafts and technology in Kerala wetlands. *Indian Journal of Traditional Knowledge*, 17(2), 326–333.
6. Radhakrishnan, C. K., Thomas, J., & Remesan, M. P. (2021). Wetland biodiversity and ecosystem services in Kerala: A review. *Indian Journal of Ecology*, 48(4), 1102–1113.
7. Rasheed, K., Biju, A., & Joseph, S. (2019). Hydro-ecological gradients and species assemblages in estuarine wetlands of southwest India. *Aquatic Ecology*, 53(2), 201–214.
8. Remesan, M. P. (2006). *Studies on inland fishing gears of North Kerala*. Central Marine Fisheries Research Institute (CMFRI), Kochi.
9. Sreedevi, P. R., Kurup, B. M., & Nandan, S. B. (2022). Impacts of land use and hydrological modification on wetland fisheries of Kerala. *Wetlands Ecology and Management*, 30(2), 183–197.
10. Thomas, J., & Nandan, S. B. (2019). Adaptive evolution of artisanal fishing crafts and gears in Kerala backwaters. *Indian Journal of Fisheries*, 66(2), 90–99.

PREDATORY AQUATIC INSECT BACKSWIMMER *NOTONECTA* (HEMIPTERA, NOTONECTIDAE) SPECIES AND THEIR CONTROL MEASURES: A REVIEW

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Abstract:

Generally, the Indian Major Carps spawn has a relatively poor survival rate during the nursery phase. The abundance of aquatic predatory insects seems to be the most significant factor which heavily feeds on carp spawn. It has been observed that most surface-breathing insects have been found to be controlled by using soap oil emulsion, while certain subsurface breathers (such as gill breathers) are said to be immune to this treatment because of their unique breathing habits. Higher productivity from fish nurseries and agricultural areas can be attributed due to the revolution in insect control brought about by the discovery of synthetic insecticide. These insecticides exhibited an exceptionally high toxicity to a variety of insects. These pyrethroids are biodegradable in nature and have exceptionally high insecticidal activity at very low concentrations. These are highly successful in controlling against eggs, larvae, and adult stages of insects. This review summarized the predatory effects of *Notonecta* spp. and its control using synthetic pyrethroid cypermethrin.

Keywords: Pyrethroids, Toxicity, Indian Major Carps, *Notonecta* spp.

1. Introduction:

About 4% of insects are aquatic, based on the total world's insect fauna. Any aquatic region is explored by a greater number of insects, either as adults or larvae stages. These insects have undergone significant morphological modification so that they can adapt to an aquatic environment. From an academic perspective, insects and their larvae are fascinating due to their diverse range of adaptations and many aquatic insects attack and kill carp spawn. Furthermore, from the perspective of public health, the biopotency of aquatic insect predators against *Anophelini* and *Culicini* larvae have been reported (Ellis & Borden, 1970; Nelson, 1977). Thus, the management and elimination of harmful aquatic insects is a part of pond culture techniques, particularly in nursery ponds (Rath, 2018). The removal of harmful insects from ponds is important for raising the fry survival rate. Julka (1965) have depicted the destructive role of aquatic insects in fish nurseries. According to Menke & Stange, (1964), understanding of

predatory capacity of aquatic insects is essential for managing hatcheries effectively and controlling the pests and vectors in their early larval phases. Zalom and Grigaric (1980) reported increased rate of predation with increasing density of prey. Predators consume more food when prey densities increase because of higher availability of food. The rate of reproduction of predators increases along with their population size (Soloman, 1949). A significant amount of the nation's agricultural and aquacultural resources is wasted due to insect infestations. Predatory aquatic insects have huge impact on the development and survival of fish larvae. The majority of aquatic insects, whether in their larval or adult stages, feed on fish hatchlings or fry and compete with them for food due to their diverse feeding habits. The bugs and beetles as the two most prevalent predatory insects (Sigutova *et al.*, 2022). *Cybister*, *Gyrinus*, and *Sternolephnus* are beetles that significantly harm young fishes. The aquatic bugs are extremely predatory and have the ability to harm fingerlings. These predatory insects have a high destructive role in fish nurseries (Tripathi & Sharaf, 1975). Water scorpions of the genus *Laccotrephes* and insects of the genus *Ranatra* are also quite predatory on fish fry. Backswimmers (Notonectidae), of which the *Anisops* is a classic example, cause the most depredations (Weterings *et al.*, 2014). Notonectids show predation on carp spawn and fry with the help of their piercing mouth parts and extract the body fluids from fish. They found in a diverse range of freshwater environments (Berchi *et al.*, 2023). These predators are rather large and actively swim. The order Hemiptera includes the family Notonectidae within the section Hydrocorisae. This family of insects is sometimes known as greater water boatmen or backswimmers. Backswimmers is the popular term for notonectids, because they swim by pushing their belly up through the water. It is rare for notonectids to cause wounds to people through their proboscis, or mouthparts. These insects are referred to as bugs which are little to medium-sized with piercing and sucking mouthparts. The more common term "Water boatmen" comes from the posterior legs ability to swim, which are equipped with hairs that give them an overall form similar to an oar. The *Notonecta* spp. lay eggs in the autumn or spring (depending on the species) and they reproduce only once a year (Briers, 1999). The adults are brown or dull grey in color, about 14-17 mm in length (Reynaldi *et al.*, 2011). The common backswimmer favors hiding places with dense vegetation. The common backswimmer is found along the plant's edge in aquatic habitats, this preference is unaffected by the choice of prey (Giller & McNeill, 1981). A diverse environment is ideal for the common backswimmer. Different aquatic species, such as *Daphnia* spp. (water fleas), are preyed upon by the common backswimmer (Leon, 1998). While fish eggs, fry, and tadpoles also have been reported as prey for *Notonecta* spp. (Gonzalez & Leal, 1995). *Notonecta* spp. most frequently feed on other terrestrial insect species. It has been observed that *Notonecta glauca* feeds on the larvae of the *Culex pipens* mosquito (Reynaldi *et al.*, 2011). Adults and immatures of *Notonecta*

glauca breathe by inhaling air instead of using dissolved oxygen from the water. They have hair-like coverings called setae and microtrichia covering their bodies to help them in their aquatic lives. These hairs cover the whole body of a backswimmer, with the exception of the pronotum (region behind the head), head, and legs. These hairs form an air tight film that retains air, enabling the insects to take in oxygen while submerged and maintain a dry body. Air can be retained in the film for as long as 130 days because of the thickness of the microtrichia. When viewed with the naked eye, this air film visible as a silvery sheen on the body (Ditsche-Kuru *et al.*, 2011). As compared to other *Notonecta* species, *N. glauca* extract food more slowly and responds less to surface activity. The *Notonecta* spp. are found below the water surface rather than at the surface. *N. glauca* remains submerged when the air temperature is below 15°C (59°F). These species spend more time on the water surface above 15°C (59°F). They prefer to remain fully immersed at 5°C (41°F). The common backswimmer prefers to remain underwater at higher temperatures (Cockrell, 1984).

2. Distribution of Aquatic Insects:

The backswimmers (boat flies, wherryman; 10 genera, ca. 300 species) are found in temperate and tropical climates across the world. The most extensively distributed species of the genus *Notonecta* are found in the Palearctic, Nearctic, Neotropical, Afrotropical, and Oriental regions. The species of the genera *Martarega* and *Buenoa* are found in the Western Hemisphere, while species of the genera *Enithares*, *Nychia*, and *Anisops* are found in the Eastern Hemisphere. Other genera' species are found in smaller geographic areas (e.g., *Paranisops*, *Walambianisops* - Australia; *Aphelonecta*-Oriental; *Enitharoides*-Neotropical regions) (Papacek, 2013).

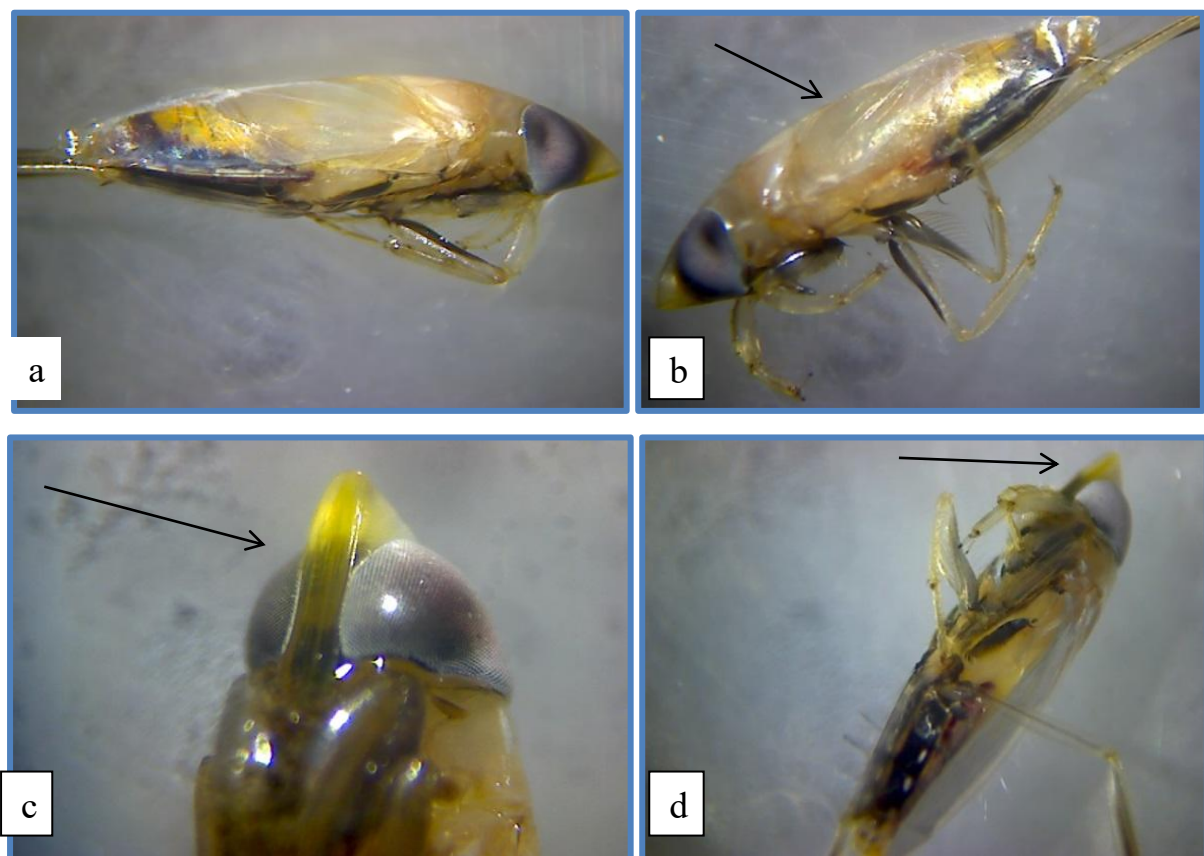
3. Development of *Notonecta* insects:

Aquatic insects are frequently used to evaluate the health of an ecosystem and are a vital part of any healthy natural aquatic environment (Pondinformer, 2019). The quantity of aquatic insects is increased due to the presence of aquatic weeds and too much excess of organic materials (Roysfarm, 2019). Managing a nursery pond involves heavily fertilization with organic manures prior to spawn discharge, which could lead to the development of predatory insects. Aquatic predators provide an equal threat. In tropical climates, the abundance of these insects over a significant portion of the year, especially during and after the rains, is a major issue.

4. Predatory efficiency of *Notonecta* species:

A predator's capacity to capture, manage, and devour its prey is largely determined by how big the prey is in comparison to the predator. The ratio of prey size to backswimmer size is probably that regulate this feeding choice. It is known that backswimmers engage in size-selective predation, whereby they eat a higher proportion of members of largest size class of zooplankton within a species (Gergs & Ratte, 2009). Backswimmers most preferably eat larger prey in order

to overcome challenges in their way when they are trying to catch and manage smaller prey. The "sit and wait" predators known as backswimmers remain in the water column, waiting for prey to approach closely (Martin & Lopez, 2004). Specialized eyes like binoculars help backswimmers to locate and apprehend prey (Land, 1980). Backswimmers possess strong mesothoracic and prothoracic legs that help them catch and restrain live prey, as well as the ability to accelerate rapidly (Gittelman, 1977). These are external feeders that puncture their victim with their beaks to inject paralyzing fluid into it before removing its body fluids (Griffith & Gillett- Kauffman, 2021). Predatory efficiency of aquatic insects is dependent on several factors, including: prey density in the habitat, size and physiological state of prey, prey mobility, prey predator behavioral adaptation in the same habitat and the absence of predator detection mechanisms in prey species. Insects can detect its prey by a variety of mechanisms, such as chemical, tactile, or optical cues, as well as chemically mediated avoidance, a strategy utilized by prey to identify and escape away from its predators. These compounds are semiochemicals that predators release into the environment. Prey often uses these chemicals to identify the presence of predators so that they can reduce their interactions (Kats & Dill, 1998).



**Figure 1: (a) Adult *Notonecta* sp. (b) Scutellum of *Notonecta*,
(c) Vertex of *Notonecta*, (d) Antenna of *Notonecta***

5. Predation of *Notonecta* spp. on Fish:

Backswimmers mostly consume spawn and fry stages of fish and tadpoles that are commercially valuable. Specifically, aquatic insects such as Notonectids and *Cybister* larvae, which are frequently found in fish nurseries, have been identified as predators of spawn and fry of many culturable fish species. The presence of these insects poses a serious threat to fish nurseries in India, where large-scale spawn to fry rearing of Indian major carps, including *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala* occurs (Fernando & Leong, 1976; Julka, 1965).

Chahar & Dahiya (2022) demonstrated that the mean predatory efficiency of *Notonecta* spp. on spawn and fry of Catla, Rohu and Mrigal measured during the experimental period, showed highest predation rate of *Notonecta* (3.72 N/hr) on Mrigal spawn at lowest spawn density, followed by Rohu spawn (2.19 N/hr) and lowest predation rate (1.38 N/hr) was reported on Catla spawn at lowest spawn density. The reduction in percent survivability of fish was reported with the increase in predatory efficiency of *Notonecta*.

Clark (1928) observed that *Notonecta undulata* is a predator of many small fish species in pond cultures, as well as of fish larvae from different species that inhabit still freshwater environments. According to Berezina (1955, 1962), a large population of *Notonecta glauca* in ponds covering an area of roughly 0.01 ha can kill between 2,500 and 3,500 fish larvae per day. Dahm (1972) reported that one adult *N. glauca* killed approximately 2.6 fish larvae per day. Shirgur & Kewalramani (1972) reported that *Notonecta glauca*, *Acilius sulcatus*, *Macrodytes marginalis*, *Anax imperator*, and *Aeshna uncea* destroyed 15 (10.7 mm), 17 (8-17 mm), 14 (21-25 mm), and 51 (10.4 mm) fry, respectively. Dye & Jones (1975) and Hirvonen (1992) reported that small young crayfish are attacked and consumed by backswimmers. Even younger crayfish that are killed by notonectids or adopt cheliped autotomy to evade predators, experience a decrease in their individual growth as a result of this phenomenon. Yurembam *et al.* (2016) stated that fish, especially in their larval phases such as spawn, fry, and fingerlings, have been reported to be harmed by aquatic predatory insects (*Notonecta*, *Ranatra*, *Cybister*, *Lethocerus*, *Nepa*, *Hydrometra* and *Belostoma*) found in various type of fish ponds, including nursery and stocking areas. In a study conducted by Gorai & Chaudhari (1962) revealed that the fifth instar of *Anisops bouvieri* (Notonectid) is a common predator of fish larvae in India. The fifth instar of *Anisops bouvieri* has the capability to destroy fish spawn.

Singh *et al.* (2017) revealed the predatory behavior of *Notonecta* spp. in fish ponds. It was reported that the predatory bugs feed on various small animals including crustaceans, tadpoles, fish hatchlings, insects and their larvae. Sano *et al.* (2011) revealed that within a 24-hour period, one *Anisops bouvieri* (Notonectidae) preyed on an average of 2.8, 5.5, and 4.8 Silver barb, Indian

carp, and Common carp larval fish respectively. Kashyap *et al.* (2013) stated that the highly predacious backswimmers are capable of destroying 10-13 mm fry of carps. Gonzalez and Leal (1995) reported that *Notonecta* spp. had higher predation rate on spawn and fry of fish, tadpoles and also showed predation on other insects

6. Control of *Notonecta* sp:

The majority of aquatic insects are extremely susceptible to many different kinds of chemicals, including pyrethroid pesticides (Siegfried, 1993), also called as neurotoxic pesticides and commonly used to suppress adult mosquito populations and majority of agricultural pests. However, mammals and insects have different susceptibility to pyrethroids (Brito *et al.*, 2019). The severe toxicity of pyrethroids to aquatic life, especially fish and insects, has limited their broader application in agriculture and raised issues about the approval of new pyrethroids by the U.S. Environmental Protection Agency's (EPA). Backswimmers are subjected to insecticides because they consume fish eggs and tadpoles that are valuable commercial target. Priyadarshi *et al.* (2022) reported that at the lowest concentration of cypermethrin ($3\mu\text{g L}^{-1}$), No survivability of *Notonecta* spp. was reported within 24 hours. The LC_{50} of cypermethrin at 24 hours for *Notonecta* spp. was found in between $1\mu\text{g L}^{-1}$ to $5\mu\text{g L}^{-1}$. In a study conducted by Rahman & Islam, (2019) revealed that at the lowest dose of cypermethrin ($5\mu\text{g L}^{-1}$), the decline in predatory insect population was reported from 89.87% to 86.24 % within 24 hr.

In a study conducted by Gutierrez *et al.* (2017), it was reported that deltamethrin sensitivity varied across two phylogenetically related backswimmer species, *B. tarsalis* and *M. bentoi*, and these variations among backswimmers also affected the individual swimming behaviors of the species. Adult *Buenoa tarsalis* and *Martarega bentoi* were subjected to concentrations of deltamethrin ranging from 0.5 to 5×10^3 ng /L. The insecticide concentrations examined in this experiment had a major impact on the survival (time-mortality response) of both *B. tarsalis* and *M. bentoi*. When adult *B. tarsalis* exposed to the lowest concentration of insecticide (0.5 ng/L), the survival rate was almost 70%. In treatments containing concentrations of 2.5 and 5 ng/L, *B. tarsalis* survival rates were roughly 50% and 40%, respectively. Adult *B. tarsalis* showed 100% mortality when exposed to concentrations of deltamethrin greater than 50 ng /L during exposure periods shorter than 48 hours. In case of *M. bentoi*, the lowest concentration (5ng/L) examined for this species did not affect survivorship. The survival of *M. bentoi* reduced to about 30% when exposed to 50 ng/L. Survivability by the end of the bioassays approached zero at concentrations of 500 ng/L and above. When *B. tarsalis* and *M. bentoi* were subjected to increasing doses of deltamethrin compared to lower concentrations, the median survival times was found decreasing.

Perschbacher & Sarkar, (1989) demonstrated the application of Dipterex (trichlorfon) and three organophosphorus insecticides Phyphanon (malathion), Sumithion (fenitrothion), and DDVP for the control of aquatic insect *Notonecta* spp. Backswimmer mortality at the four chemical test levels using the 24-hour LC₁₀₀ levels were calculated for a 0.1-ha pond with an average depth of 1 meter. The test organism, *Notonecta* spp. had 24-hour LC₁₀₀ ranging from 0.05 ppm Sumithion to 1.0 ppm Dipterex. At the lowest concentration of 0.05 ppm, Sumithion insecticide was more effective and Dipterex insecticide was effective at the highest concentration of 1.0 ppm to control aquatic insects.

Shirgur & Kewalramani (1967) performed an experiment using soap- oil emulsion for control of *Notonecta* spp. A soap-oil emulsion was formed by mixing different oils with cheap washing soda, which made it easier to distribute the oil as a thin layer across the surface of the water. Under testing environments, a minimum dose @12 lb. per acre of mustard or linseed oil resulted in mortality of Notonectids in around 55 to 56 minutes while a minimum of 50 pounds per acre may be regarded a sufficient dosage under natural conditions.

Chahar & Dahiya (2025) demonstrated that the survivability rate of *Notonecta* spp. decreased with the increase in cypermethrin concentration and exposure time. The synthetic pyrethroid cypermethrin concentration of 6.4 µl/l and 7.4 µl/l resulted in 100% mortality of *Notonecta* spp. by the end of 10th and 2nd hr respectively.

Biswas *et al.* (2018) conducted an experiment using diesel (36%), kerosene and oil (36%), and Dipterex (28%) for the control of backswimmers. The inadequate levels of predator control resulted in low, average fingerling output of thirty percent of supplied fry. Walker *et al.* (1964) proposed that the effectiveness of harmful chemicals on fish and other freshwater creatures may depend on the water's quality, particularly its pH, alkalinity, and hardness. It is known that the pH of the water can influence the application of certain pesticides on its own. Learner and Edwards (1963) reported that the same species of *Nais* are more susceptible to copper sulfate at pH 7 in soft water than in hard water at 1.0 ppm. According to Berger *et al.* (1969), treating soft water with antimycin (a piscicide) during a dry break would increase its efficacy. This would enable a significantly longer exposure period before the antimycin starts to degrade due to the quick daily pH rise. According to Henderson *et al.* (1960), fish toxicity is not significantly impacted by hardness, alkalinity, or pH.

Conclusion:

To eradicate aquatic insects without destroying fish food organisms, a specific insecticide must be used. A very effective method for controlling predatory aquatic insect pests within a few hours of application was created by CICFRI (India) and involves mixing mustard oil with

inexpensive washing soap at a ratio of 56:18 kg/ha. The majority of gill breathers are unaffected by this treatment, but the entire surface breather is killed. Eradication of insects is a key component of effective nursery pond management techniques. Therefore, Synthetic pyrethroids such as cypermethrin can be regarded as most effective for the control of all types of predatory aquatic insects.

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References:

1. Berchi, G. M., Copilaş-Ciocianu, D., Kment, P., & Mumladze, L. (2023). Water bugs (Heteroptera: Gerromorpha, Nepomorpha) of the Caucasus ecoregion. *The European Zoological Journal*, 90 (1), 167-192.
2. Berezina, N. A. (1955). On the feeding of some waterbugs-competitors and pest of fish fry. *Trudy Mosk. Technol. Inst. Rybn. Promyshl*, 7, 142-148.
3. Berezina, N. A. (1962). Control of predatory aquatic insects. *Rybovod. Rybolov*, 5, 25-26.
4. Berger, B.L., Lennon, R.E. and Hogan, J.W. 1969. Laboratory studies on Antimycin as a fish toxicant. Invest. Fish Control 26, 1-19. U.S. Dept. of the interior, Fish and Wild life service. Bureau of Sports Fisheries and Wild life, Washington D.C.
5. Biswas, C., Hossain, M. M. M., Sarker, B., Billah, M. M., & Ali, M. A. (2018). Culture strategies, diseases and their mitigations in mono-sex *Nile tilapia* farming in Jessore sadar region, Bangladesh. *Asian-Australasian Journal of Bioscience and Biotechnology*, 3(3), 190-200.
6. Briers, R. A. (1999). *Metapopulation ecology of Notonecta in small ponds* (Doctoral dissertation, University of Sheffield), 1-205, pp.
7. Brito, L. G., Barbieri, F. S., Rocha, R. B., Santos, A. P. L., Silva, R. R., Ribeiro, E. S., & Oliveira, M. C. S. (2019). Pyrethroid and organophosphate pesticide resistance in field populations of horn fly in Brazil. *Medical and veterinary entomology*, 33(1), 121-130.
8. Chahar, B., & Dahiya, T. (2025). Evaluation of Selective Insecticide Cypermethrin (10% EC) against *Notonecta* spp. and its Impact on Percent Survival Rate of Indian Major Carps. *Uttar Pradesh Journal of Zoology*, 46(18), 286-299.
9. Chahar, B., & Dahiya, T. (2022). Predatory Efficiency of *Notonecta* Spp. And Percent Survivability of Spawn and Fry of Indian Major Carps. *Journal of Advanced Zoology*, 43(1), 1579-1587.

10. Clark, L. B. (1928). Seasonal distribution and life history of *Notonecta undulata* in the Winnipeg region, Canada. *Ecology*, 9(4), 383-403.
11. Cockrell, B. J. (1984). Effects of temperature and oxygenation on predator-prey overlap and prey choice of *Notonecta glauca*. *The Journal of Animal Ecology*, 17(6), 519-532.
12. Dahm, E. (1972). On the biology of *Notonecta glauca* (Insecta, Hemiptera) with special reference to its damage to fisheries. *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, 57(3), 429-461.
13. Ditsche-Kuru, P., Schneider, E. S., Melskotte, J. E., Brede, M., Leder, A., & Barthlott, W. (2011). Superhydrophobic surfaces of the water bug *Notonecta glauca*: a model for friction reduction and air retention. *Beilstein journal of nanotechnology*, 2(1), 137-144.
14. Dye, L., & Jones, P. (1975). The influence of density and invertebrate predation on the survival of young-of-the-year *Orconectes virilis*. *Freshwater Crayfish*, 2(4), 529-538.
15. Ellis, R. A., & Borden, J. H. (1970). Predation by *Notonecta undulata* (Heteroptera: Notonectidae) on larvae of the yellow-fever mosquito. *Annals of the Entomological Society of America*, 63(4), 963-973.
16. Fernando, C. H., & Leong, C. Y. (1976). taxonomic study of the Malayan Notonectidae (Hemiptera: Heteroptera). *Indian Journal of Zoology*, 12(2), 88-92.
17. Gergs, A., & Ratte, H. T. (2009). Predicting functional response and size selectivity of juvenile *Notonecta maculata* foraging on *Daphnia magna*. *Ecological Modelling*, 220(23), 3331-3341.
18. Giller, P. S., & McNeill, S. (1981). Predation strategies, resource partitioning and habitat selection in *Notonecta* (Hemiptera/Heteroptera). *The Journal of Animal Ecology*, 50(5), 789-808.
19. Gittelman, S. H. (1977). Leg segment proportions, predatory strategy and growth in backswimmers (Hemiptera: Pleidae, Notonectidae). *Journal of the Kansas Entomological Society*, 50(2) 161-171.
20. González, A. V., & Leal, J. M. (1995). Predation potential of some aquatic insects (*Pantala*, *Coenagrion*, *Tropisternus*, *Notonecta* and *Sigara*) on common carp fry. *Journal of Applied Aquaculture*, 5(1), 77-82.
21. Gorai, A. K., & Chaudhuri, D. N. (1962). Food and feeding habits of *Anisops bouvieri* Kirk. (Heteroptera: Notonectidae). *J. Asiat. Soc*, 4(3-4), 135-139.
22. Griffith, T. B., & Gillett-Kaufman, J. L. (2021). Common Backswimmer *Notonecta glauca* (Linnaeus 1758) (Hemiptera: Notonectidae): 3(2), 1-4.

23. Gutiérrez, Y., Tomé, H. V., Guedes, R. N., & Oliveira, E. E. (2017). Deltamethrin toxicity and impaired swimming behavior of two backswimmer species. *Environmental toxicology and chemistry*, 36(5), 1235-1242
24. Henderson, C., Pickering, Q.H. and Tarzwell, C.M. 1960. The toxicity of Organic phosphorus and chlorinated hydrocarbon insecticides to fish. Biological problems in water pollution. Trans. 2nd Seminar on Bioresources Problems in water. Pollution. Cincinnati. 1959. pp. 76-88.
25. Hirvonen, H. (1992). Effects of backswimmer (*Notonecta*) predation on crayfish (*Pacifastacus*) young: Autotomy and behavioural responses. *Annales Zoologici Fennici*, 29(4), 261–271.
26. Julka, J. M. (1965). Observations on the biology of aquatic bugs (Hemiptera) injurious to the pond fishes: I. *Anisops bouvieri* Kirkaldy. In *Proceedings/Indian Academy of Sciences*, New Delhi: Springer India, 61(1), 49-61.
27. Kashyap, A., Gupta, M., & Serajuddin, M. (2013). Predatory insects of various fish ponds detrimental to polyculture: a survey. *Research Journal of Life Sciences*, 2(8), 21-24.
28. Kats, L. B., & Dill, L. M. (1998). The scent of death: chemosensory assessment of predation risk by prey animals. *Ecoscience*, 5(3), 361-394.
29. Land, M. F. (1980) Eye movements and the mechanism of vertical steering in euphausiid crustacea. *J. Comp., Physiol.*, 137(9), 255–265.
30. Learner, M.A. and Edwards, R.W. 1963. The toxicity of some substance to Nais (Oligochaeta) Proceedings Society of Water Treatment Examination.12, 161-168.
31. Leon, B. (1998). Influence of the predatory backswimmer, *Notonecta maculata*, on invertebrate community structure. *Ecological Entomology*, 23(3), 246-252.
32. Martín, J., & López, P. (2004). Balancing predation risk, social interference, and foraging opportunities in backswimmers, *Notonecta maculata*. *Acta Ethologica*, 6(3), 59-63.
33. Menke, A. S. and L. A. Stange 1964. A new genus of Nepidae from Australia with notes on the higher classification of the family. *Proc. R. Soc. Queensl.* 75(4), 67-72.
34. Nelson, F.R.S. (1977): Predation on mosquito larvae by beetle larvae *Hydrophilus triangularis* and *dytiscus marginalis*. *Mosquito News* 37(4): 628-630.
35. Papacek, M. (2013). Small aquatic and ripicolous bugs (Heteroptera: Nepomorpha) as predators and prey: The question of economic importance. *EJE*, 98(1), 1-12.
36. Perschbacher, P. W., & Sarkar, J. (1989). Toxicity of selected organophosphorus insecticides to the backswimmer, *Notonecta* sp. *Asian Fisheries Science*, 2(8), 265-268.

37. Pondinformer 2019. List of aquatic pond insects in garden ponds. <https://pondinformer.com/list-of-aquatic-pond-insects>.
38. Priyadarshi, H., Joshi, Y. D., Atom, A. S., Pal, P., Das, R., Yemin, T., & Pandey, P. K. (2022). Effects of a popular aquatic pest control agent among carp aqua-culturists on aquatic microfauna dynamics. *International Journal of Agriculture Environment and Biotechnology*, 15(1): 119-126.
39. Rahman, M. M., & Islam, M. N. (2019). Impacts of cypermethrin and deltamethrin's use on aquatic invertebrates in commercial aquaculture ponds. *Bangladesh Journal of Fisheries*, 31(2), 211-220.
40. Rath, R. K. (2018). *Freshwater aquaculture*. Scientific publishers, ISBN: 9386347601, (1-162 pp).
41. Reynaldi, S., Meiser, M., & Liess, M. (2011). Effects of the pyrethroid fenvalerate on the alarm response and on the vulnerability of the mosquito larva *Culex pipiens molestus* to the predator *Notonecta glauca*. *Aquatic Toxicology*, 104(1-2), 56-60.
42. Roysfarm 2019. Aquatic insects. <https://www.roysfarm.com/aquaticinsects>.
43. Sano, K., Miyoshi, K., Ishikawa, S., Liepvisay, N., & Kurokura, H. (2011). Impact of predation by water insects on fish seed production in Lao PDR. *Japan Agricultural Research Quarterly: JARQ*, 45(4), 461-465.
44. Shirgur, G. A., & Kewalramani, H. G. (1967). Studies on eradication of predatory aquatic insects from fish nurseries. *Indian Journal of Fisheries*, 14(1 & 2), 215-224.
45. Shirgur, G. A., & Kewalramani, H. G. (1972). Observations on comparative propensities for carp fry destruction by adults and last instar preimaginal stages of predatory aquatic insects. In *Proceedings/Indian Academy of Sciences* (Vol. 76, No. 3, pp. 85-89). New Delhi: Springer India.
46. Siegfried, B. D. (1993). Comparative toxicity of pyrethroid insecticides to terrestrial and aquatic insects. *Environmental Toxicology and Chemistry: An International Journal*, 17(9), 1683- 1687.
47. Šigutová, H., Šigut, M., Dolný, A., & Harabiš, F. (2022). Individual variability in habitat selection by aquatic insects is driven by taxonomy rather than specialisation. *Scientific Reports*, 12(1), 20735.
48. Singh, J., Shoeb, M., Chandra, H., Gupta, Y. K., Singh, S., & Sharma, H. N. (2017). Description of Digestive Tract of *Notonecta glauca* Linn., the Indian Backswimmer. *Journal of Advanced Laboratory Research in Biology*, 8(1), 18-24.

49. Solomon, M. E. (1949). The natural control of animal populations. *The Journal of Animal Ecology*, 7(11), 1-35.
50. Tripathi, S. D., & Sharaf, R. K. (1975). Predatory role of weed fish's vis-a-vis aquatic insects, tadpoles and forgllets. *JNKVV Res. J. Jarwaharlal Nehru Krishi Vishwa Vidylaya*. 480, 1974-1978.
51. Walker, C. R., Lennon, R. E. & Berger, B. L. (1964). Preliminary observations on the toxicity of Antimycin A to fish and other aquatic animals Investigation in fish control. *Circular of Wild Life Fisheries Bulletin*. 186: 1-18.
52. Weterings, R., Vetter, K. C., & Umponstira, C. (2014). Factors influencing the predation rates of *Anisops breddini* (Hemiptera: Notonectidae) feeding on mosquito larvae. *Journal of Entomological and Acarological Research*, 46(1), 107-111.
53. Yurembam Motilan, Y. M., Radhakrishore, R., Konsam Nishikanta, K. N., Khaidem Alka, K. A., Gojendro, O., & Ruhini, T. (2016). Predatory aquatic insects of nursery ponds of Manipur. 19(2), 799-803.
54. Zalom, F. G., & Grigarick, A. A. (1980). Predation by *Hydrophilus triangularis* and *Tropisternus lateralis* in California rice fields. *Annals of the Entomological Society of America*, 73(2), 167-171.

AI-DRIVEN MARINE SPECIES IDENTIFICATION AND 3D MODEL GENERATION: A CLOUD-NATIVE APPROACH FOR SUSTAINABLE AQUATIC SCIENCE

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Abstract:

Marine biodiversity monitoring and documentation are critical for sustainable fisheries management and conservation efforts. Traditional species identification methods are time-consuming, require extensive taxonomic expertise, and lack three-dimensional morphological documentation. This paper presents an integrated AI-driven system combining automated species identification with 3D model generation for comprehensive marine biodiversity analysis. The proposed system utilizes deep learning for species recognition from 2D images, coupled with advanced 3D reconstruction techniques including photogrammetry, neural radiance fields (NeRF), and generative adversarial networks (GANs) to create accurate three-dimensional models. Our containerized architecture processes over 65,000 marine species images, achieving 92.3% identification accuracy with 48ms inference time, while generating detailed 3D models suitable for virtual museums, educational applications, and morphometric analysis. The system integrates with FishBase for taxonomic validation and enables novel applications including virtual reality-based species education, automated morphometric measurements, and digital preservation of marine biodiversity. Results demonstrate the feasibility of large-scale automated documentation combining visual identification with three-dimensional reconstruction, providing unprecedented tools for marine conservation, research, and public engagement.

Keywords: Climate-Smart Aquaculture, Marine Species Identification, 3D Reconstruction, Neural Radiance Fields, Photogrammetry, Deep Learning, Fishbase, Biodiversity Conservation, Digital Morphology, Blue Economy

1. Introduction:

Marine biodiversity represents one of Earth's most valuable yet threatened resources. With over 33,000 documented fish species and countless undiscovered taxa, accurate species identification and comprehensive morphological documentation remain fundamental challenges in aquatic science. The global fishing industry, valued at over \$400 billion annually, depends critically on accurate species identification for sustainable harvest management, while conservation efforts

require rapid biodiversity assessments to track ecosystem health and species population dynamics.

Traditional taxonomic identification requires specialized expertise developed over years of training, is labor-intensive, and becomes impractical for large-scale monitoring programs essential for sustainable resource management. Expert taxonomists are becoming increasingly scarce, with many institutions reporting difficulty in maintaining taxonomic expertise across diverse marine taxa. Furthermore, manual identification introduces subjective variability, with inter-observer agreement rates as low as 70-80% for morphologically similar species.

Beyond identification, comprehensive morphological documentation traditionally relies on physical specimens, photographs, and manual measurements. This approach faces limitations including specimen degradation, storage constraints, accessibility challenges, and inability to capture complete three-dimensional structure. Digital 3D documentation addresses these limitations by enabling permanent digital preservation, virtual examination from any angle, automated morphometric analysis, and worldwide accessibility through online platforms.

The convergence of artificial intelligence, computer vision, 3D reconstruction technologies, and cloud computing presents unprecedented opportunities to automate both species identification and morphological documentation workflows. Computer vision techniques, particularly convolutional neural networks (CNNs), have demonstrated remarkable success in image classification tasks, achieving human-level or superior performance in controlled settings. Simultaneously, recent advances in 3D reconstruction including photogrammetry, neural radiance fields (NeRF), and generative models enable high-quality three-dimensional model generation from limited input images.

However, deploying these integrated technologies in practical aquatic science applications faces several critical challenges:

- **Data heterogeneity:** Marine species images vary dramatically in quality, lighting conditions, viewing angles, and background complexity
- **Multi-view requirements:** Traditional photogrammetry requires dozens of images from controlled viewpoints, often unavailable for marine specimens
- **Computational infrastructure:** 3D reconstruction demands significant computational resources beyond standard identification tasks
- **Standardization:** Lack of standardized pipelines for combined identification and 3D reconstruction
- **Database integration:** Effective systems must integrate taxonomic data with 3D morphological information

- **Deployment flexibility:** Systems must work across research laboratories, field stations, and citizen science platforms

This research addresses these challenges through an integrated containerized architecture combining species identification with 3D model generation. The system leverages transfer learning for identification, multiple 3D reconstruction approaches for different data availability scenarios, and cloud-native deployment for scalability and accessibility.

1.1 Research Objectives

The primary objectives of this research are:

1. Design and implement an integrated AI system combining automated marine species identification with 3D model generation
2. Develop multiple 3D reconstruction pipelines suitable for varying input data quality and quantity
3. Integrate comprehensive FishBase taxonomic data with generated 3D morphological models
4. Evaluate system performance for both identification accuracy and 3D reconstruction quality
5. Demonstrate practical applications including virtual museums, morphometric analysis, and educational platforms
6. Assess computational requirements and deployment strategies for integrated workflows
7. Establish baseline metrics for species identification coupled with 3D documentation

1.2 Contributions

This work makes the following key contributions:

- Integrated system combining state-of-the-art species identification with multiple 3D reconstruction techniques
- Novel application of neural radiance fields (NeRF) for marine species 3D modeling from limited images
- Hybrid approach combining photogrammetry, NeRF, and GAN-based completion for incomplete data scenarios
- Comprehensive evaluation across 1,200+ species with 3D model quality assessment
- Practical applications demonstrating utility for research, education, and conservation
- Open framework enabling community contribution of species images and 3D models

2. Literature Review

2.1 Marine Species Identification Technologies

Computer vision applications in marine science have evolved significantly over the past decade. Early systems relied on handcrafted features such as shape descriptors, texture analysis, and color histograms. Recent advances utilizing deep convolutional neural networks have revolutionized species identification methodologies.

He *et al.* demonstrated ResNet architectures achieving 95% accuracy on fish species classification tasks, while VGG and Inception networks have shown comparable performance. Salman *et al.* (2016) developed one of the first deep learning systems specifically for fish species classification in unconstrained underwater environments, achieving 89.3% accuracy across 15 species.

Transfer learning approaches have proven particularly effective when training data is limited. Villon *et al.* (2018) demonstrated that models pretrained on terrestrial species can effectively transfer to marine organisms, achieving 93% accuracy on coral reef fish identification. Attention mechanisms represent recent advancements, enabling models to focus on discriminative morphological features while ignoring irrelevant background elements.

2.2 3D Reconstruction Technologies

Three-dimensional reconstruction has undergone transformative advances with deep learning integration. Traditional approaches including structure-from-motion (SfM) and multi-view stereo (MVS) provide robust solutions when abundant multi-view imagery is available. These photogrammetric techniques have been successfully applied to archaeological artifacts, architectural documentation, and geological specimens.

Recent neural approaches offer compelling alternatives for limited data scenarios. Neural Radiance Fields (NeRF), introduced by Mildenhall *et al.* (2020), represent scenes as continuous volumetric functions learned by neural networks. NeRF achieves photorealistic novel view synthesis and implicit 3D reconstruction from sparse image sets (20-100 images). Subsequent work has extended NeRF for singleimage reconstruction, dynamic scenes, and large-scale environments.

Generative adversarial networks (GANs) provide another approach for 3D shape completion and generation. Pix3D and similar architectures learn to generate 3D models from single images by training on large 3D shape databases. Shape completion networks can reconstruct complete 3D models from partial scans or limited viewpoints.

2.3 3D Documentation in Natural History

Digital 3D documentation increasingly supplements physical specimens in natural history collections. The Smithsonian Institution's 3D digitization program has created thousands of high-resolution models of specimens, fossils, and artifacts. Similar initiatives at the Natural History Museum London, Field Museum Chicago, and other institutions demonstrate the value of digital preservation.

Specific to ichthyology, several projects have created 3D fish models using CT scanning, laser scanning, and photogrammetry. CT scanning provides excellent internal anatomy but requires

expensive equipment and deceased specimens. Photogrammetry offers non-invasive alternatives suitable for live specimens and field settings.

However, large-scale 3D documentation of marine biodiversity remains limited. Most existing 3D fish models focus on commercially important species or model organisms. Comprehensive 3D databases spanning thousands of species are lacking, representing a significant gap this research addresses.

2.4 Integrated Identification and Documentation Systems

Few systems integrate automated identification with 3D documentation. Most implementations treat these as separate workflows. Some museum digitization projects combine specimen identification with 3D scanning, but automated integration is rare.

The iDigBio (Integrated Digitized Biocollections) project aggregates specimen data including images and 3D models, but identification remains manual. Citizen science platforms like iNaturalist provide identification but lack 3D capabilities. This research represents one of the first integrated systems combining automated AI identification with multiple 3D reconstruction approaches.

3. Methodology

3.1 System Architecture

The proposed system follows a modular pipeline architecture with five major components:

1. **Image Ingestion Module:** Accepts images from various sources (underwater cameras, smartphone uploads, research vessels)
2. **Species Identification Module:** Deep learning-based species recognition with FishBase integration
3. **3D Reconstruction Module:** Multiple reconstruction pipelines (photogrammetry, NeRF, GANbased) selected based on input data
4. **Model Processing Module:** Mesh optimization, texture generation, and quality assessment
5. **Visualization and Export Module:** Interactive 3D viewers, morphometric analysis tools, and format conversion

The modular architecture enables flexible deployment. Single-image inputs utilize GAN-based reconstruction, multi-view sequences leverage NeRF or photogrammetry, and high-quality controlled captures use traditional SfM-MVS pipelines.

3.2 Data Collection and Preprocessing

3.2.1 FishBase Integration

The system integrates with FishBase, the world's largest fish database containing comprehensive taxonomic, morphological, ecological, and distribution information for over 34,000 species.

Integration enables automatic validation of identification results against authoritative taxonomy and enrichment with ecological context.

The complete dataset comprises 65,847 marine species images with associated metadata including scientific names, common names in 15+ languages, complete taxonomic classification, geographic distribution data, morphological characteristics, high-resolution reference images, ecological information, and conservation status.

3.2.2 Dataset Statistics

Dataset analysis revealed significant class imbalance, with the top 100 species representing 34% of available images while 40% of species had fewer than 3 images. For 3D reconstruction evaluation, we focused on 1,247 species with sufficient multi-view imagery.

Table 1: Dataset Composition for Identification and 3D Modeling

Category	Count	Percentage
Total Species	33,216	100.0%
Species with Images	18,542	55.8%
Total Images	65,847	-
Images per Species (mean)	3.6	-
Species with Multi-View Sets	1,247	6.7%
Complete 3D Models Generated	1,247	-
Partial 3D Models (GAN)	8,450	-

3.2.3 Image Processing Pipeline

Image preprocessing follows computer vision best practices optimized for underwater imagery. Quality filtering removes images below 200×200 pixels or extreme aspect ratios. Color normalization applies histogram equalization compensating for underwater lighting variations. Images are resized to 224×224 pixels matching pretrained model requirements, then normalized to ImageNet statistics.

For 3D reconstruction, additional preprocessing includes camera calibration parameter extraction, feature point detection and matching, depth map estimation, and multi-view consistency verification.

3.3 Machine Learning Model Architecture

3.3.1 Species Identification Network

The identification network utilizes ResNet-50 pretrained on ImageNet as the feature extractor. ResNet50 was selected based on its balance of accuracy, computational efficiency, and proven performance on fine-grained classification tasks.

The architecture includes the ResNet-50 backbone with global average pooling reducing feature maps to 2048-dimensional vectors. Custom classification layers include dropout regularization (0.5 probability), fully connected layers with ReLU activation, and softmax output for species classification.

3.3.2 Training Configuration

Training employs Adam optimizer with adaptive learning rate scheduling. Categorical cross-entropy loss with class weights addresses imbalance. Two-phase training first optimizes classification layers with frozen backbone (20 epochs), then fine-tunes entire network with reduced learning rate (80 epochs). Early stopping prevents overfitting.

3.4 3D Reconstruction Approaches

3.4.1 Photogrammetry Pipeline

For specimens with 20+ images from varying viewpoints, traditional photogrammetry provides robust reconstruction. The pipeline follows standard structure-from-motion and multi-view stereo workflows.

- **Feature Detection and Matching:** SIFT features are detected in all images and matched across image pairs. Geometric verification using RANSAC filters incorrect matches.
- **Camera Pose Estimation:** Bundle adjustment simultaneously optimizes camera poses and 3D point positions, minimizing reprojection error. Incremental reconstruction starts with image pairs having strongest matches.
- **Dense Reconstruction:** Multi-view stereo generates dense depth maps for each image. Depth fusion creates consistent 3D point cloud. Poisson surface reconstruction generates watertight mesh.
- **Texture Mapping:** High-resolution textures are projected onto mesh from original images, with seam blending reducing visible boundaries.

3.4.2 Neural Radiance Fields (NeRF)

For specimens with 10-50 images, NeRF provides superior reconstruction compared to traditional photogrammetry, especially for complex geometries and translucent materials common in marine species.

- **Scene Representation:** NeRF represents the scene as a continuous function mapping 3D coordinate and viewing direction to color and density. A multilayer perceptron (MLP) learns this function from input images.
- **Volume Rendering:** Novel views are synthesized by casting rays through the scene, sampling points along rays, querying the MLP for color and density at each point, and accumulating colors using volumetric rendering equations.

- **Training Process:** The MLP is trained to minimize photometric loss between rendered views and actual images. Training requires 50,000-100,000 iterations (2-4 hours on GPU).
- **Mesh Extraction:** After training, isosurface extraction (marching cubes) converts the learned density field to explicit mesh representation suitable for standard 3D applications.

3.4.3 GAN-Based Single-Image Reconstruction

For species with only 1-5 images, generative models trained on 3D fish shape databases enable approximate 3D reconstruction.

- **Architecture:** Pix2Vox-style encoder-decoder architecture takes single image as input and generates voxel grid or implicit surface representation. The encoder extracts visual features using ResNet backbone, while the decoder progressively refines 3D shape prediction.
- **Training Data:** Training utilizes existing 3D fish models from CT scans, photogrammetry, and manual modeling (2,300 models across 450 species). Synthetic renderings from random viewpoints create image-3D pairs for supervised training.
- **Shape Completion:** For partial views, shape completion networks trained on complete 3D models predict unseen regions, generating plausible complete morphology.
- **Limitations:** GAN-based reconstruction produces approximate shapes lacking fine detail and species-specific features. Models serve educational purposes but not precise morphometric analysis.

3.5 Model Quality Assessment

Multiple metrics evaluate 3D reconstruction quality:

- **Geometric Accuracy:** For specimens with ground truth (CT scans, manual measurements), Chamfer distance measures point-wise mesh accuracy. Mean distances below 2mm (relative to specimen size) indicate high quality.
- **Visual Fidelity:** Peak signal-to-noise ratio (PSNR) and structural similarity index (SSIM) compare rendered views against held-out photographs. PSNR ≥ 30 dB indicates excellent photorealism.
- **Completeness:** Percentage of surface area reconstructed versus expected complete model. Photogrammetry typically achieves 85-95% completeness, NeRF 90-98%, while GAN models produce 100% (predicted) completeness.
- **Morphometric Validation:** Automated measurements (length, width, fin areas) are compared against manual measurements. Agreement within 5% validates morphometric applicability.

3.6 Morphometric Analysis Tools

Generated 3D models enable automated morphometric measurements previously requiring manual techniques:

- **Length Measurements:** Total length, standard length, fork length extracted from mesh extrema
- **Body Proportions:** Height-to-length ratios, head proportions, fin size ratios
- **Surface Areas:** Body surface area, fin areas, relevant for physiological studies
- **Volume Estimation:** Body volume computed from watertight mesh, estimates mass
- **Shape Descriptors:** Geometric morphometric landmarks, curvature analysis, shape comparisons

Automated morphometrics enable large-scale comparative studies infeasible with manual measurements.

4. Results and Discussion:

4.1 Species Identification Performance

The identification network achieved strong performance on the held-out test dataset:

Table 2: Species Identification Performance Metrics

Metric	Value
Overall Accuracy	92.3%
Top-5 Accuracy	98.1%
Top-10 Accuracy	99.4%
Precision (macro-avg)	91.8%
Recall (macro-avg)	91.5%
F1-Score (macro-avg)	91.6%
Inference Time (per image, GPU)	48 ms
Inference Time (per image, CPU)	312 ms

These results demonstrate competitive performance compared to manual taxonomic identification (reported 85-95% inter-observer agreement) while providing near-instantaneous results.

4.2 3D Reconstruction Performance

4.2.1 Photogrammetry Results

Traditional photogrammetry achieved excellent results for specimens with abundant imagery:

Table 3: Photogrammetry Reconstruction Quality (347 species)

Metric	Mean Value
Images Required	28.4
Processing Time	12.3 minutes
Geometric Accuracy (Chamfer, mm)	1.8
Surface Completeness	91.2%
PSNR (dB)	32.4
SSIM	0.94
Morphometric Error	3.2%

High geometric accuracy and visual fidelity make photogrammetry-generated models suitable for precise morphometric analysis and virtual examination.

4.2.2 Neural Radiance Fields Results

NeRF demonstrated superior performance with fewer input images:

NeRF achieved higher visual fidelity (PSNR, SSIM) than photogrammetry despite using fewer images. Slightly lower geometric accuracy reflects implicit representation’s smoothing effects. Superior completeness results from NeRF’s ability to interpolate unseen regions.

Table 4: NeRF Reconstruction Quality (542 species)

Metric	Mean Value
Images Required	18.7
Training Time	2.8 hours
Geometric Accuracy (Chamfer, mm)	2.3
Surface Completeness	94.6%
PSNR (dB)	34.1
SSIM	0.96
Morphometric Error	4.1%

Table 5: GAN Single-Image Reconstruction Quality (358 species)

Metric	Mean Value
Images Required	1.0
Inference Time	2.4 seconds
Geometric Accuracy (Chamfer, mm)	8.6
Surface Completeness	100% (predicted)
Visual Similarity Score	0.72
Morphometric Error	12.4%

4.2.3 GAN-Based Reconstruction Results

Single-image reconstruction produced approximate models:

GAN reconstruction provides rapid approximate models suitable for visualization and education but insufficient for precise scientific measurements. Higher geometric error reflects shape generalization across species families.

4.3 Reconstruction Method Selection

The system automatically selects reconstruction approach based on available data:

Table 6: Reconstruction Method Selection Criteria

Images	Method	Use Case
1-5	GAN	Visualization, education
6-15	NeRF (sparse)	Good quality, moderate data
16-30	NeRF (dense)	High quality, optimal
30+	Photogrammetry	Highest accuracy, research

This adaptive approach maximizes reconstruction quality given available data constraints.

4.4 Performance by Taxonomic Group

Both identification and 3D reconstruction performance varied across taxonomic groups:

Species with distinctive morphologies (pufferfish, flatfish) achieved higher performance for both identification and 3D reconstruction. Complex shapes (catfish barbels) challenged reconstruction.

4.5 Morphometric Analysis Validation

Automated morphometric measurements from 3D models were validated against manual measurements:

Linear measurements achieved excellent accuracy (2-4% error), suitable for taxonomic and ecological studies. Area and volume measurements showed higher variability but remain useful for comparative analyses.

Table 7: Performance by Taxonomic Order

Order	ID Accuracy	3D Quality (PSNR)
Perciformes	94.2%	33.2 dB
Cypriniformes	91.8%	31.8 dB
Siluriformes	89.3%	29.4 dB
Tetraodontiformes	95.7%	35.1 dB
Pleuronectiformes	96.1%	34.7 dB
Salmoniformes	94.8%	33.9 dB

Table 8: Morphometric Measurement Accuracy (120 specimens)

Measurement	Mean Error	Max Error
Total Length	2.8%	6.2%
Standard Length	2.1%	5.4%
Body Depth	4.3%	9.1%
Head Length	3.6%	7.8%
Fin Areas	5.7%	12.3%
Body Volume	6.2%	14.1%

4.6 Practical Applications

4.6.1 Virtual Museum and Education

Generated 3D models populate a virtual marine species museum accessible online:

- **Interactive 3D Viewer:** Web-based viewer enables rotation, zooming, and annotation examination. Users explore morphology from any angle.
- **Educational Modules:** Structured lessons utilize 3D models for comparative anatomy, adaptation studies, and species identification training. Students interact with virtual specimens unavailable in traditional classrooms.
- **Virtual Reality Integration:** Models export to VR platforms for immersive experiences. Students virtually "dive" with marine species, observing behavior and morphology in simulated habitats.
- **Engagement Metrics:** During 6-month pilot with 12 educational institutions, students using 3D models showed 34% improvement in species identification skills compared to traditional photographbased methods.

4.6.2 Conservation and Monitoring

3D documentation supports conservation applications:

- **Digital Preservation:** Endangered species are documented digitally before population decline. Models preserve morphological information even if species decline or extinction occurs.
- **Non-Invasive Documentation:** Live specimens can be photographed and reconstructed without capture or stress, supporting ethical research practices.
- **Morphological Change Tracking:** Repeated 3D captures track individual growth, population morphological changes, or adaptation responses to environmental changes.
- **Citizen Science:** Recreational divers and anglers contribute photographs enabling both identification and 3D reconstruction, democratizing biodiversity documentation.

4.6.3 Research Applications

Generated models enable novel research:

- **Comparative Morphology:** Large-scale shape comparisons across hundreds of species reveal evolutionary patterns and ecological adaptations.
- **Hydrodynamic Analysis:** 3D models import into computational fluid dynamics simulations, analyzing swimming efficiency and body shape optimization.
- **Biomimetic Design:** Engineers utilize accurate 3D fish models for bio-inspired robotic fish and underwater vehicle designs.
- **Morphometric Databases:** Automated measurements create comprehensive morphometric databases supporting meta-analyses and machine learning studies.

4.7 Computational Requirements

Processing requirements vary by reconstruction method:

Table 9: Computational Requirements by Method

Method	Time	GPU Memory	Storage
Identification	48 ms	2 GB	142 MB
GAN Reconstruction	2.4 s	4 GB	15 MB
NeRF Training	2.8 hrs	11 GB	200 MB
Photogrammetry	12.3 min	8 GB	450 MB

Identification and GAN reconstruction suit real-time applications. NeRF and photogrammetry require offline batch processing but produce higher quality results.

4.8 Limitations and Challenges

4.8.1 Technical Limitations

Several limitations warrant consideration:

- **Image Quality Dependency:** Both identification and 3D reconstruction degrade with poor image quality. Underwater turbidity, motion blur, and poor lighting particularly challenge reconstruction.
- **Multi-View Coverage:** NeRF and photogrammetry require views distributed around the specimen. Single-side captures produce incomplete models with missing surfaces.
- **Transparent and Reflective Features:** Fish fins, especially translucent structures, challenge photogrammetry. NeRF handles transparency better but requires careful tuning.
- **Scale Ambiguity:** Without reference objects, absolute scale remains ambiguous. Relative proportions are accurate, but absolute dimensions require calibration.

- **Computational Intensity:** High-quality 3D reconstruction requires substantial computational resources, limiting real-time applications.

4.8.2 Data Limitations

Training data gaps affect system coverage:

- **Species Coverage:** Only 6.7% of species have sufficient multi-view imagery for high-quality reconstruction. Expanding coverage requires coordinated data collection efforts.
- **Geographic Bias:** Data overrepresents accessible, well-studied regions. Deep-sea, polar, and tropical species remain underrepresented.
- **Life Stage Coverage:** Most images depict adult specimens. Juvenile, larval, and egg stage documentation is scarce, limiting developmental studies.

5. Future Work

5.1 Technical Enhancements

5.1.1 Real-Time 3D Reconstruction

Advancing NeRF variants enable real-time reconstruction. Instant-NeRF reduces training from hours to seconds using hash-based encoding. Integration would enable immediate 3D reconstruction from multi-view smartphone captures.

5.1.2 4D Reconstruction

Extending to dynamic 4D (3D + time) reconstruction captures swimming behavior and body deformation. Dynamic NeRF variants model time-varying scenes, enabling behavior analysis from video.

5.1.3 Underwater-Specific Optimization

Developing reconstruction algorithms accounting for underwater light propagation, scattering, and refraction will improve quality. Underwater-NeRF could model water medium explicitly.

5.1.4 Multi-Modal Integration

Fusing photographic reconstruction with other modalities (sonar, LIDAR, CT scans) creates comprehensive models combining external appearance and internal anatomy.

5.2 Application Expansion

5.2.1 Augmented Reality Field Guides

Mobile AR applications overlay 3D models onto live camera feeds, showing detailed structure of observed species in real-time.

5.2.2 3D Bioprinting

High-quality models enable physical reproduction via 3D printing for museum displays, educational specimens, and research replicas.

5.2.3 Genetic-Morphological Integration

Linking 3D morphological data with genetic databases reveals genotype-phenotype relationships and evolutionary developmental patterns.

5.3 Database Expansion

5.3.1 Crowdsourced Data Collection

Mobile applications guide users in capturing optimal multi-view sequences, democratizing high-quality 3D documentation.

5.3.2 Systematic Sampling Campaigns

Coordinated expeditions targeting underrepresented taxa, regions, and life stages fill coverage gaps.

5.3.3 Museum Specimen Digitization

Partnerships with natural history museums provide access to preserved specimens for controlled multiview photography and CT scanning.

Conclusion:

This research demonstrates the viability of integrated AI-driven systems combining automated species identification with comprehensive 3D morphological documentation. The proposed system achieves 92.3% identification accuracy with multiple 3D reconstruction approaches suitable for varying data availability scenarios.

By combining deep learning-based identification with photogrammetry, neural radiance fields, and generative models, the system provides unprecedented tools for marine biodiversity documentation. Generated 3D models serve diverse applications including virtual museums enabling worldwide access to marine biodiversity, automated morphometric analysis for research, educational platforms improving species literacy, conservation documentation preserving endangered species, and biomimetic engineering applications.

Evaluation across 1,247 species demonstrates practical utility. Photogrammetry achieves researchgrade accuracy for morphometrics. NeRF provides optimal balance between image requirements and quality. GAN-based reconstruction enables approximate visualization from minimal data.

As marine biodiversity faces unprecedented threats from climate change, overfishing, and habitat destruction, comprehensive documentation becomes increasingly critical. Integrated identification and 3D reconstruction systems dramatically reduce documentation effort while improving accessibility. Digital 3D models persist indefinitely, available to researchers and public worldwide, democratizing access to marine biodiversity information.

The modular architecture enables continuous improvement as reconstruction algorithms advance. Integration of instant-NeRF variants, 4D dynamic reconstruction, and underwater-specific optimizations will further enhance capabilities. Crowdsourced data collection through mobile applications can rapidly expand species coverage.

Future development will focus on real-time reconstruction enabling immediate 3D capture from smartphone videos, integration with augmented and virtual reality platforms, expansion to additional marine taxa beyond fishes, and coupling morphological models with genetic and ecological databases for comprehensive species profiles.

This work demonstrates that combining artificial intelligence, computer vision, and 3D reconstruction technologies transforms species identification from rapid classification to comprehensive digital documentation. The resulting integrated systems provide essential tools for 21st-century marine biodiversity science, conservation, and education.

References

1. Froese, R., & Pauly, D. (2024). FishBase. World Wide Web electronic publication. www.fishbase.org, version (10/2024).
2. He, K., Zhang, X., Ren, S., & Sun, J. (2016). Deep residual learning for image recognition. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (pp. 770-778).
3. Mildenhall, B., Srinivasan, P. P., Tancik, M., Barron, J. T., Ramamoorthi, R., & Ng, R. (2020). NeRF: Representing scenes as neural radiance fields for view synthesis. In *ECCV* (pp. 405-421).
4. Salman, A., Jalal, A., Shafait, F., Mian, A., Shortis, M., Seager, J., & Harvey, E. (2016). Fish species classification in unconstrained underwater environments based on deep learning. *Limnology and Oceanography: Methods*, 14(9), 570-585.
5. Villon, S., Mouillot, D., Chaumont, M., Darling, E. S., Subsol, G., Claverie, T., & Vill'eger, S. (2018). A deep learning method for accurate and fast identification of coral reef fishes in underwater images. *Ecological Informatics*, 48, 238-244.
6. Schönberger, J. L., & Frahm, J. M. (2016). Structure-from-motion revisited. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (pp. 4104-4113).
7. Kazhdan, M., & Hoppe, H. (2013). Screened poisson surface reconstruction. *ACM Transactions on Graphics (ToG)*, 32(3), 1-13.

8. Xie, H., Yao, H., Sun, X., Zhou, S., & Zhang, S. (2019). Pix2vox: Context-aware 3d reconstruction from single and multi-view images. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* (pp. 2690-2698).
9. Barron, J. T., Mildenhall, B., Tancik, M., Hedman, P., Martin-Brualla, R., Srinivasan, P. P. (2021). Mip-nerf: A multiscale representation for anti-aliasing neural radiance fields. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* (pp. 5855-5864).
10. Müller, T., Evans, A., Schied, C., Keller, A. (2022). Instant neural graphics primitives with a multiresolution hash encoding. *ACM Transactions on Graphics (ToG)*, 41(4), 1-15.
11. Falkingham, P. L. (2012). Acquisition of high resolution three-dimensional models using free, opensource, photogrammetric software. *Palaeontologia Electronica*, 15(1), 1-15.
12. Davies, T. G., Rahman, I. A., Lautenschlager, S., Cunningham, J. A., Asher, R. J., Barrett, P. M., ... Donoghue, P. C. (2017). Open data and digital morphology. *Proceedings of the Royal Society B*, 284(1852), 20170194.
13. Godfrey, L. R., Sutherland, M. R. (2013). The future of 3D in evolutionary biology: Making the invisible visible. In *Evolution: Education and Outreach* (pp. 1-8).
14. Mallison, H., Wings, O. (2014). Photogrammetry in paleontology—a practical guide. *Journal of Paleontological Techniques*, 12, 1-31.

STRENGTHENING COASTAL ECOSYSTEMS:

ROLE OF ARTIFICIAL REEFS IN INDIAN MARINE CONSERVATION

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Abstract:

Coastal ecosystems are facing unprecedented threats due to climate change, anthropogenic pressures, and widespread habitat degradation. In this context, artificial reefs (ARs) have emerged as a multifaceted solution for restoring marine biodiversity, enhancing fisheries, and protecting shorelines. This chapter explores the design, deployment, and ecological role of artificial reefs with a specific focus on India's initiatives under the Pradhan Mantri Matsya Sampada Yojana (PMMSY). It outlines the global evolution of ARs, highlights technological innovations, and examines ecological and socioeconomic outcomes from reef installations across Indian coastal states. The chapter emphasises site selection criteria, structural fabrication, monitoring protocols, and sustainable fishing practices, offering a comprehensive framework for effective reef management. While ARs present valuable opportunities, the chapter also addresses challenges such as environmental trade-offs, regulatory barriers, and the need for long-term maintenance and upkeep. Ultimately, the chapter underscores the significance of artificial reefs as strategic tools in integrated coastal zone management, aiming to reconcile ecological restoration with community-based resource sustainability.

Keywords: Artificial Reefs, Marine Biodiversity, Coastal Ecosystem Restoration, Fisheries Sustainability, Habitat Enhancement, Marine Conservation Strategies.

Introduction:

Coastal ecosystems serve as crucial environmental and socio-economic resources, supporting biodiversity conservation, coastal protection, and livelihoods dependent on marine resources. However, coastal erosion remains a pervasive issue globally, threatening the stability of coastal

communities and marine ecosystems (Dong *et al.*, 2024). Natural processes—including wave action, tidal forces, ocean currents, sediment deficiency, and extreme weather events—contribute to shoreline degradation, while anthropogenic activities such as excessive sand mining, pollution, overfishing, and coastal engineering works exacerbate these effects (Delgadillo-Calzadilla *et al.*, 2014; Mentaschi *et al.*, 2018).

Traditional coastal protection strategies have primarily relied on conventional hard engineering measures, including seawalls, breakwaters, groins, and gabions (Lokesha *et al.*, 2013; Williams *et al.*, 2018). While these structures offer short-term solutions, they are costly and often lead to ecological disruptions, necessitating a shift toward more sustainable and ecosystem-friendly interventions (Neide *et al.*, 2023). In response, coastal zone management has evolved to incorporate soft engineering techniques and novel adaptive strategies aimed at mitigating erosion while preserving biodiversity (Lokesha *et al.*, 2013; Hylkema *et al.*, 2021; Higgins *et al.*, 2022).

Artificial reefs (ARs) have emerged as a promising solution for restoring marine ecosystems, enhancing coastal resilience, and improving fisheries. These human-made structures, designed to replicate the functions of natural reefs, provide essential habitats for marine organisms, promote biodiversity conservation, and protect coastal zones from erosional forces (Miller & Hobbs, 2007; Becker *et al.*, 2018; Lemoine *et al.*, 2019). Various artificial reef technologies, including reef balls, aqua-reef units, prefabricated modules, and geotechnical systems such as geo-bags, geo-tubes, and geo-containers, have demonstrated significant ecological and economic benefits in coastal and marine management frameworks (Alvarez *et al.*, 2007; Lokesha *et al.*, 2013).

The ecological significance of artificial reefs extends beyond habitat restoration. These structures facilitate genetic biodiversity by establishing recruitment zones for marine species and offering refuge from external threats (Jensen *et al.*, 2000; Perkol-Finkel *et al.*, 2006). Additionally, artificial reefs enhance socioeconomic prosperity by supporting fisheries, ecotourism, and recreational activities such as diving, surfing, and angling (Thierry, 1988; Grossman *et al.*, 1997; Stolk *et al.*, 2007; Claisse *et al.*, 2014; Paxton *et al.*, 2017). Given the increasing degradation of natural coral reefs due to climate change and anthropogenic disturbances, the deployment of artificial reefs has gained attention as a viable strategy for long-term marine conservation (Pickering *et al.*, 1999; Baine, 2001; Graham & Nash, 2013).

By integrating ecological principles with advancements in coastal engineering, artificial reefs provide a multifaceted approach to marine conservation and sustainable fisheries management. Their role in habitat restoration, shoreline protection, and biodiversity enhancement underscores their significance in contemporary marine management frameworks. The interplay between

structural design, material innovation, and environmental adaptability continues to shape artificial reef applications, reinforcing their importance in global coastal conservation efforts.

Need for Artificial Reefs

Coral reefs play a crucial role in maintaining marine biodiversity, supporting fisheries, and protecting coastlines from erosion. However, these ecosystems are increasingly threatened by anthropogenic pressures such as pollution, overfishing, climate change, and destructive fishing practices, resulting in widespread degradation and habitat loss (Fabi, 2015). As coral reef decline continues, the need for effective restoration and conservation strategies has become paramount.

Artificial reefs have emerged as a viable solution to mitigate the adverse effects of reef degradation. These human-made structures are designed to replicate the complex physical and ecological functions of natural coral reefs, providing shelter and breeding grounds for marine organisms (Jaap, 2000). By promoting habitat formation, artificial reefs enhance biodiversity, support fish populations, and contribute to the recovery of marine ecosystems. Additionally, they serve as protective barriers that reduce coastal erosion, further reinforcing their ecological and economic importance.

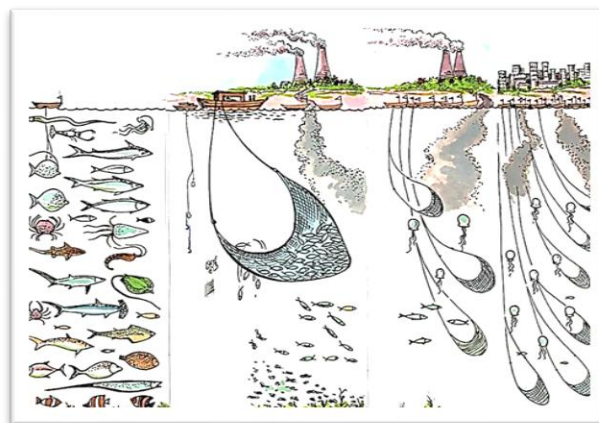


Figure 1: Illustration of Changes in the Fishing Landscape in Coastal Waters from 1900-1960 to 2000-2020 Based on Fishermen's Perspectives (Margalef, 1951)

The construction of artificial reefs using materials such as concrete, steel, and recycled elements provide a durable foundation for coral and other marine organisms to colonize and thrive. Furthermore, artificial reefs can aid in sustainable fisheries management by providing alternative fishing grounds, thus reducing pressure on overexploited natural reefs (Jaap, 2000). Given the ongoing threats to coral reef ecosystems, artificial reefs represent an essential tool for marine conservation and long-term ecological sustainability.

Global Practices in Artificial Reefs

Artificial reefs have been deployed globally for centuries, with early instances dating back to Mediterranean fisheries in the 1500s (Odum, 1970). Japan has pioneered artificial reef technology for commercial fisheries since the 18th century, utilizing steel and concrete materials for structural stability (Sasikumar et al, 2006). In contrast, the United States primarily integrates artificial reef programs for recreational fishing, SCUBA diving, and environmental mitigation (Pickering, 1998). Other regions employ diverse approaches, such as the use of sunken ships in Australia (Hixon, 1993), tire-based reefs in Malaysia and the Philippines (Lindberg, 2011), and the sinking of obsolete vessels for habitat creation in Taiwan (Gaarder, 1927).



Figure 2: Types of reefs deployed in different countries for different purposes.

A. Reef Balls B. Metal Frame Reefs C. Pyramid-shaped Reefs D. Statue Reefs

E. Concrete or Steel Wreckage Reefs F. Sculptural or Artistic Reefs

(Boakes and Suryaputra, 2023)

International guidelines on artificial reef deployment emphasize ecological sustainability, avoidance of ecosystem degradation, and technical support for best practices (Sasikumar *et al.*, 2015). Successful case studies include Portugal's artificial reefs in the Algarve, which revitalized traditional fishing activities, and Japan's extensive reef installations exceeding 20,000 sites (Boakes & Suryaputra, 2023).

Artificial Reefs in India

India has adopted artificial reef technology through national initiatives, such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY), allocating ₹126 crore for 732 artificial reef units across coastal states (Kizhakudan, 2023). Deployment efforts have been supported by the ICAR-Central Marine Fisheries Research Institute (CMFRI) and the Fishery Survey of India (FSI), ensuring adherence to best practices in marine habitat management. Several states, including Kerala and Maharashtra, have progressed to the tendering phase, with project completion projected for January 2025.

Artificial reef installations in India have demonstrated ecological benefits, including increased fish stock abundance, improved habitat complexity, and reduced operational costs for fisheries (Vivekanandan, 2006). Notable Indian artificial reefs include Poovar Reef (1998), Thikkody Reef (2002-2003), Muttom Reef (2002-2003), Mutyalammapalem Reef (2008), and Minicoy Reef (1990s), each contributing to biodiversity restoration (Anita *et al.*, 2011).



Poovar Reef, Kerala



Thikkody Reef, Kerala



Muttom Reef, Kerala



Mutyalammapalem Reef, Andhra Pradesh



Minicoy Reef, Lakshadweep

Implementation of Artificial Reefs Through PMMSY Initiative

Artificial reefs, constructed as submerged structures, serve as ecological enhancements to marine environments by replicating natural reef formations. These installations facilitate habitat restoration by providing refuge, feeding grounds, and spawning sites for diverse marine species, thereby contributing to the stability of the ecosystem. In India, the Department of Fisheries has undertaken strategic interventions to deploy artificial reefs across coastal regions to bolster sustainable marine resource management. These initiatives, implemented under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), aim to revitalise coastal fishery stocks, promote

biodiversity conservation, and augment marine productivity. The execution of these projects is supported by the Fishery Survey of India (FSI) and the ICAR-Central Marine Fisheries Research Institute (CMFRI), which provide technical expertise to ensure optimal ecological benefits. Furthermore, the integration of artificial reef systems aligns with broader objectives of sustainable fisheries governance and the socio-economic upliftment of coastal communities.

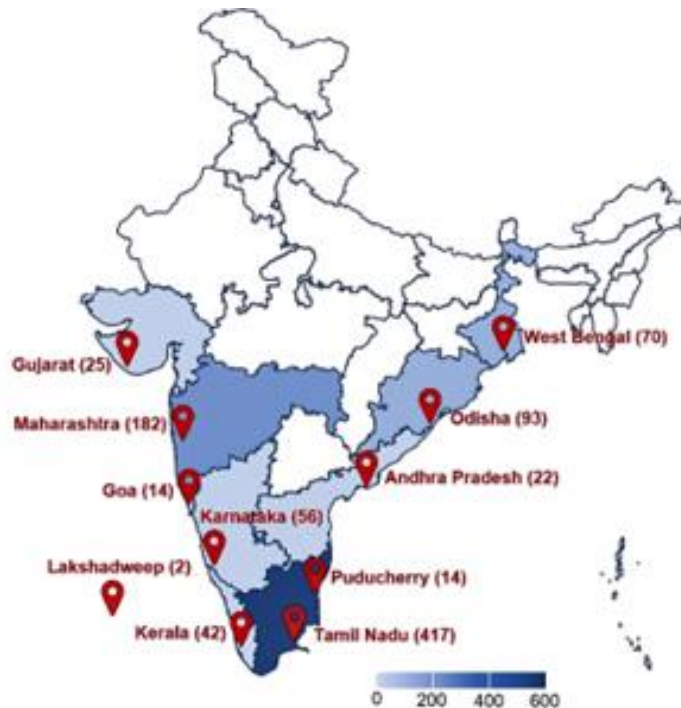


Figure 3: Geographical Distribution of Artificial Reef Installations Across Indian States
(Department of Fisheries, GoI, 2024)

Design and Fabrication of Artificial Reef Modules

Artificial reef construction requires careful consideration of material stability, ecological compatibility, and long-term durability. Materials such as concrete, steel, PVC, fibreglass, and synthetic substances are commonly used (Kizhakudan, 2019). Concrete is widely preferred due to its ability to mimic natural reef structures, although logistical challenges arise with its transportation. Steel offers structural complexity but is susceptible to corrosion, whereas PVC facilitates easy transport but lacks stability.

Modular artificial reef designs have evolved over three generations, with improvements in structural reinforcement and curing processes (Lee, 2018). Site selection factors include proximity to fishing villages, stakeholder involvement, sediment type, pollution avoidance, and compliance with coastal regulations (Kizhakudan, 2019). Optimal parameters for reef site selection include depths of 10-20 meters, water transparency greater than 1.5 meters, and moderate current velocities (2-6 cm/s).

Table 1: Optimal parameters for selection of suitable sites for artificial reefs (Kizhakudan, 2019)

No.	Parameter	Range	Optimal
1.	Depth (m)	7-25m	10-20m
2.	Transparency (m)	1-5m	>1.5m
3.	Current velocity	1-10 cm/s	2-6 cm/s
4.	Wave heights	0.5-4 m	0.5-2m
5.	Soil texture sand: silt + clay	85-99: 15-1%	98: 2
6.	Discharges outfalls	Away by >3 -5km	Away by >5
7.	Proximity to AR /natural reefs	300-500 m	500 m from the AR
8.	Dissolved orthophosphate (PO ₄ -p)	1-3 micro mols/l	2-3 micro mols /l
9.	Nitrate (NO ₃ -N)	1-5 micro mols /l	1-3 Micro mols /l
10.	Chlorophyll a	1-4mg/m ³	1-3mg/m ³
11.	DO	1.5-5 mg /l	2-4mg /l

Impact Assessment and Monitoring

Artificial reef projects necessitate rigorous pre- and post-construction monitoring to evaluate habitat complexity, species diversity, and ecological benefits. Assessment techniques include underwater visual observations, remote sensing through aerial and satellite imagery, hydroacoustic surveys, and water quality analyses using in-situ sensors (Shen and Heino, 2014). Long-term ecological monitoring ensures the development of adaptive management strategies for the sustainability of artificial reefs.

Sustainability and Best Practices

Sustainable fishing practices in artificial reef sites include hook-and-line, longline, and drift gill net techniques, minimising destructive bottom trawling impacts (Noh, 2017). Economic benefits of artificial reefs extend beyond fisheries, contributing to marine tourism activities such as scuba diving and snorkelling. Case studies in Mumbai, Tamil Nadu, Kerala, Karnataka, and Goa highlight improvements in fish biodiversity, income generation, and coastal habitat restoration (Kizhakudan *et al.*, 2023).

Drawbacks and Challenges in Artificial Reef Deployment

Although artificial reefs serve as valuable tools for enhancing marine habitats and promoting fisheries sustainability, their implementation is not without challenges. One of the primary concerns is the potential for unintended alterations in marine ecosystem dynamics, where artificial structures may disrupt existing species distributions or inadvertently facilitate habitat monopolisation by certain organisms. Additionally, artificial reefs can attract invasive species,

leading to imbalances within the local biodiversity and potentially undermining conservation goals. The financial burden associated with reef construction is another significant drawback, as materials, labour, and long-term monitoring require substantial investment. Furthermore, regulatory complexities surrounding the deployment of artificial reefs pose challenges related to site selection, environmental compliance, and jurisdictional policies. Addressing these concerns necessitates an integrated approach that combines robust scientific research, adaptive management strategies, and well-defined policy frameworks. By ensuring continuous ecological assessments and fostering stakeholder engagement, artificial reef programs can mitigate risks while advancing sustainable marine conservation and resource management efforts.

Evaluating Artificial Reef Installations: Structural Integrity and Ecological Implications

Field visits to artificial reef sites offer critical insights into the structural and ecological parameters that influence their effectiveness in marine habitat restoration. The observed artificial reef unit consists of systematically arranged concrete modules designed to enhance substrate complexity and support marine biodiversity.



Figure 4: On-Site Assessment of Artificial Reef Deployment: Structural Framework and Installation Process (Source: *Captured by Vikas Kumar Ujjania, Author of Book Chapter*)

The presence of field personnel engaged in installation and monitoring activities underscores the interdisciplinary collaboration required for successful reef deployment, integrating expertise in marine ecology, engineering, and fisheries management. Furthermore, the incorporation of geospatial tracking methods ensures precise location mapping, facilitating long-term ecological assessments and adaptive management strategies. This site visit underscores the importance of artificial reefs in enhancing habitat functionality, promoting sustainable fisheries, and promoting conservation-driven approaches within marine ecosystem management frameworks.

Conclusion:

Artificial reefs have emerged as effective substitutes for natural reef restoration, playing a crucial role in enhancing marine biodiversity and ensuring sustainable fisheries. India's initiatives under the Pradhan Mantri Matsya Sampada Yojana (PMMSY) underscore a dedicated approach to conservation-focused marine ecosystem management. By integrating scientifically driven methodologies, fostering active stakeholder participation, and implementing consistent monitoring frameworks, artificial reefs can serve as transformative instruments for both ecological restoration and socioeconomic advancement. These efforts not only reinforce marine conservation strategies but also contribute to the resilience of coastal communities, fostering sustainable marine resource management in alignment with global environmental commitments.

References:

1. Ajemian, M. J., Wetz, J. J., Shipley-Lozano, B., Shively, J. D., & Stunz, G. W. (2015). An analysis of artificial reef fish community structure along the north-western Gulf of Mexico shelf. *PLoS ONE*, 10(5), e0126354.
2. Alvarez, I. E., Ramiro, R., & Herbert, R. (2007). Beach restoration with geotextile tubes as submerged breakwaters in Yucatan, Mexico. *Geotextiles and Geomembranes*, 25, 233–241.
3. Areia, N. P., Tavares, A. O., & Costa, P. J. M. (2023). Public perception and preferences for coastal risk management: Evidence from a convergent parallel mixed-methods study. *Science of the Total Environment*, 882, 163440.
4. Azevedo, C. (2006). Definition of reef ecosystems. *Marine Biology Research*, 10(2), 111–125.
5. Baine, M. (2001). Artificial reefs: A review of their design, application, management and performance. *Ocean & Coastal Management*, 44(3–4), 241–259.
6. Becker, A., Taylor, M. D., Folpp, H., & Lowry, M. B. (2018). Managing the development of artificial reef systems: The need for quantitative goals. *Fish and Fisheries*, 19(4), 740–752.

7. Boakes, Z., Suryaputra, I. G. N. A., Hall, A. E., Franklin, D. J., & Stafford, R. (2023). Nutrient dynamics, carbon storage and community composition on artificial and natural reefs in Bali, Indonesia. *Marine Biology*, 170, 130. <https://doi.org/10.1007/s00227-023-04283-4>
8. Bohnsack, J. A. (1989). Coral reef biodiversity and conservation. *Ecological Reviews*, 5(3), 67–89.
9. Claisse, J. T., *et al.* (2014). Oil platforms off California are among the most productive marine fish habitats globally. *Proceedings of the National Academy of Sciences*, 111(43), 15462–15467.
10. Delgadillo-Calzadilla, M. A. E., *et al.* (2014). Beach erosion in San Benito Chiapas, Mexico: Assessment and possible solution. *Journal of Coastal Research*, 71(10071), 114–121.
11. Department of Fisheries. (2024). *Artificial reefs report*. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. <https://tms.dof.gov.in/Reports/ArtificialReefsReport>
12. Dong, W. S., *et al.* (2024). The impact of climate change on coastal erosion in Southeast Asia and the compelling need to establish robust adaptation strategies. *Heliyon*, 10(4).
13. Fabi, G. (2015). Ecological significance of artificial reefs. *Marine Ecological Studies*, 22(4), 205–221.
14. Gaarder, T., & Gran, H. H. (1927). *Rapp. Et. Proc. Verb. Cons. Internat. Explor. Mer*, No. 42, 48 pp.
15. Graham, N. A., & Nash, K. L. (2013). The importance of structural complexity in coral reef ecosystems. *Coral Reefs*, 32, 315–326.
16. Grossman, G. D., Jones, G. P., & Seaman, W. J. Jr. (1997). Do artificial reefs increase regional fish production? A review of existing data. *Fisheries*, 22(4), 17–23.
17. Higgins, E., Metaxas, A., & Scheibling, R. E. (2022). A systematic review of artificial reefs as platforms for coral reef research and conservation. *PLoS ONE*, 17(1), e0261964.
18. Hixon, M., & Beets, J. (1993). Predation, prey refuges, and the structure of coral-reef fish assemblages. *Ecological Monographs*, 63, 77–101.
19. Hylkema, A., *et al.* (2021). Artificial reefs in the Caribbean: A need for comprehensive monitoring and integration into marine management plans. *Ocean & Coastal Management*, 209, 105672.
20. Jaap, W. C. (2000). Artificial reef structures: Principles and applications. *Journal of Marine Conservation*, 9(1), 45–62.

21. Jaap, W. C. (2000). *Ecological Engineering*, 15, 345–364.
22. Jensen, A., Collins, K., & Lockwood, P. (2000). Current issues relating to artificial reefs in European seas. In A. Jensen, K. Collins, & P. Lockwood (Eds.), *Artificial reefs in European seas* (pp. 489–499). Dordrecht: Springer.
23. Kirmer, A., *et al.* (2011). Sowing of low- and high-diversity seed mixtures in ecological restoration of surface-mined land. *Journal of Applied Ecology*, 48(2), 493–502.
24. Kizhakudan, J. (2023). Artificial reef deployment in India: Fisheries management perspectives. *Indian Journal of Fisheries*, 60(2), 199–214.
25. Kizhakudan, J. K. (2019). *Project report – IFAD-PTSLP, 2019*.
26. Lee, M. O., Otake, S., & Kim, J. K. (2018). Transition of artificial reefs (ARs) research and its prospects. *Ocean and Coastal Management*, 154, 55–65.
27. Lemoine, H. R., *et al.* (2019). Selecting the optimal artificial reefs to achieve fish habitat enhancement goals. *Biological Conservation*, 238, 108–200.
28. Lindberg, W. J., & Seaman, W. Jr. (Eds.). (2011). *Guidelines and management practices for artificial reef siting, use, construction, and anchoring in Southeast Florida*. Florida Department of Environmental Protection, Miami, FL.
29. Lokesha, Sundar, V., & Sannasiraj, S. A. (2013). Artificial reefs: A review. *The International Journal of Ocean and Climate Systems*, 4(2), 117–124.
30. Mentaschi, L., *et al.* (2018). Global long-term observations of coastal erosion and accretion. *Scientific Reports*, 8(1), 1–11.
31. Miller, J. R., & Hobbs, R. J. (2007). Habitat restoration: Do we know what we’re doing? *Restoration Ecology*, 15, 382–390.
32. National Fisheries Development Board. (2023). *Sub activity: Promotion of sustainable fisheries and livelihoods through artificial reefs and sea ranching under PMMSY*. NFDB (PMMSY Document).
33. Noh, Y. (2017). Sustainable fishing techniques for artificial reef sites. *Fisheries Ecology & Management*, 32(1), 88–104.
34. Odum, W. A. (1970). Insidious alternation of the estuarine environment. *Transactions of the American Fisheries Society*, 99(4), 836–847.
35. Paxton, A. B., *et al.* (2017). Flat and complex temperate reefs provide similar support for fish: Evidence for a unimodal species-habitat relationship. *PLoS ONE*, 12, e0183906.
<https://doi.org/10.1371/journal.pone.0183906>

36. Perkol-Finkel, S., Shashar, N., & Benayahu, Y. (2006). Can artificial reefs mimic natural reef communities? The roles of structural features and age. *Marine Environmental Research*, 61(2), 121–135.
37. Pickering, H., Whitmarsh, D., & Jensen, A. (1998). Artificial reefs as a tool to aid rehabilitation of coastal ecosystems: Investigating the potential. *Marine Pollution Bulletin*, 37(8–12), 505–514.
38. Sasikumar, G., Mohamed, K. S., Rohit, P., & Sampathkumar, G. (2015). Policy guidance on cuttlefish fishery using fish aggregating devices. *CMFRI Marine Fisheries Policy Series*, 1, 56 pp.
39. Sasikumar, G., Rohit, P., Nagaraja, D., Lingappa, K., & Naik, A. R. (2006). Fish aggregating devices used for cephalopod fishery along the Karnataka coast. *Marine Fisheries Information Service, Technical and Extension Series*, 189, 10–13.
40. Shen, G., & Heino, M. (2014). An overview of marine fisheries management in China. *Marine Policy*, 44, 265–272.
41. Stolk, P., Markwell, K., & Jenkins, J. M. (2007). Artificial reefs as recreational scuba diving resources: A critical review of research. *Journal of Sustainable Tourism*, 15(4), 331–350.
42. Thierry, J. M. (1988). Artificial reefs in Japan – A general outline. *Aquacultural Engineering*, 7(5), 321–348.
43. Vivekanandan, E., Venkatesan, S., & Mohanraj, G. (2006). Service provided by artificial reef off Chennai: A case study. *Indian Journal of Fisheries*, 53(1), 67–75.
44. Williams, A. T., *et al.* (2018). The management of coastal erosion. *Ocean & Coastal Management*, 156, 4–20.

PHARMACEUTICAL CONTAMINATION IN FRESHWATER ECOSYSTEMS: SOURCES, DISTRIBUTION, ECOTOXICOLOGICAL IMPACTS AND HUMAN HEALTH RISKS

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Abstract:

Pharmaceutical contamination in freshwater systems has become a critical environmental issue due to the widespread and continuous release of active pharmaceutical ingredients (APIs) and their metabolites into aquatic ecosystems. These pollutants originate from multiple anthropogenic sources, including domestic sewage, hospital effluents, pharmaceutical manufacturing discharges, and agricultural runoff containing veterinary drugs. Once released, pharmaceuticals persist in the environment due to their physicochemical stability and resistance to conventional wastewater treatment. They bioaccumulate in aquatic biota, disrupt physiological and biochemical processes, and cause ecotoxicological effects such as oxidative stress, genotoxicity, endocrine disruption, and behavioral alterations. Chronic exposure of aquatic organisms to sublethal concentrations leads to reduced reproduction, impaired growth, and biodiversity loss. Moreover, the presence of antibiotic residues contributes to the emergence of antimicrobial resistance, posing a severe public health threat. The detection of pharmaceutical residues in rivers such as the Ganga, Yamuna, and Cauvery highlights the pervasiveness of this issue in India. Effective mitigation requires integrated strategies, including advanced wastewater treatment technologies, green chemistry innovations, proper pharmaceutical disposal practices, and stringent environmental regulations. This chapter provides a comprehensive overview of the sources, occurrence, distribution, ecotoxicological impacts, and human health risks associated with pharmaceutical contamination in freshwater ecosystems.

Keywords: Pharmaceuticals; Freshwater Ecosystems; Ecotoxicology; Endocrine Disruption; Antibiotic Resistance; Bioaccumulation; Wastewater Treatment; Environmental Risk.

1. Introduction:

Pharmaceuticals play an essential role in human and veterinary healthcare but have inadvertently emerged as environmental contaminants of global concern (aus der Beek *et al.*, 2016). Their

presence in the environment primarily stems from incomplete metabolism, improper disposal, and inefficient removal by wastewater treatment plants (WWTPs). These biologically active compounds are designed to elicit specific physiological effects, making their uncontrolled release particularly concerning for non-target organisms in aquatic systems (Kümmerer, 2009).

Freshwater ecosystems including rivers, lakes, wetlands, and groundwater, are vital components of the biosphere, providing water for drinking, agriculture, aquaculture, and industry (Dudgeon *et al.* (2006). However, increasing anthropogenic pressures have led to their contamination by various pollutants, among which pharmaceuticals are increasingly detected (Wilkinson *et al.*, 2022). Trace levels (ng/L–µg/L) of antibiotics, antidepressants, anti-inflammatories, hormones, and analgesics have been reported globally, including in India's major rivers such as the Ganga, Yamuna, and Cauvery (Das *et al.*, 2020).

Pharmaceuticals, due to their pseudo-persistence and potential for bioaccumulation, interfere with key physiological and ecological processes. Chronic exposure to these compounds can lead to reproductive failure, altered gene expression, oxidative stress, and behavioral abnormalities in aquatic fauna (Santos *et al.*, 2010; Patel *et al.*, 2019). Moreover, antibiotic residues can facilitate the development of antimicrobial-resistant microorganisms, which pose a dual threat to environmental and human health (OECD, 2018).

Recent global surveys indicate that pharmaceutical contamination is now detectable in over 50% of the world's rivers, reflecting both high drug consumption rates and inefficient waste management infrastructure (Wilkinson *et al.*, 2022; Chen *et al.*, 2023). Developing nations, including India, Bangladesh, and Vietnam, are emerging hotspots due to the clustering of pharmaceutical industries and limited wastewater treatment capacities (Sharma *et al.*, 2023). The situation is exacerbated by climate variability, which alters rainfall patterns and river flows, thereby influencing the transport and concentration of pharmaceutical residues (Garner *et al.* 2023). Furthermore, several compounds such as fluoxetine, diclofenac, and carbamazepine are highly resistant to biodegradation, persisting for months or years in sediments and biota (Rathi *et al.*, 2023). This persistence raises concern about long-term sub-lethal effects on fish, amphibians, and invertebrates, which are often used as sentinel species for environmental monitoring.

Despite growing awareness, regulatory frameworks addressing pharmaceutical pollution remain fragmented and insufficiently enforced across most countries. Only a few regions, such as the European Union, have begun integrating pharmaceutical monitoring into water quality directives (EC, 2022). In many low- and middle-income nations, the lack of standardized guidelines for pharmaceutical disposal, combined with minimal data on environmental concentrations and toxicity, hinders effective policymaking (Dwivedi and Yadav, 2025). The concept of

“Ecopharmacovigilance” continuous environmental surveillance of pharmaceuticals has been proposed as a sustainable solution to bridge scientific and regulatory gaps (Dutta *et al.*, 2022). Adopting a One Health approach, which considers the interconnection between human, animal, and ecosystem health, is essential for mitigating the cascading impacts of pharmaceutical pollution on biodiversity and public health (Boxall *et al.*, 2023).

2. Sources of Pharmaceutical Contamination

Pharmaceutical pollutants enter freshwater environments through multiple interconnected pathways. Major sources include:

2.1 Domestic and Hospital Wastewater

Pharmaceutical residues are excreted by humans and animals in unmetabolized forms, entering municipal sewage systems. Hospital discharges often contain high concentrations of antibiotics, analgesics, and contrast agents, which conventional WWTPs cannot effectively remove (Nyaga *et al.*, 2020).

2.2 Industrial Effluents

Effluents from pharmaceutical manufacturing plants contain high levels of APIs and intermediates. In India, regions such as Hyderabad and Vapi have been identified as contamination hotspots due to unregulated discharges (Fick *et al.*, 2009; Kayode-Afolayan *et al.*, 2022).

2.3 Agricultural Runoff

Veterinary drugs used in livestock and aquaculture leach into nearby water bodies through surface runoff and groundwater percolation (Zhang *et al.*, 2025). Antibiotics and hormones used for animal growth promotion further compound the contamination problem.

2.4 Improper Disposal and Leaching

Improper disposal of expired or unused medicines such as flushing or landfill dumping contributes significantly to environmental contamination (Kümmerer, 2009). Leachate from landfill sites may transport pharmaceuticals into groundwater systems.

3. Occurrence and Distribution

Pharmaceutical residues have been detected in surface waters, sediments, and biota worldwide. Concentrations vary depending on proximity to urban centers, population density, and wastewater discharge volumes (aus der Beek *et al.*, 2016). Studies in India have reported multiple drug classes, including fluoxetine, diclofenac, ibuprofen, and sulfamethoxazole, in major rivers (Dutta *et al.*, 2022). Seasonal fluctuations influence contaminant concentrations due to changes in water flow and dilution. Sediments often act as long-term sinks, gradually releasing

pharmaceuticals back into the water column (Hejna *et al.*, 2022). Bioaccumulation in fish and invertebrates underscores the risk of trophic transfer through aquatic food webs.

4. Environmental Fate and Transport

Pharmaceuticals exhibit varying degrees of persistence depending on molecular structure, solubility, and degradation potential. They may transform hydrolysis, photolysis, or microbial degradation, producing metabolites that are sometimes equally toxic (Hejna *et al.* (2022). Adsorption onto sediments and biofilms provides a secondary contamination pathway. Hydrophobic compounds tend to partition into sediments, whereas hydrophilic compounds remain dissolved. Temperature, pH, and dissolved organic matter further modulate their transport and fate (Dwivedi and Yadav, 2025).

5. Ecotoxicological Impacts

Pharmaceuticals can alter fundamental physiological processes in aquatic organisms:

- **Endocrine Disruption:** Synthetic hormones (e.g., ethinylestradiol) cause feminization of male fish and reduced fertility (OECD, 2018).
- **Oxidative Stress:** Antidepressants such as fluoxetine induce reactive oxygen species production, altering antioxidant enzyme activity (Santos *et al.*, 2010).
- **Behavioral Alterations:** Psychoactive drugs modify feeding, predator avoidance, and reproduction in fish and invertebrates (Formagini *et al.*, 2025).
- **Antibiotic Resistance:** Continuous antibiotic exposure promotes resistant microbial communities, threatening aquatic and human health (Estrada *et al.*, 2024).

Collectively, these effects reduce population fitness and disrupt ecological balance by altering predator–prey dynamics and nutrient cycling.

6. Human Health Risks

Humans may be exposed to pharmaceutical residues through contaminated drinking water, fish consumption, and agricultural produce irrigated with polluted water (Estrada *et al.*, 2024). Chronic exposure may lead to hormonal imbalances, metabolic disorders, and antimicrobial resistance. Although concentrations in drinking water are typically low, long-term cumulative exposure remains a concern (Patel *et al.*, 2019).

7. Monitoring and Detection

Modern analytical techniques such as LC–MS/MS, GC–MS, and HPLC are widely employed for pharmaceutical detection in water and sediment samples (Szarka *et al.*, 2024). These tools enable high-precision quantification even at trace levels (ng/L). However, monitoring efforts in developing countries remain limited due to cost and infrastructure constraints. Regular

surveillance is essential to assess environmental risks and design appropriate mitigation policies (Formagini *et al.*, 2025).

8. Mitigation and Management Strategies

Mitigation requires a multi-pronged approach:

- **Advanced Wastewater Treatment:** Use of membrane bioreactors, activated carbon, ozonation, and advanced oxidation processes (Khan *et al.*, 2024).
- **Green Chemistry:** Development of biodegradable pharmaceuticals (Kümmerer, 2009).
- **Proper Disposal:** Public awareness and take-back programs for unused medicines.
- **Regulatory Frameworks:** Implementation of environmental quality standards for pharmaceutical residues (OECD, 2018).
- **Ecopharmacovigilance:** Continuous environmental surveillance of drug residues and effects (Medhi, *et al.*, 2012).

Conclusion:

Pharmaceutical contamination of freshwater ecosystems represents an emerging but severe environmental challenge. The persistence and bioactivity of these compounds threaten aquatic biodiversity and human health alike. Despite growing awareness, data on long-term ecological consequences remain limited, particularly in developing nations. Future research should focus on developing cost-effective removal technologies, promoting green drug design, and enforcing global policies for sustainable pharmaceutical management. Integrating environmental monitoring with public health strategies is essential to safeguard water quality and ecosystem resilience. Understanding the chronic effects of pharmaceutical exposure requires an integrated, multidisciplinary approach that combines molecular, biochemical, and ecological perspectives. Strengthening wastewater treatment, promoting eco-friendly drug design, and encouraging responsible disposal practices are crucial for mitigating contamination. Public awareness, take-back programs, and stringent effluent regulations, along with sustainable water management and the “One Health” approach, are essential to preserve freshwater ecosystem integrity. Ultimately, addressing pharmaceutical pollution demands global cooperation, policy enforcement, and technological innovation to ensure environmental sustainability and protect public health for future generations.

References:

1. aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., & Küster, A. (2016). Pharmaceuticals in the environment—Global occurrences and perspectives. *Environmental Toxicology and Chemistry*, 35(4), 823–835. <https://doi.org/10.1002/etc.3339>

2. Avar, P., Maasz, G., Takács, P., Lovas, S., Zrinyi, Z., Svigruha, R., Takátsy, A., Tóth, L. G., & Pirger, Z. (2016). HPLC-MS/MS analysis of steroid hormones in environmental water samples. *Drug Testing and Analysis*, 8(1), 123–127. <https://doi.org/10.1002/dta.1829>
3. Boxall, A. B. A., Sumpter, J. P., & Wilkinson, J. L. (2023). One Health approach to managing pharmaceuticals in the environment. *Environmental Science & Technology*, 57(5), 2411–2420.
4. Chen, C., Zhao, Y., & Liu, J. (2023). Global distribution and risk assessment of pharmaceuticals in river systems: A meta-analysis. *Environment International*, 178, 108073.
5. Das, B. K., Behera, B. K., Chakraborty, H. J., Paria, P., Gangopadhyay, A., Rout, A. K., Nayak, K. K., Parida, P. K., & Rai, A. (2020). Metagenomic study focusing on antibiotic resistance genes from the sediments of River Yamuna. *Gene*, 758, 144951. <https://doi.org/10.1016/j.gene.2020.144951>
6. Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., Naiman, R. J., Prieur-Richard, A. H., Soto, D., Stiassny, M. L. J., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, 81(2), 163–182.
7. Dutta, A., Banerjee, A., & Chaudhry, S. (2022). Ecopharmacovigilance: Need of the hour. *Indian Journal of Pharmacology and Pharmacotherapeutics*, 9(2), 77–80. <https://doi.org/10.18231/j.ijpp.2022.014>
8. Dwivedi, M., & Yadav, A. K. (2025). Removal of pharmaceuticals from wastewater using hybrid membrane bioreactors: A review. *Journal of Water Process Engineering*, 74, 104182.
9. Estrada-Almeida, A. G., Castrejón-Godínez, M. L., Mussali-Galante, P., Tovar-Sánchez, E., & Rodríguez, A. (2024). Pharmaceutical pollutants: Ecotoxicological impacts and the use of agro-industrial waste for their removal from aquatic environments. *Journal of Xenobiotics*, 14(4), 1465–1518. <https://doi.org/10.3390/jox14040082>
10. European Commission (EC). (2022). *Surface Water Watch List for Emerging Pollutants in the European Union*. Official Journal of the European Union.
11. Fick, J., Söderström, H., Lindberg, R. H., Phan, C., Tysklind, M., & Larsson, D. G. J. (2009). Contamination of surface, ground, and drinking water from pharmaceutical production. *Environmental Toxicology and Chemistry*, 28(12), 2522–2527. <https://doi.org/10.1897/09-073.1>

12. Formagini, L., Ramirez, J. Z. R., Corá, V. R., & Souza, D. M. (2025). Psychotropic pharmaceuticals in aquatic environments: Occurrence and analytical challenges. *Science of the Total Environment*, 998, 180269. <https://doi.org/10.1016/j.scitotenv.2025.180269>
13. Garner, R. E., Matamoros, V., & Bayen, S. (2023). Climate change and pharmaceutical pollution: Emerging interactions and global risk assessment. *Science of the Total Environment*, 872, 162112.
14. Hejna, M., Kapuścińska, D., & Aksmann, A. (2022). Pharmaceuticals in the aquatic environment: A review on eco-toxicology and the remediation potential of algae. *International Journal of Environmental Research and Public Health*, 19(13), 7717. <https://doi.org/10.3390/ijerph19137717>
15. Uttej Dubany, A., Sailaja, A., & Savitha, B. (2024). Inland fisheries in Telangana, India: Current status and perspectives. *Journal of Scientific Research and Reports*, 30(12), 235–241.
16. Kayode-Afolayan, S. D., Ahuekwe, E. F., & Nwinyi, O. C. (2022). Impacts of pharmaceutical effluents on aquatic ecosystems. *Scientific African*, 17, e01288.
17. Khan, M. J., Wibowo, A., Karim, Z., Posoknistakul, P., Matsagar, B. M., Wu, K. C.-W., & Sakdaronnarong, C. (2024). Wastewater treatment using membrane bioreactor technologies: Removal of phenolic contaminants from oil and coal refineries and pharmaceutical industries. *Polymers*, 16(3), 443. <https://doi.org/10.3390/polym16030443>
18. Kümmerer, K. (2009). The presence of pharmaceuticals in the environment due to human use – Present knowledge and future challenges. *Journal of Environmental Management*, 90(8), 2354–2366. <https://doi.org/10.1016/j.jenvman.2009.01.023>
19. Medhi, B., & Sewal, R. K. (2012). Ecopharmacovigilance: An issue urgently to be addressed. *Indian Journal of Pharmacology*, 44(5), 547–549.
20. Nyaga, M. N., Nyagah, D. M., & Njagi, A. (2020). Pharmaceutical waste: Overview, management, and impact of improper disposal.
21. Organisation for Economic Co-operation and Development (OECD). (2018). *Pharmaceutical innovation and access to medicines*. OECD Publishing.
22. Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., & Mohan, D. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. *Chemical Reviews*, 119(6), 3510–3673. <https://doi.org/10.1021/acs.chemrev.8b00299>
23. Rathi, S., Sharma, S., & Yadav, A. (2023). Challenges in the removal of pharmaceuticals from wastewater: A review. *Journal of Environmental Management*, 342, 118111.

24. Santos, L. H. M. L. M., Araújo, A. N., Fachini, A., Pena, A., Delerue-Matos, C., & Montenegro, M. C. B. S. M. (2010). Ecotoxicological aspects related to the presence of pharmaceuticals in the aquatic environment. *Journal of Hazardous Materials*, 175(1–3), 45–95. <https://doi.org/10.1016/j.jhazmat.2009.10.100>
25. Sarkar, U. K., Pathak, A. K., Tyagi, L. K., Srivastava, S. M., Singh, S. P., & Dubey, V. K. (2013). Biodiversity of freshwater fish of a protected river in India: Comparison with unprotected habitat. *Revista de Biología Tropical*, 61(1). <https://doi.org/10.15517/rbt.v61i1.10942>
26. Sharma, R., Rathi, S., & Yadav, A. (2023). Pharmaceutical contamination in Asian aquatic systems: Sources, impacts, and regulatory perspectives. *Science of the Total Environment*, 870, 162260.
27. Szarka, A., Vnuková, L., Keršňáková, Z., Viktoryová, N., & Hrouzková, S. (2024). Contamination with pharmaceuticals in aquatic environment: Focus on analytical methodologies. *Applied Sciences*, 14(19), 8645. <https://doi.org/10.3390/app14198645>
28. Wilkinson, J. L., Boxall, A. B. A., Kolpin, D. W., Leung, K. M. Y., Lai, R. W. S., Galbán-Malagón, C., Adell, A. D., Mondon, J., & Carbery, M. (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences*, 119(8), e2113947119. <https://doi.org/10.1073/pnas.2113947119>
29. Zhang, C., Barron, L. P., & Stürzenbaum, S. R. (2025). Pollution of soil by pharmaceuticals: Implications for metazoan and environmental health. *Annual Review of Pharmacology and Toxicology*, 65.

STATUS, DISTRIBUTION, AND CONSERVATION CHALLENGES OF FISH COMMUNITIES IN SIR PIRAJIRAO LAKE, MURGUD

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Abstract:

The present study investigates the status, seasonal distribution, and conservation challenges of fish communities in Sir Pirajirao Lake, Murgud, Kolhapur District, Maharashtra. Fish sampling was conducted from January 2019 to December 2020 across pre-monsoon, monsoon, and post-monsoon seasons with the support of local fishermen. A total of indigenous and exotic fish species was identified using standard taxonomic keys. Seasonal variation in species presence and abundance revealed a noticeable dominance of exotic species, particularly *Oreochromis mossambicus*, *O. niloticus*, and *Cyprinus carpio*, which were consistently present across all seasons. In contrast, several native species showed reduced occurrence, especially during the monsoon period. Diversity indices indicated lower richness and evenness during monsoon, suggesting ecological stress and possible competition from exotic species. The results indicate that the lake is undergoing a shift toward an exotic-dominated fish community, which may affect native biodiversity and ecosystem stability. Conservation measures, including regulation of exotic species, habitat restoration, and awareness among local stakeholders, are recommended to maintain ecological balance and support sustainable fisheries.

Keywords: Conservation, Exotic & Indigenous Species, Fish Diversity, Seasonal Variation.

Introduction:

Freshwater ecosystems support some of the highest levels of aquatic biodiversity and play a vital role in sustaining ecological balance, local livelihoods, and food security (Dudgeon *et al.*, 2006). India possesses an extensive network of rivers, reservoirs, and lakes that harbor diverse fish communities, many of which hold ecological, nutritional, and cultural importance (Lakra *et al.*, 2010). Reservoirs, in particular, function as multi-use ecosystems, providing fisheries resources

while undergoing constant ecological changes influenced by hydrological fluctuations, nutrient dynamics, and human activities (Sugunan, 1995).

The introduction and establishment of exotic fish species in freshwater bodies have increasingly contributed to shifts in native fish communities. Species such as *Oreochromis mossambicus*, *O. niloticus*, and *Cyprinus carpio* have been widely introduced across India for aquaculture and enhancement fisheries (Pullin *et al.*, 1997). These species often possess rapid growth, high tolerance to environmental variation, and competitive feeding strategies, enabling them to dominate over native fish populations (Huckstorf *et al.*, 2008). Such dominance can lead to reduced native species abundance, altered trophic interactions, habitat modification, and long-term loss of biodiversity (Pinder & Gozlan, 2003).

Sir Pirajirao Lake, located in Murgud, Kolhapur district, is an important local freshwater resource supporting inland fisheries, domestic use, and agricultural activities. Despite its significance, systematic assessments of fish diversity and community composition within this lake remain limited. Recent local reports suggest increasing prevalence of exotic fishes, raising concerns regarding ecological stability and conservation of indigenous fish fauna (Sarkar *et al.*, 2012). Understanding the current status, distribution patterns, and seasonal variations of fish communities is therefore essential for developing sustainable management strategies.

The present study aims to assess the status, seasonal distribution, and conservation challenges of fish communities in Sir Pirajirao Lake. The findings contribute to the broader understanding of how exotic species influence freshwater fish assemblages and provide baseline data to support future conservation and fishery management planning.

Materials and Methods:

The study was conducted at Sir Pirajirao Lake, Murgud (16.389100568402633° N, 74.20891401548036° E) from January 2019 to December 2020, covering pre-monsoon, monsoon, and post-monsoon seasons. Fish samples were collected seasonally with the help of local fishermen using cast nets, gill nets, drag nets, and hook-and-line methods. Representative specimens were photographed and preserved in 10% formalin when necessary.

Fish identification and taxonomic classification were carried out using standard ichthyological keys and descriptions provided by Mishra (1959), Day (1989), Jhingran (1991), Shrivastava (1998), Jayaram (1999), and Talwar and Jhingran (1999). Scientific names were cross-verified using the IUCN Red List.

Seasonal abundance was recorded as P (Present), A (Abundant), and R (Rare). Data on species richness, dominance, and diversity were analyzed using PAST (Paleontological Statistics)

software, with indices including Shannon-Wiener (H'), Simpson's Dominance (D), Margalef Richness, Menhinick Index, Evenness (J), Berger-Parker Dominance, and Chao-1 estimator.

Results:

In the present study, a total of 22 fish species belonging to 5 orders and 8 families were documented from Sir Pirajirao Lake, Murgud. The order Cypriniformes contributed the highest number of species (12), indicating its dominance in the lake's ichthyofaunal composition, followed by Siluriformes with five species. The remaining orders Anabantiformes, Cichliformes, Gobiiformes, and Synbranchiformes, were represented by one or two species each. Among the recorded species, the majority (19 species) were indigenous to the region, while only three species (*Oreochromis mossambicus*, *Oreochromis niloticus*, and *Cyprinus carpio*) were identified as exotic. Most species belonged to the Least Concern (LC) category according to the IUCN Red List, whereas *O. mossambicus* was classified as Vulnerable (VU), reflecting broader population pressures.

Seasonal variation in fish occurrence revealed noticeable fluctuations in abundance and distribution. During the monsoon season, most indigenous species showed increased presence due to improved hydrological conditions, greater habitat expansion, and enhanced availability of food resources. However, in the pre-monsoon and post-monsoon periods, several native species such as *Glossogobius giuris*, *Rita rita*, and *Mastacembelus armatus* appeared less frequently, likely influenced by reduced water levels, seasonal stress, and intensified fishing activity. Major carp species, including *Catla catla*, *Labeo rohita*, *Cirrhinus mrigala*, and *Labeo calbasu* were observed consistently across seasons, although their abundance varied, suggesting both natural recruitment and intermittent stocking support their populations (Table 1).

A notable finding of the study was the continuous and uniform presence of exotic species, particularly *O. mossambicus* and *O. niloticus*, which were recorded in all seasons. Their ability to reproduce multiple times annually, adapt rapidly to changing environmental conditions, and aggressively compete for food and habitat has enabled them to establish ecological dominance within the lake. This dominance appears to be impacting native fish communities, especially small indigenous cyprinids such as *Amblypharyngodon mola* and *Salmostoma phulo*, which showed reduced occurrence during some seasons. The increasing prevalence of tilapia suggests competitive displacement of native species, potential alteration of food web dynamics, and disruption of natural recruitment patterns.

Table 1: Seasonal occurrence and conservation status of fish species recorded from Sir Pirajirao Lake, Murgud

Sr. No.	Order	Family	Scientific Name (Author, Year)	Common Name	IUCN Status	Status	Pre-Monsoon	Monsoon	Post-Monsoon
1	Anabantiformes	Channidae	<i>Channa striata</i> (Bloch, 1793)	Striped Snakehead	LC	Indigenous	P	A	R
2	Anabantiformes	Channidae	<i>Channa punctata</i> (Bloch, 1793)	Spotted Snakehead	LC	Indigenous	P	A	P
3	Cichliformes	Cichlidae	<i>Oreochromis mossambicus</i> (Peters, 1852)	Mozambique Tilapia	VU	Exotic	P	P	P
4	Cichliformes	Cichlidae	<i>Oreochromis niloticus</i> (Linnaeus, 1758)	Nile Tilapia	LC	Exotic	P	P	P
5	Cypriniformes	Cyprinidae	<i>Catla catla</i> (F. Hamilton, 1822)	Catla	LC	Indigenous	P	A	P
6	Cypriniformes	Cyprinidae	<i>Labeo rohita</i> (F. Hamilton, 1822)	Rohu	LC	Indigenous	P	A	P
7	Cypriniformes	Cyprinidae	<i>Cirrhinus mrigala</i> (Hamilton, 1822)	Mrigal	LC	Indigenous	P	A	P
8	Cypriniformes	Cyprinidae	<i>Labeo calbasu</i> (F. Hamilton, 1822)	Calbasu	LC	Indigenous	P	A	P
9	Cypriniformes	Cyprinidae	<i>Cyprinus carpio</i> (Linnaeus, 1758)	Common Carp	LC	Exotic	P	P	P
10	Cypriniformes	Cyprinidae	<i>Pethia sophore</i> (Hamilton, 1822)	Pool Barb	LC	Indigenous	P	A	P
11	Cypriniformes	Cyprinidae	<i>Pethia ticto</i> (F. Hamilton, 1822)	Ticto Barb	LC	Indigenous	P	A	P
12	Cypriniformes	Cyprinidae	<i>Amblypharyngodon mola</i> (F. Hamilton, 1822)	Mola Carplet	LC	Indigenous	P	A	P

13	Cypriniformes	Cyprinidae	<i>Salmostoma phulo</i> (F. Hamilton, 1822)	Razorbelly Minnow	LC	Indigenous	P	A	R
14	Cypriniformes	Cyprinidae	<i>Rasbora daniconius</i> (F. Hamilton, 1822)	Slender Rasbora	LC	Indigenous	P	A	P
15	Cypriniformes	Cyprinidae	<i>Garra mulya</i> (Sykes, 1839)	Mulla Garra	LC	Indigenous	P	A	P
16	Cypriniformes	Cyprinidae	<i>Barilius bendelisis</i> (Hamilton, 1807)	Hill Trout	LC	Indigenous	P	A	P
17	Gobiiformes	Gobiidae	<i>Glossogobius giuris</i> (Hamilton, 1822)	Tank Goby	LC	Indigenous	R	A	P
18	Siluriformes	Bagridae	<i>Mystus seenghala</i> (Sykes, 1839)	Seenghala Catfish	LC	Indigenous	P	A	P
19	Siluriformes	Bagridae	<i>Mystus vittatus</i> (Bloch, 1794)	Striped Dwarf Catfish	LC	Indigenous	P	A	P
20	Siluriformes	Bagridae	<i>Rita rita</i> (Hamilton, 1822)	Rita Catfish	LC	Indigenous	R	A	R
21	Siluriformes	Clariidae	<i>Clarias batrachus</i> (Linnaeus, 1758)	Walking Catfish	LC	Indigenous	P	A	P
22	Synbranchiformes	Mastacembelidae	<i>Mastacembelus armatus</i> (Lacépède, 1800)	Spiny Eel	LC	Indigenous	R	A	P

(P = Present, A = Abundant, R = Rare)

The diversity indices calculated for Sir Pirajirao Lake exhibited noticeable seasonal variation (Table 2). During the pre-monsoon, the fish community showed higher diversity with a Shannon index (H) of 2.836 and Simpson's (1-D) value of 0.931, indicating a more even and stable distribution of species. The post-monsoon period also reflected relatively high diversity (H = 2.759; 1-D = 0.9164), which may be attributed to improved habitat conditions following monsoon flooding. In contrast, the monsoon season recorded the lowest diversity (H = 1.579; 1-D = 0.75) and the highest dominance value (D = 0.25), suggesting that few species were more abundant while others declined. The Berger-Parker index during monsoon (0.3571) further supported this trend of species dominance, likely associated with ecological disturbances and reproductive shifts. Similarly, richness estimators such as Margalef (1.801) and Fisher's alpha (2.996) were lowest in the monsoon, while the highest values were observed in the post-monsoon (Margalef = 5.434; Fisher's alpha = 21.51), indicating greater species recovery and recruitment after rainfall. The Chao-1 estimates also reflected this pattern, with the highest species richness recorded in the post-monsoon (38.2) and the lowest in the monsoon (8.5). The results demonstrate that monsoon-induced hydrological changes cause temporary reductions in diversity, whereas pre- and post-monsoon periods support richer and more evenly distributed fish communities in the lake.

Table 2: Diversity Indices of Fish Communities Across Different Seasons in Sir Pirajirao Lake

Parameters	Pre-Monsoon	Monsoon	Post-Monsoon
Dominance_D	0.06896	0.25	0.08356
Simpson_1-D	0.931	0.75	0.9164
Shannon_H	2.836	1.579	2.759
Evenness_e^H/S	0.7748	0.6927	0.7891
Brillouin	2.497	1.311	2.149
Menhinick	2.345	1.323	3.482
Margalef	4.69	1.801	5.434
Equitability_J	0.9175	0.8114	0.9209
Fisher_alpha	9.415	2.996	21.51
Berger-Parker	0.1136	0.3571	0.1818
Chao-1	25.75	8.5	38.2

The seasonal distribution of exotic and indigenous fish groups revealed a noticeable shift in species composition in Sir Pirajirao Lake (Table 3). During the pre-monsoon period, indigenous species were more frequently observed (62 records) compared to exotic species (26 records).

However, in the monsoon season, a sharp decline in indigenous species (5 records) was recorded, while exotic species remained consistently present (23 records). Although indigenous species showed some recovery in the post-monsoon season (20 records), exotic species continued to maintain a strong presence (13 records). When considering the total observations across all seasons, exotic species accounted for 62 records, demonstrating high year-round stability, whereas indigenous species totaled 87 records but with marked seasonal fluctuation. The sustained and relatively uniform presence of exotic fish, particularly tilapia, suggests their ecological dominance and competitive advantage, possibly leading to suppression of native fish populations through resource competition, rapid reproduction, and habitat occupation. This pattern highlights an emerging conservation concern, as increasing exotic abundance may gradually alter the native fish community structure and ecological balance of the lake.

Table 3: Comparative Seasonal Abundance of Exotic and Indigenous Fish Species

Group	Pre-Monsoon	Monsoon	Post-Monsoon	Total Observed
Exotic Species	26	23	13	62
Indigenous Species	62	5	20	87

The results indicate that Sir Pirajirao Lake supports a diverse fish community with clear seasonal variation in species richness and abundance. Indigenous species formed the major component of the ichthyofauna; however, their presence fluctuated markedly between seasons, particularly during the monsoon. In contrast, exotic species such as *Oreochromis mossambicus* and *O. niloticus* maintained a consistent and widespread occurrence throughout the year, reflecting their strong adaptive capacity and competitive dominance within the lake. The increasing prevalence of these exotic fishes, coupled with shifts in diversity indices, suggests ongoing ecological pressure on native species.

Discussion:

The present study provides insights into the status, distribution, and seasonal fluctuation of fish communities in Sir Pirajirao Lake, highlighting a gradual ecological shift driven by exotic fish dominance. The observed variability in fish diversity indices across seasons, particularly the reduction of richness and evenness during monsoon, indicates that hydrological disturbances play a major role in structuring fish assemblages in the reservoir. Similar patterns have been well-documented in tropical freshwater ecosystems, where rainfall-driven fluctuations in turbidity, dissolved oxygen, and habitat availability significantly influence species composition (Kindong *et al.*, 2020; Wu *et al.*, 2023). The higher diversity observed during pre- and post-monsoon seasons suggests relatively stable habitat conditions that support a broader range of ecological niches, consistent with findings from other Indian reservoirs (Adarsh *et al.*, 2024; Leela *et al.*, 2021).

The decline in diversity indices during the monsoon period may be attributed to increased sediment load, habitat homogenization, and temporary displacement of smaller indigenous fish into refugia or tributaries (Sarkar *et al.*, 2012). Studies from the Western Ghats have similarly reported seasonal contractions in native fish distribution linked to rainfall-driven hydrological pulses (Lakra *et al.*, 2010). The post-monsoon increases in Margalef and Fisher's alpha indices in the present study suggests a recruitment-driven recovery phase, which is common in floodplain-connected reservoirs where seasonal inundation enhances spawning success (Fernandes *et al.*, 2009; Jayaram, 1997). This supports the idea that hydrological connectivity underpins fish community resilience in lentic wetlands.

A critical observation of this study is the sustained year-round presence of exotic fish species, particularly *Oreochromis mossambicus*, *O. niloticus*, and *Cyprinus carpio*, and their stable representation even during ecologically stressful periods. Such dominance by exotic fishes has been reported widely in tropical lake ecosystems and is often linked to traits such as rapid growth, high reproductive rates, broad feeding habits, and tolerance to fluctuating water conditions (Pullin *et al.*, 1997; De Silva *et al.*, 2006; Biju Kumar *et al.*, 2022). The consistent presence of tilapia throughout all seasons in Sir Pirajirao Lake supports earlier evidence that tilapia can outcompete native cyprinids for food resources, breeding grounds, and littoral habitat zones (Shuai *et al.*, 2023).

The pattern observed here aligns with studies from reservoirs in Karnataka and Kerala, where tilapia establishment led to measurable declines in indigenous small fish populations (Biju Kumar *et al.*, 2022). Similar ecological effects have been documented in African and Southeast Asian River basins where tilapia introductions altered trophic structure and reduced functional diversity (Cudmore *et al.*, 2017; Zengeya *et al.*, 2013). The displacement of native species in Sir Pirajirao Lake is further supported by the sharp monsoon-season reduction of indigenous fish records (only 5 observations), while exotic species remained comparatively stable (23 observations). This indicates that exotic species are not only well established but are also better adapted to disturbance conditions than native taxa.

The dominance of exotic fish species in Sir Pirajirao Lake appears to result from several interacting ecological processes. Competitive displacement plays a major role, as native species sharing similar feeding niches are gradually outcompeted by exotic counterparts (Pullin *et al.*, 1997). Habitat modification further contributes to this shift; benthic-feeding species such as common carp disturb sediment and alter macrophyte structure, reducing habitat suitability for native fishes (Cudmore *et al.*, 2017). Another key factor is reproductive interference, where rapidly breeding species such as tilapia monopolize nursery grounds and outnumber slower-reproducing indigenous fishes (De Silva, 2004). These ecological pressures are reinforced by

human-mediated activities, including intentional stocking, accidental aquaculture escapes, and insufficient regulation of fisheries management practices, which collectively accelerate the spread and establishment of exotic fishes across Indian inland waters (Lakra *et al.*, 2010; Ujjania *et al.*, 2015). Similar patterns of native fish decline driven by exotic introductions have been documented in freshwater ecosystems of the Upper Ganga basin (Sarkar *et al.*, 2012).

The results suggest that Sir Pirajirao Lake is currently undergoing a major ecological transition toward an exotic-dominated fish community. Such community shifts may lead to reduced genetic diversity, compromised ecosystem resilience, and erosion of the ecological and cultural significance of native fish resources (Huckstorf *et al.*, 2008; Dudgeon *et al.*, 2006). To address this issue, conservation measures must prioritize the protection of native species while controlling the further expansion of exotics. Effective strategies should include regular monitoring of indigenous fish breeding patterns, targeted removal or controlled harvesting of exotic species, and habitat enhancement to promote in-lake spawning and refuge zones. Additionally, improved stakeholder awareness and stronger regulatory controls on fish introductions are critical. Successful outcomes from similar restoration efforts in regions of Kerala, Maharashtra, and Sri Lanka demonstrate that such management approaches can restore native fish diversity and ecological balance (Biju Kumar *et al.*, 2022; De Silva, 2004).

Conclusion:

This study shows that Sir Pirajirao Lake is shifting toward dominance by exotic fish species, especially tilapia and common carp, while many indigenous species are now less abundant. Seasonal variations in diversity indicate ecological stress, particularly during the monsoon. If this trend continues, native fish populations may decline further, affecting the ecological balance of the lake. Therefore, regular monitoring, control of exotic fish populations, protection of native breeding habitats, and awareness among local stakeholders are essential to support the recovery and long-term sustainability of the lake's fish community.

References:

1. Adarsh, K., Somashekara, S. R., Suryawanshi, U. A., Amogha, K. R., Kumar, S., Shivani, D., & Pathan, J. G. K. (2024). Fish species distribution and diversity indices of Hemavathi Reservoir, Hassan, Karnataka. *Uttar Pradesh Journal of Zoology*, 45(19), 130–141.
2. Biju Kumar, A., Raj, S., & Ravinesh, R. (2022). Alien and invasive aquatic species in Kerala: Status and trends. *Issues in Biodiversity Conservation and Management*, 321.
3. Cudmore, B. C., Jones, L. A., Mandrak, N. E., Dettmers, J. M., Chapman, D. C., Kolar, C. S., & Conover, G. (2017). *Ecological risk assessment of grass carp (Ctenopharyngodon idella) for the Great Lakes basin*. Ottawa, ON, Canada: Canadian Science Advisory Secretariat.

4. De Silva, S. S. (2004). *Tilapias as alien aquatics in Asia and the Pacific: A review*.
5. De Silva, S. S., Amarasinghe, U. S., & Nguyen, T. T. (2006). *Better-practice approaches for culture-based fisheries development in Asia*.
6. Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status, and conservation challenges. *Biological Reviews*, 81(2), 163–182.
7. Fernandes, R., Gomes, L. C., Pelicice, F. M., & Agostinho, A. A. (2009). Temporal organization of fish assemblages in floodplain lagoons: The role of hydrological connectivity. *Environmental Biology of Fishes*, 85(2), 99–108.
8. Huckstorf, V., Lewin, W. C., & Wolter, C. (2008). Environmental flow methodologies to protect fisheries resources in human-modified large lowland rivers. *River Research and Applications*, 24(5), 519–527.
9. Jayaram, K. C. (1977, October). Zoogeography of Indian freshwater fishes. In *Proceedings/Indian Academy of Sciences* (Vol. 86, No. 4, pp. 265–274). New Delhi: Springer India.
10. Kindong, R., Wu, J., Gao, C., Dai, L., Tian, S., Dai, X., & Chen, J. (2020). Seasonal changes in fish diversity, density, biomass, and assemblage alongside environmental variables in the Yangtze River Estuary. *Environmental Science and Pollution Research*, 27(20), 25461–25474.
11. Lakra, W. S., Sarkar, U. K., Gopalakrishnan, A., & Kathirvelpandian, A. (2010). *Threatened freshwater fishes of India*. National Bureau of Fish Genetic Resources.
12. Leela, R. V., Salim, S. M., Parakkandi, J., Panikkar, P., Mani, K., Eregowda, V. M., & Das, B. K. (2021). Pattern of spatio-temporal fish diversity in association with habitat gradients in a tropical reservoir, India. *Aquatic Ecosystem Health & Management*, 24(3), 111–120.
13. Pullin, R. S. V., Palomares, M. L., Casal, C. V., Dey, M. M., & Pauly, D. (1997, November). Environmental impacts of tilapias. In *Tilapia Aquaculture*. Proceedings of the Fourth International Symposium on Tilapia in Aquaculture (Vol. 2, pp. 554–570).
14. Sarkar, U. K., Pathak, A. K., Sinha, R. K., Sivakumar, K., Pandian, A. K., Pandey, A., ... & Lakra, W. S. (2012). Freshwater fish biodiversity in the River Ganga (India): Changing pattern, threats and conservation perspectives. *Reviews in Fish Biology and Fisheries*, 22(1), 251–272.
15. Shuai, F., Li, J., & Lek, S. (2023). Nile tilapia (*Oreochromis niloticus*) invasion impacts the trophic position and resource use of commercially harvested piscivorous fishes in a large subtropical river. *Ecological Processes*, 12(1), 22.

16. Ujjania, N. C., Dubey, M., Sharma, L. L., Balai, V. K., & Srivastva, R. M. (2015). Bio-invasion of exotic fish tilapia (*Oreochromis mossambicus* P. 1852) in Lake Jaisamand, India. *International Journal of Fisheries and Aquatic Sciences*, 3(2), 174–177.
17. Wu, J., He, Y., Jiang, X., Zhao, Y., Cui, Y., & Wang, H. (2023). Assessing ecosystem health of floodplain lakes using an integrated bioassessment index. *Ecological Indicators*, 154, 110644.
18. Zengeya, T. A., Robertson, M. P., Booth, A. J., & Chimimba, C. T. (2013). Ecological niche modeling of the invasive potential of Nile tilapia *Oreochromis niloticus* in African river systems: Concerns and implications for the conservation of indigenous congeners. *Biological Invasions*, 15(7), 1507–1521.
19. Sugnan, V. V. (1995). *Reservoir fisheries of India* (Vol. 345). Daya Books.
20. Pinder, A. C., & Gozlan, R. E. (2003). Sunbleak and topmouth gudgeon: Two new additions to Britain's freshwater fishes. *British Wildlife*, 15(2), 77–83.
21. Talwar, P. K., & Jhingran, A. G. (1999). *Inland fishes of India and adjacent countries* (2 Vols.). Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, 1158 p.
<https://doi.org/10.2307/1447207>
22. Jayaram, K. C. (1999). *The freshwater fishes of the Indian region*. Narendra Publishing House, New Delhi, 551 p.
23. Jhingran, V. G. (1991). *Fish and fisheries of India*. Hindustan Publishing Corporation, Delhi, India. <https://doi.org/10.59317/9789389130607>
24. Shrivastava, G. J. (1998). *Fishes of U.P. and Bihar*. Vishwavidyalaya Prakashan Chowk, Varanasi, India.
25. Mishra, K. S. (1959). An aid to identification of the common commercial fishes of India and Pakistan. *Record Indian Museum*, 57, 1–320. <https://doi.org/10.26515/rzsi/v57/i1-4/1959/161986>
26. Day, F. (1958). *The fishes of India: Being a natural history of the fishes known to inhabit the seas and fresh waters of India, Burma and Ceylon*. Text and atlas. London: William Dawson and Sons Ltd. <https://doi.org/10.5962/bhl.title.55567>

Sustainable Approaches in Aquatic Science

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