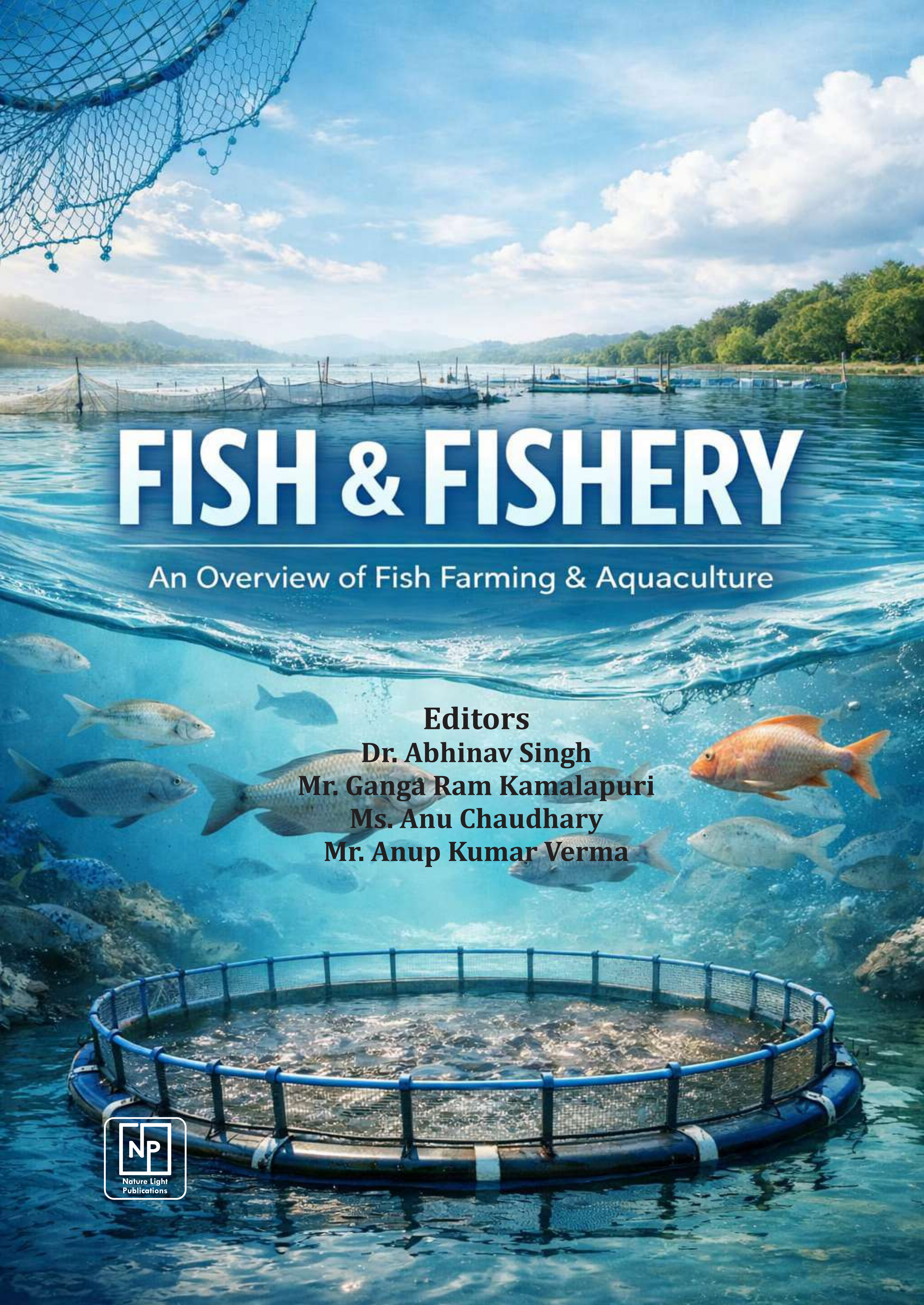

FISH & FISHERY

An Overview of Fish Farming & Aquaculture

Editors
Dr. Abhinav Singh
Mr. Ganga Ram Kamalapuri
Ms. Anu Chaudhary
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Nature Light Publications

An International Edited Book *ISBN-978-93-49938-76-2*

FISH AND FISHERIES: AN OVERVIEW OF FISH FARMING AND AQUACULTURE

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Published By

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First Edition: April, 2026

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ISBN- 978-93-49938-76-2

Published by:
Nature Light Publications, Pune
309 West 11, Manjari VSI Road, Manjari Bk.,
Haveli, Pune- 412 307.
Website: www.naturelightpublications.com
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Contact No: +91 9822489040 / 9922489040

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Preface

The edited volume Fish and Fisheries: An Overview of Fish Farming and Aquaculture is a comprehensive academic effort that highlights the growing importance of fisheries and aquaculture in ensuring food security, rural development, environmental sustainability, and economic growth across the globe. Fisheries science has evolved significantly in recent decades, integrating traditional practices with advanced technologies and sustainable management approaches to address emerging environmental and socio-economic challenges.

Aquaculture today represents one of the fastest-growing food production sectors worldwide. However, rapid industrialization, climate change, pollution, habitat degradation, antibiotic resistance, and biodiversity loss have created serious concerns for aquatic ecosystems and fish production systems. In this context, this volume brings together scholarly contributions that examine both the opportunities and challenges associated with modern fish farming and fisheries management.

The chapters included in this book explore a wide range of contemporary themes. The discussion on integrated fish farming systems emphasizes sustainable livelihood generation and resource optimization in rural communities. The impact of climate stress on urban rivers and aquatic biodiversity reflects the urgent need for ecological conservation and adaptive management strategies. Important issues related to quality control and food safety standards in fisheries products are also critically examined.

The volume further highlights cutting-edge scientific developments such as CRISPR and genetic engineering in aquaculture, which offer promising possibilities for improving fish growth, disease resistance, and climate resilience. Emerging interdisciplinary topics including nanotechnology applications in fisheries and the fascinating snapping mechanisms of pistol shrimp demonstrate the expanding scope of fisheries research.

Environmental concerns remain central to this collection. Chapters *addressing microplastic pollution, habitat degradation, and antibiotic resistance provide valuable insights into the ecological and public health implications of unsustainable aquaculture practices. Additionally, the review of exotic fish species and their impact on Indian fisheries contributes significantly to understanding biodiversity conservation and ecosystem balance.*

This book is intended to serve as a useful resource for researchers, academicians, students, policymakers, environmentalists, fisheries professionals, and all those interested in sustainable aquaculture and aquatic resource management. The editors sincerely hope that the ideas, analyses, and findings presented in this volume will inspire further research, innovation, and policy interventions in the field of fisheries and aquaculture.

We express our heartfelt gratitude to all contributing authors, reviewers, and collaborators whose valuable efforts and scholarly contributions made this publication possible. We also extend our appreciation to the publishing team for their continuous support and dedication throughout the completion of this work.

We believe that this edited volume will contribute meaningfully to the advancement of fisheries science and promote sustainable practices for the conservation and responsible utilization of aquatic resources for future generations.

Editors

Fish and Fisheries: An Overview of Fish Farming and Aquaculture

Table of Content

Integrated Fish Farming Systems: A Sustainable Method of Enhancement of Rural Livelihood

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Article DOI Link: https://zenodo.org/uploads/20108846

DOI: 10.5281/zenodo.20108846

Abstract

Sustainable and eco-friendly agriculture system where fish cultivation is adjoining with other farming activities is known as Integrated Fish Forming such as livestock, poultry, pig and cattle farming with mushroom or crops like paddy, piggery or any flower cultivation, all these activities perform in the same area. There are sequential linkages between different farming activities are established in such way to waste or by product from one system is effectively recycled. A unique and lucrative venture, it provides higher income through two different crops available cheap protein sources for the rural population, and increases and maximizing overall productivity. It offers high yielding at low cost. Its aim is to increase productivity, profitability, sustainability, balance food, clean environment and reuses resources.

Keywords: Integrated fish farming, cultivation, fish farming, sustainability, poultry manures

Introduction

In India, integrated farming systems have emerged as a result of a rising demand for land and water. The foundation of integrated farming is the idea that by combining two or more production systems, farm profits can be maximised. The production of a greater variety of agricultural products, an increase in cash incomes, an improvement in the quality and quantity of agricultural products, a decrease in pollution, and a more effective exploitation of resources that would otherwise go unused are all benefits of this synergistic approach to agriculture that combines livestock and fish farming. Fish feed and pond fertilisers account for about 60% of the costs associated with fish cultivation. The carefully considered integration of fish production with other suitable farming methods can significantly lower these expenses.

Integrated farming is commonly and narrowly equated with the direct use of fresh livestock manure in fish culture (Little and Edwards, 1999). However, there are broader definitions that better illustrate potential linkages. Indeed, the term 'integrated farming' has been used for integrated resource management which may not include either livestock or fish components. Our focus is the integration of livestock and fish, often within a larger farming or livelihood system. Although housing of livestock over or adjacent to fish ponds facilitates loading of wastes, in practice livestock and fish may be produced at separate locations and by different people yet be integrated. Chen et al. (1994) distinguished between the use of manures produced next to the fishpond and elsewhere on the same farm. A wider definition includes manures obtained from off-farm and transported in bags, e.g. poultry manure, or as a slurry in tanks, such as for pig and large ruminant manure. Integrated farming involving aquaculture defined broadly is the concurrent or sequential linkage between two or more activities, of which at least one is aquaculture. These may occur directly on-site, or indirectly through off-site needs and opportunities, or both (Edwards, 1997). Benefits of integration are synergistic rather than additive; and the fish and livestock components may benefit to varying degrees. The term "waste" has not been omitted because of common usage but philosophically and practically it is better to consider wastes as "resources out of place" (Taiganides, 1978).

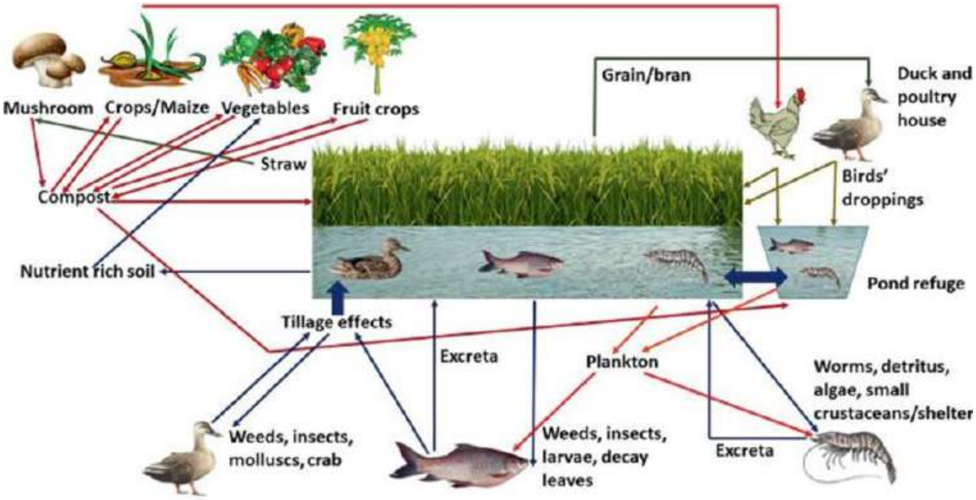

Figure. Schematic diagram of Integrated fish farming

Potential Linkages Between Livestock and Fish Production

The main potential linkages between livestock and fish production concern use of nutrients, particularly reuse of livestock manures for fish production. The term nutrients mainly refer to elements such as nitrogen (N) and phosphorous (P) which function as fertilizers to stimulate natural food webs rather than conventional livestock nutrition usage such as feed ingredients, although solid slaughterhouse wastes fed to carnivorous fish fall into the latter category. There are also implications for use of other resources such as capital, labour, space and water. A variety of factors affect the potential linkages between livestock and fish production. Both production and processing of livestock generate by-products that can be used for aquaculture. Direct use of livestock production wastes is the most widespread and conventionally recognized type of integrated farming. Production wastes include manure, urine and spilled feed; and they may be used as fresh inputs or be processed in some way before use. Use of wastes in static water fishponds imposes limitations in terms of both species and intensity of culture. Stimulation of natural food webs in the pond by organic wastes can support relatively low densities of herbivorous and omnivorous fish but not a large biomass of carnivorous fish. These biological processes are also temperature dependent.

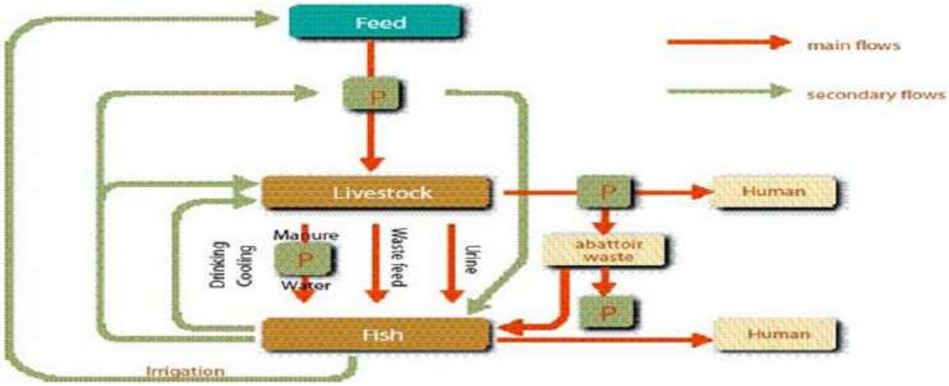

Figure. Linkage between livestock and fish farming

Our study focuses on the integration of fish and livestock. The use of cultured fish or fish products as livestock feeds, although currently uncommon, holds promise and is reviewed. Other, more minor beneficial linkages between fish and livestock production include use of fish culture water for drinking/bathing livestock and cooling livestock housing. Nutrients contained in culture water and sediments may be used to produce arable crops for livestock. The viability of these options depends on a variety of factors, including the types of livestock and fish that can be raised profitably and the production systems used.

Integrated farming may be defined as sequential linkages between two or more agri-related farming activities with one farming as major component. When fish becomes the major commodity in the system it is termed as integrated fish farming (IFF). The integration of fish farming with agriculture and animal husbandry is considered as sustainable farming system, which offers greater efficiency in resource utilization, reduces risk by diversifying crop, and provides additional income and food for small scale farming household. The basic principle involved in integrated farming are the utilization of the synergetic effects of inter-related farm activities, and the conservation, including the full utilization, of farm wastes. It is based on the concept that there is no waste, and waste is only a misplaced material for another product (FAO, 1977).

The integrated fish farming is well recognized in Asian countries like China, Malayasia, India, Vietnam, Indonesia, Philippines and Bangladesh having tropical climate, and later countries like Hungary, Germany, Ghana accepted IFF as an alternative land use, livelihood option and promoted as a strategy to improve nutritional standards. To meet the demand and supply the integration with fish and livestock is very encouraging and could bring a significant profitability from a unit area particularly for small holding farmers. Integrated farming may be defined as a sequential linkage between two or more farming activities. When the fish becomes a major commodity of this system it is known as integrated fish farming (IFF). Thus, the practice of Combining Fish Culture with Agriculture or livestock for full Utilization of resources and increased production is commonly known as Integrated Fish Farming. IFF include efficiency in resource utilization, efficient utilization of wastes from other culture practices, reduction in risks by diversifying crops, recycling of wastes/ byproducts of one farming system as input for another system, efficient utilization of available farming space for maximum production, additional source of food and income, a reduction in additional cost for supplementary feeding & fertilization. In fact, IFF is an artificial balanced ecosystem without any waste. It generates more avenues for employment; it reduces the input and increases output and economic efficiency. IFF provides fish, meat, milk, vegetables, fruits, fodder, eggs, grains, & mushroom etc. Altogether, IFF has enough potential for rural livelihood & socio-economic status.

Most of the small holder farmers cannot afford the concentrate feed requirements of the fishes in intensive fish farming. Hence, the integrated fish farming with livestock and utilization of livestock excreta could meet demand by growing fish food organism i.e. plankton in the pond or water bodies along with direct feeding of animal waste. The common livestock- fish integrated farming systems are-

- Duck cum fish integration system
- Poultry cum fish integration system
- Pig cum fish integration system
- Sheep/Goat cum fish integration system
- Cattle cum fish integration system
- Buffalo cum fish integration system

Integrated Livestock-Fish Farming: Basic principles

The basic principles for livestock-fish integrated farming system are full utilization of livestock farm wastes and conversion of waste in to valuable fish protein. The spilled over feed or feed derived from livestock manure may be utilized as direct feed or the manure from livestock helps in production of planktons which form the feed for fishes in the pond.

In this integrated farming system optimal stocking density with desired fish species, optimum utilization of manure and lime also play an important role for successful production of fish. Excess manuring with livestock excreta may cause poor water quality and may lead to depletion of dissolved oxygen in water causing mortality to fishes. The livestock-fish farming may be extensive, intensive or semi-intensive system depending upon the availability of resources and capital.

Rationale of Integrated Farming

The rationale behind integrated farming is to minimize wastes from the various subsystems on the farm: wastes or by-products from each subsystem are used as inputs to other subsystems to improve the productivity and lower the cost of production of the outputs of the various subsystems (Edwards et al., 1986).

Integrated fish farming is generally considered particularly relevant to benefit the rural poor. In Asia, fish farming has been a part-time activity of peasant farmers, who developed it as an efficient means of utilizing farm resources to the maximum capacity.

Integrated farming can play a role in increasing employment opportunities, nutrition and income of rural populations and has received considerable attention in recent years. Besides many developing countries of Asia, some in Africa (Central African Republic, Cote d'Ivoire, Cameroon, Zambia) and South America (Brazil, Ecuador, Panama) have introduced this system on a pilot or larger scale. Some of the East European countries (Hungary, Czechoslovakia, Poland) have expanded and improved in recent years, the practice of integrating animal production with fish culture (Pillay, 1990).

Simultaneous production of fish in ponds, with pigs, duck or chicken rearing in pens, beside or over the ponds constitutes a continuous organic fertilization of the pond by the livestock. This practice increases the efficiency and rentability of both livestock farming and fish culture through the profitable utilization of animal and feed wastes (Vincke, 1988).

Selection of Fish Species

The most suitable species of fishes for integrated livestock-fish farming are those fishes that can filter and feed on phytoplankton, zooplankton and bacteria from water. The objective of integrated livestock cum fish farming is to produce maximum plankton in water through manuring which is rich in protein and a natural feed for fishes. The species of fishes which are consumed by the people and are efficient utilizer of phyto and zooplankton and also with macrophytic feeding nature are excellent for integrated livestock fish culture. Depending on the feeding nature the fishes are divided into three categories viz. Surface feeder, Column feeder and Bottom feeder. In integrated system of fish farming both indigenous and exotic species are recommended. Indigenous species like Catla (*Catla catla*) which are zooplankton feeder and exotic species Silver carp (*Hypophthalmichthys molitrix*) which are phytoplankton consumer are best example of surface feeder, whereas Rohu (*Labio rohita*) an indigenous species is omnivorous in nature and column feeder. The indigenous species Mrigal (*Cirrhinus mrigala*), Kalabasu (*Labeo calbasu*) are detritivorous and common carp (*Cyprinus carpio*) an exotic species which are detritivorous/ omnivorous in nature are bottom feeder. Exotic species like Grass carp (*Ctenopharyngodon idella*) which are herbivorous cover surface, column and marginal area of feeding zone.

Model Housing for Livestock- Fish Integrated Farming System

Considering the easy operation of day-to-day farm management and optimum production the livestock house is constructed above the water bodies especially for duck or poultry, nearby the pond or bank of pond for pig, poultry, cattle or buffaloes etc or partly in water and land. In duck cum fish farming the duck house may be constructed above the pond thus the excreta and feed waste directly goes to the pond and serve as a feed for fishes. When the house is constructed in bank of the water bodies, a channel is diverted from animal shed to the pond, so that the feed waste or excreta rinsed to the pond. In this case optimum livestock-fish ratio should be maintained to avoid excess manuring in water. In this type of housing duck, poultry, pig or cattle is recommended. In third type i.e. slatted floor is considered for both birds and animals like pigs. The animal excreta channelized in the pond directly. The slatted type floor may be constructed with wood, bamboo etc.

Pond Management

The pond should be water retentive and not to be situated in flood prone area. There should be constant water supply or throughout the year there should be water in the pond. Seasonal ponds, which can retain 8-to-9-month water also, can be considered for integrated farming system. At least there should be 1.0 m of water and ideal is 1.5 to 3.0 m. Soil pH should be within the 10 range of 6.5 to 7.5. If the soil pH is not up to the desired level, the pH may be corrected by application of lime and the quantity of lime is 2000 kg/ ha for 4.0 to 5.0 pH, 1200 kg for 5.1 to 6.0, 1000 kg for 6.1 to 6.5 (mild acidic), 400 kg for 6.6 to 7.0 (more or less neutral) and 200 kg/ ha for pH 7.1 to 7.5, which is mildly alkaline.

Lime helps in maintaining pH, kills and decomposes parasites. The lime should be applied in 3 to 4 split doses. The basal dose of lime and cow dung application in per hectare of water bodies is 1200 kg and 5000 kg, respectively. The pond should be regularly cleaned from aquatic plants which prevents sunlight penetration and oxygen circulation in water as well as shelter fish predators. The weeding can be done by manually, mechanically, biologically, chemically or by increasing the water depth in the pond. To kill predatory fishes Mahua (*Bassicala tifolia*) may be applied at the rate of 2500 kg/ ha of water bodies. By repeated netting unwanted fishes may also be removed. The ammonia, tea seed cake and bleaching powder also can be applied to remove enemy fishes.

Fish Stocking and Harvesting

The stocking time varies depending upon the climate in different regions of the country and also the availability of optimum water level in pond. Most suitable months for stocking of fingerlings is June and July. Water Temperature below 18 to 20ºC growth of the fishes restricted. During winter months growth is slow but in rainy season faster growth observed in fishes. Moreover, in winter months and in dry season water level comes down drastically in the water bodies. It is advisable to stocking fingerlings after winter months i.e. in rainy season and harvested before the water scarcity in pond. Generally, fishes are harvested after 12 months of stocking. But, where water bodies remain functional for 8 to 9 months fingerlings may be stocked in April and harvested in the month of November/ December. In composite fish culture 3 species, 4 species or 6 species may be stocked depending upon the availability of fingerlings in the market. In integrated livestock cum fish farming considering the surface, column and bottom feeder the ratio of fishes viz. Catla, Rohu and Mrigal should be 4: 3: 3 (3 species), in 4 species Catla, Rohu, Mrigal and Common carp ratio 3:3: 3:2 whereas, in 6 species Catla, Rohu, Mrigal, Silver carp, Grass carp and Common carp ratio should be 1.5: 2.0: 1.5: 1.5: 1.5: 2.0, respectively. For example, as Catla and Silver carp are surface feeder, the combined stocking density should not be more than 30 to 35%, but for Rohu which is column feeder grows well in ponds 11 with 3 to 4 m water depth should be stocked at the rate of 15 to 20%, whereas, bottom feeder like Mrigal and Common carp the ratio may be 40 to 45%. Grass carp should not be more than 5 to 10%, which can be fed with land grasses, vegetable refuse, banana leaves (practiced at ICAR RC ER, Patna) or with aquatic plants. Central Inland Fisheries Research Institute and ICAR Research Complex for NEH Region, Barapani recommended 6000 fingerlings/ ha for duck-fish integrated system and 6000 to 7000 fingerlings for integrated and non-integrated pig-fish farming system, respectively.

Potentiality of Livestock Manure in Integrated Fish Farming

Livestock excreta contain about 70 to 80% water and 20 to 25% dry matter. A cow produces 15 to 18 kg dung/ day. A poultry layer bird can produce 68 kg of excreta per year. A pig of 50 kg can produce 2.5 kg dung per day whereas; 90 kg pig produces 5 kg dung per day. Livestock excreta generally used as a potential manure in agricultural production system. It is rich in Nitrogen (N), Phosphorous (P) and Potassium (K) and also contains micronutrients. Thus, it makes the soil fertile. The average dung production in different animals varies according to their body size, body weight and feed and water consumption. In domestic animals like sheep, goat, cattle, buffalo, pig and poultry manure production is 0.15, 0.15, 1.10, 1.35, 0.25, and 0.014 tonnes/ animal/ year, respectively on dry weight basis. The N, P, K level in excreta varies in different species of animals. Like sheep/ goat 0.65, 0.50 and 0.03%, cattle 0.15, 0.01 and 0.05%, pig 0.60, 0.50 and 0.20%, poultry 0.76, 0.63 and 0.22%, duck 0.91, 0.38 and 0.36%, respectively.

Types of Livestock- Fish Integrated Farming Systems

Duck cum Fish Farming

As presently practised, the combination of duck and fish farming is considered as a means of reducing the cost of feed for ducks and a convenient and inexpensive way of fertilizing ponds for the production of fish (Pillay, 1990). In this integrated system, ponds provide living and foraging areas for the ducks and fish.

Ducks are reared in shelters built on the banks of the ponds or constructed over the ponds on stilts, or sometimes built on floating platforms. The ducks should be kept away from the dykes of the ponds since they search for insects, frogs and snails, damaging the earthen walls with their beaks and provoking erosion and the collapse of the dykes. Fencing inside the pond is therefore recommended. Ducks are known to eliminate almost all the snails in ponds in depths of up to 30–40 cm, thus controlling the immediate host of bilharziasis.

There are different duck strains. Peking ducks are used in Central Europe, China, the Philippines, Africa and Latin America. The Khaki-Campbell strain is raised in Thailand and the mule duck in Taiwan. Muskovy ducks are sometimes used in Africa. Each strain has different fattening periods and a marketable size of 2.0–2.8 kg is obtained within 7–9 weeks, depending on the strain, the size at stocking and feeding.

Figure. Duck cum fish farming

Ducks are reared at different densities, depending on the climatic conditions, the method of raising (extensive or intensive), water quality, and other factors.

In Eastern Europe (where the growing season is only about 150 days) 150–500 duckling are stocked per ha of pond; in Asia between 750 and 4,000 ducklings are stocked per ha, and in Africa and Latin America, 1,000 to 1,500 ducklings are stocked per ha.

In Hong Kong, in a system with 2,500–3,500 ducks/ha/year integrated with the polyculture of Chinese carps, 5–6 t. of duck meat and 2,750–5,640 kg/ha/year of fish has been produced (Delmendo, 1980).

Demonstration trials conducted in India in polyculture of Indian and common carps (at a stocking density of 6,340 fingerlings/ha) raised with ducks (100/ha) have yielded 4,323 kg of fish/ha/year, 250 kg of ducks (live weight) and 1,835 eggs (Jhingran and Sharma, 1980).

In the Philippines, comparative polycultures were implemented during two 90-day test periods, with *O. niloticus* (85%), common carp (14%) and *Ophiocephalus straitus* (1%), at stocking rates of 10,000-20,000 fingerling/ha, combined with Peking ducks at 750–1,250 ducks/ha. The highest net yields 1.69 t/ha of fish in 90 days were obtained with the 750 ducks: 20,000 fish stocking combination. Combining the two 90-day periods, the highest fish yields were 2.58 t/180 days with the 1,250 ducks: 20,000 fish stocking combination and 2.42 t/180 days with the 750 ducks: 20,000 fish stocking combination (Cruz and Shehadeh, 1980).

In Taiwan, approximately 3.5 t/ha/year of fish (without additional fertilization or supplementary feeding) have been achieved by raising 1,500 ducks/ha (Chen and Li, 1980).

Raising 1,000–2,000 ducks/ha on ponds in Vietnam, increased the average fish yield to 5 t/ha/year from 1 t/ha/year without ducks (Delmendo, 1980).

In Hungary, a yield of 1.6 – 2 t/ha/year of fish is obtained in polyculture of Chinese carps and common carp integrated with 500 ducks/ha. The duck production is between 1,000 and 1,200 kg/ha (Woynarovich, 1980).

In the Central African Republic, ponds stocked with *O. nilotius* (20,000 fingerlings/ha) and *Clarias gariepinus* (100 fingerlings/ha), combined with 1,500 Peking ducks/ha have produced 3.8–4.5 t of fish/ha/year and between 4–6 t/ha/year (live weight) of ducks (Vincke, 1976).

Trials conducted in Madagascar, in the cool forestry area, using common carp (2,500 fingerlings/ha) and *O. niloticus* (between 2,500 and 10,000/ha) integrated with ducks (1,5000 ducklings/ha), yielded 1.8-2.5 t/ha/year of fish and 2.0–2.5 t/ha/year of ducks (live weight) (Vincke, 1976).

In Zambia, *O. andersonii* integrated with Peking ducks, yielded of 5 t fish/ha/year.

In Ecuador, *O. nilotius* at stocking densities of 4,500 to 8,000 fingerlings/ha integrated with ducks (800 to 1,500/ha), farmers obtained between 3.3 and 4.67 t fish/ha/year and 1.76–3.75 t/ha/year of duck (Vincke and Schmidt, 1979).

Poultry cum Fish Farming

The integrated farming of chickens and fish is only practised in a few countries in Asia (Philippines, China, Indonesia, Thailand). Trials of chicken integrated with fish farming have also been conducted in Africa (Central African Republic, Cote d'Ivoire, Gabon and Madagascar), in Latin America (Ecuador, Panama) and in the USA. Not all the results of these experiments have been published.

Chicken (broilers or layers) are reared in pens beside or over the ponds, in the traditional way, in roughly the same conditions as ducks, generally at a density of 1,000 to 6,000 chickens/ha.

In the Philippines, in fish polyculture (*O. niloticus*, common carp and snakeheads with broilers (up to 5,000/ha), an extrapolated yield of about 7.3 t of fish/ha/year was obtained (20 kg/ha/day) (Little and Muir, 1987).

Figure. Poultry cum fish farming

In Indonesia, in monoculture of *Puntius gonionotus* in a 400 m2 pond (stocking rate of 125 kg of fingerling/ha) integrated with 6,000 layers/ha during a culture period of 3 months, the extrapolated yield was 5.1 t of fish/ha/year, plus 54,750 eggs/year (Djajadiredja et al., 1980). In polyculture of *Osteochilus hasselti* C. & V. (33% in weight), common carp (19%), *Helostoma temmincki* (29%) and *Puntius gonionotus* (19%) in a 2,408 m2 pond (stocking rate of 872 kg of fish/ha) integrated with 120 broilers/ha during a culture period of 3 months for the fish and 2 months for the chickens, the extrapolated yield was 10.8 t of fish/ha/year, plus 1,395 kg/ha/year of chickens (Djajadiredja et al., 1980).

In the Central Plain of Thailand a three-tier system is applied where chicken are raised above the pigsty constructed over the fish pond. In this combination, the chicken droppings are eaten by the pigs and, whatever is not consumed, is washed down to the pond with the pig manure, both as fish food and fertilizer. The total production of a 1.5 rai (=2400 m2) pond area is 4 t of Pangasius pangasius (equivalent to 16.67 t of fish/ha/year). 8 t of pigs (42 pigs/2400 m2 of pond, equivalent to 33.3 t of pigs/ha/year) and 15,330 chicken eggs from 60 hens/2400 m2 (equivalent to 63,875 eggs per ha/year) (Delmendo, 1980).

In the Central African Republic, egg laying chickens (at a stocking density of 3,000 chickens/ha) integrated with *O. niloticus* (30,000 fingerlings/ha), during a grow-out period of 189 days in 500 m2 ponds, have produced an extrapolated yield of 5.5 t of fish/ha/year, plus 2,746 eggs/year.

According to Burns and Stickney (1980), in Little and Muir (1987), chickens (4,000 broilers/ha of pond) raised with *Oreochromic aureus* Steindachner yielded 5.9 t of fish/ha/year in the USA.

Milkfish, Tilapia, Shrimp Plus Chickens

In 1984-86, the Leganes Research Station of the SEAFDEC Aquaculture Department developed the polyculture of milkfish, tilapia, and shrimp with poultry. The fish swim in the water and the chickens grow to slaughter-size in poultry houses built above the water. The two forms of husbandry mesh well in the biological food chain. Chicken droppings that pass through a welded-wire floor in the poultry house into the water below become a fertilizer for plankton, the natural food organisms on which fish feed. The milkfish, tilapia, and shrimp then thrive on the plankton. Further research showed that a 4m x 8m poultry house was right for a 1000 m2 fish pond. A bamboo catwalk connected the poultry house to the dike. Stocking in the pond consisted of 200 milkfish fingerlings, 1 500 tilapia fingerlings, and 5000 shrimp juveniles - and above it, 90 3-wk old chicks were put in the poultry house. This mix was found to give the best productivity. The chickens were harvested after 45 days - half the period for the fish. Two chicken crops were harvested for one fish crop. At harvest time; farmers who go into polyculture have both fish and chickens for household food and for sale. For sanitation, it is suggested that chickens be harvested a week before the fish, and the pond water, immediately changed. When the fish are harvested after another week, the pond has the healthy smell of fresh fish.

Sheep/Goat cum Fish Farming

Fifty to fifty-five goats are sufficient for one hectre water bodies for sheep/goat integrated farming system. Sheep/goat manure is also rich in N, P and K. Moreover, there is a great demand for mutton and chevron and no religious taboo is attached with these meats. A adult goat weighing about 20kg discharges 300-400g excreta on daily basis. For manuring 1h water body, 50-60 goats herd are needed. This integration could produce 3.5 – 4 tonnes fish /ha/year without supplementary feed or fertilizer in pond. These types of IFF produce fish and 750-900kg Sheep/goat meat.

Cattle/Buffalo cum Fish Farming

This system is very common in rural India. People generally mix cow dung with paddy husk or wheat bhusa and spread over water bodies as a ready source of fish food. A healthy cow weighing 400-450kg excretes over 400-500kg of dung and

3500 – 4000 litres of urine on annual basis. Sometimes cow dung and cattle/ buffalo shed waste channelized directly in to the pond which serve as excellent fish food directly or indirectly as a source of plankton growth in the pond. But caution should be taken for number of animals per unit of water bodies; otherwise, there may be fish mortality due to excess manure in water. A unit of 5-6 cows can provide adequate quantity of dung and urine to produce 3000 – 4000kg of fish per ha per year.

Figure. Cattle cum fish farming

Pig Cum Fish Farming

Pigs are reared in pens or sties built on the banks of the fish ponds (and wastes are washed out) or constructed over the ponds on piles or wooden stilts and have a lattice type of floor (allowing wastes to fall directly into the pond). The number of pigs per ha of ponds area varies from 40 to 300, according to the literature. However, the number of piglets recommended is generally 100 per ha (or 1 piglet per 100 m2 of pond).

Piglets are weaned at two months (average weight 12–15 kg) and are ready for fattening. They reach 70–85 kg after 6–7 months.

In China fish ponds stocked with 60,000 fingerlings per ha (average weight 20–30g) of different species raised together with about 45–75 pigs/ha produced between 2–18 t. of fish and 4–7 t. of pigs (live weight) per ha/year (Pillay, 1990).

Figure. Pig cum fish farming

Polycultures were conducted in the Philippines with *Oreochromis niloticus* (85 %), common carp Cyprinus Carpio Linnaeus (14%) and *Ophiocephalus striatus* Bloch (1%) at stocking rates of 10,000 and 20,000 fingerlings/ha, combined with pigs (average initial weight 20 kg) at 40–60 animals/ha during a 90 day test period. The best results were obtained with the 60 pigs - 20,000 fish/ha, or 1950 kg (1.95 t) of fish/ha/90 days and 60 pigs at an average weight of 57 kg (3.42 t). The total gain in weight of the 60 pigs was 2,220 kg (2.22 t) (live weight) in 90 days (Cruz and Shehadeh, 1980). In 3 cycles of 90 days (270 days) the combined production could reach 3,866 kg (3.87 t) of fish and 6,660 kg (6.66 t) of pigs.

In some African countries (Central African Republic, Cameroon, Congo, Cote d'Ivoire, Gabon), in ponds stocked with *T. niloticus* at a rate of 20,000 fingerlings/ha, the combined production can reach 8,000 kg (8 t) of fish and 6,000 to 9,000 kg (6–9t) of pigs (on the hoof) per ha/year (Vincke, 1976).

With *T. andersonii* (monoculture) combined with pigs, 7,000 kg (7 t) of fish per ha/year were obtained in Zambia. Monoculture of *Clarias gariepinus* with pigs yielded 7,510 kg (7.51 t) of fish per ha/year in Central Africa. The grow out period was 90 days and the daily growth rate of *C. gariepinus* was 2.9 g/day (Vincke, 1988).

In a polyculture, 20,000–30,000 fingerlings/ha of *O. niloticus* and 1,000–10,000 C. gariepinus fingerlings/ha integrated with 100–200 pigs/ha and small quantities of brewery waste and spoiled flour, the average yield of 4 trials was 11,140 kg (11.14 t) of fish per ha/year (Vincke, 1988).

If for socio-cultural reasons pig farming is not possible, the combination of chicken or ducks and fish is recommended.

Integrated Farming of Other Animals Combined with Fish

According to Pillay (1990), the culture of geese integrated with fish farming is practised on a very limited scale in East European countries and in Hong Kong. Geese have also been raised more extensively on fish ponds in Thailand (Little and Muir, 1987) and geese-fish trials have been conducted in Madagascar (Vincke, 1976). The geese are fattened in sheds build over the ponds. The floor is covered with wire netting or with lattice work, allowing goose droppings into the pond. A slanting platform extends from the shed into the pond to allow the geese to enter a fenced area of the pond. In Hong Kong, in polyculture of grey mullet (38%), grass carp (23%), common carp (21%), silver carp (9%) and bighead carp (9%), at a stocking rate of 12,2000 fish/ha, integrated with geese (4,000 to 4,500 geese/ha), yields of 3.69 t/ha/year of fish and 2.25 t of geese (live weight)/ha/year were obtained (Sin, 1980). In Madagascar, with geese (stocking density of 500–800/ha) raised over ponds stocked with *O. niloticus* (10,000–20,000 fingerlings/ha) and common carp (2,500 fingerlings/ha), fish yields of 2.62 to 2.47 t/ha/year were obtained and 250–600 kg of geese (live weight) per ha/year (Vincke, 1976).

Present Status of Integrated Farming of Fish and Livestock

It is clear that integrated livestock-fish farming systems are mainly concentrated in Asia. In recent years however, some of these systems have been successfully applied in other developing countries and impressive fish yields have been obtained. Except in the state-owned farms and cooperatives in Eastern Europe, China and Vietnam, integrated livestock-fish farming is practised mostly on a small-scale level, by rural communities. The aims of the farmers are to make use of their land at the lowest cost and to increase their income. In Asia, the integrated production systems have been developed empirically by the farmers themselves and are still largely aimed at fulfilling only their own food requirements (Rajbanshi and Shrestha, 1980).

In the social and economic conditions prevailing in developing countries, integration of livestock may be the only source of fertilizers available, at low cost, to make fish culture economically feasible.

Future Development of Livestock-Cum-Fish Production

The commercial aquaculture enterprises focus on the production of expensive luxury species for export, and thus fish are not for local consumption. To resolve the persistent and widespread malnutrition in developing countries, it is absolutely necessary to increase the availability of animal products, at prices that the masses can afford. As pointed out by New (1991), fortunately most farmed fish is raised in ponds receiving organic fertilization. This must remain so if aquaculture is to play its role in “feeding the masses”. This again emphasizes on integrated aquaculture (New, 1991).

The potential for integrated aquaculture exists in many developing countries but more research is needed if the development of integrated livestock-fish farming systems is to be enchanced. Socio-cultural factors should be given due consideration together with the economic and technical feasibility studies. Successful trials and demonstrations have been carried out in developing countries, but more comparative feasibility studies on the economics of the different livestock-fish farming systems have to be conducted, analyzed and published. On-farm tests are of particular interest and should be planned and implemented to generate the information that is now lacking. One has to remember that most of the farmers do not keep any records concerning their investment, cost of labour and inputs.

Some of the economic aspects of integrated fish farming have been described by several authors (Delmendo, 1980; Djajadiredja et al., 1980; Edwards et al., 1986; Lovshin et al., 1986; Shang and Costa-Pierce, 1983; Sin, 1980; Tan and Khoo, 1980; Vincke, 1976). As stressed by Shang and Costa-Pierce (1983), most of the economic aspects concentrate on rudimentary budget analysis which estimates costs of production and profit of operation. Such studies, usually provide little sensitivity analysis in relations to variations of production, input costs and market prices.

Conclusion

It can be concluded that an integrated fish farming system gives better returns than crop production, livestock income and fish farming alone. The integrated fish farming system is very beneficial for marginal farmers with lesser land holdings and capable of providing year-round income. Integrating fish farming with other livestock and agricultural practices can help to increase overall food production and provide a reliable source of food, especially in areas where arable land is limited; it can create new income and job opportunities for farmers, especially in rural areas with limited employment options. Integrated fish farming can increase the resilience of farming systems by providing a backup source of food and income in the event of a crop failure.

- **Higher Economic Returns:** Studies show that integrated fish farming systems provide higher income and net profits compared to traditional, non-integrated farming, boasting a superior benefit-cost ratio.
- **Optimal Resource Use:** It acts as an artificial balanced ecosystem where waste products from one system (e.g., livestock manure) are utilized as inputs for another (e.g., fish feed or pond fertilization), promoting cleaner, more sustainable production.
- **Enhanced Sustainability & Resilience:** By diversifying products (fish + rice/poultry/fruit), this method offers a safety net for farmers against crop failure and improves economic stability.
- **Environmental & Socio-economic Benefits:** It promotes eco-friendly practices by minimizing reliance on chemical fertilizers and provides significant food security through diverse protein sources (fish, meat, eggs).
- **Need for Optimization:** Continued success requires proper scientific planning, such as selecting appropriate species and managing, local resources efficiently, to fully unlock the potential of this farming approach.

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ISBN: 978-93-49938-76-2| Year: 2026 | pp: 18 - 26 |

Urban Rivers Under Climate Stress: Implications for Aquatic Ecosystems and Biodiversity

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Article DOI Link: https://zenodo.org/uploads/20108908

DOI: 10.5281/zenodo.20108908

Abstract

Climate change is increasingly becoming a major threat to aquatic ecosystems, particularly in urban rivers where natural processes are already under pressure from human activities. Rising temperatures, irregular rainfall patterns, and more frequent extreme weather events are altering the natural flow and balance of these river systems. In many cases, prolonged droughts have reduced water levels, affecting both the physical structure and ecological health of rivers. This study focuses on an urban river system as a representative example to understand how climate-related changes influence aquatic life and ecosystem functioning. Urban rivers play an important role in supporting fisheries, providing water for irrigation and domestic use, and holding cultural and social significance for nearby communities. However, ongoing environmental changes are leading to habitat degradation, a decline in species diversity, and noticeable shifts in the population dynamics of fish and other aquatic organisms. Native species, as well as migratory birds that depend on these habitats, are becoming increasingly vulnerable. The review explores how rising temperatures, changing precipitation patterns, and extreme climatic events impact different components of aquatic biodiversity, including fish, invertebrates, and aquatic plants. It also highlights how these ecological changes affect key ecosystem services such as water purification, flood control, and recreational use. Overall, the study aims to better understand the link between climate change and the health of urban river ecosystems. It seeks to identify major environmental threats and suggest practical strategies for conservation and sustainable management to protect both biodiversity and the valuable services these ecosystems provide

Keywords: Climate change, Aquatic Biodiversity, Ecosystem services, Urban River.

Introduction

Climate change has gradually become one of the most pressing environmental concerns of the present century, affecting natural systems across the globe in complex and interconnected ways. Among the ecosystems that respond most rapidly to these changes are freshwater systems, particularly rivers. Rivers are highly dynamic in nature, and even small variations in temperature, rainfall, or flow patterns can significantly influence their structure and functioning[1]. As a result, they serve as sensitive indicators of environmental change. In recent decades, the combined effects of climatic shifts and increasing human activities have placed urban and semi-urban river systems under considerable stress, raising serious concerns about their long-term sustainability[2].

Ecological and Socio-Economic Importance of Rivers

Freshwater ecosystems play a crucial role in maintaining ecological balance while also supporting human survival and development. Rivers, in particular, provide essential services such as drinking water supply, irrigation for agriculture, fisheries, and waste assimilation. They also support a rich diversity of aquatic life, including fish, plankton, aquatic plants, and microorganisms[3]. These biological communities are interconnected through complex food webs and nutrient cycles, making rivers vital for sustaining biodiversity. In addition to their ecological and economic importance, rivers hold deep cultural and social significance, especially in regions where communities have historically depended on them for their livelihoods and daily activities. Despite their importance, freshwater ecosystems are inherently fragile and highly vulnerable to disturbances.

Vulnerability of Freshwater Ecosystems to Climate Change

Climate change has introduced new challenges by altering key environmental parameters such as temperature, precipitation, and hydrological cycles. These changes are not always immediately visible, but their effects accumulate over time, gradually transforming river systems[4]. Rising temperatures, irregular rainfall, and changing flow regimes are now commonly observed in many parts of the world, including India. Such alterations not only affect the physical characteristics of rivers but also have profound implications for aquatic biodiversity and ecosystem services. On one hand, they are influenced by broader climatic trends, and on the other, they are subjected to intense human pressure due to urbanization and industrialization.

Combined Impact of Climate Change and Human Activities

Rapid population growth and unplanned development have led to increased pollution, habitat modification, and over-extraction of water resources. These pressures interact with climate change, often intensifying its impacts and accelerating the degradation of river ecosystems[5]. Urban rivers are increasingly becoming hotspots of environmental stress, where ecological imbalance and biodiversity loss are more pronounced. In regions such as eastern Uttar Pradesh, rivers form the backbone of rural and semi-urban life. They serve as primary sources of water for domestic use, agriculture, and fisheries, while also supporting diverse aquatic species. For local communities, rivers are not merely natural resources but integral parts of their cultural and economic identity. Festivals, rituals, and traditional practices are often closely associated with river systems, reflecting their social importance[6]. However, the health of these rivers has been declining over time, raising concerns about both environmental sustainability and human well-being. One of the most noticeable effects of climate change on river systems is the increase in water temperature. Warmer climatic conditions have led to a gradual rise in river water temperatures, which can have significant consequences for aquatic organisms[7]. Many species are adapted to specific temperature ranges, and even slight deviations can disrupt their physiological processes. Fish species often rely on particular temperature conditions for breeding and growth. When these conditions are altered, their reproductive success may decline, leading to reductions in population size. Changes in precipitation patterns have also emerged as a major concern. Instead of consistent and predictable rainfall, many regions now experience irregular and extreme weather events. Intense rainfall over short periods can lead to sudden flooding, while prolonged dry spells reduce water availability[8]. These fluctuations have a direct impact on river flow and hydrological stability. Flood events can cause physical damage to river habitats, washing away aquatic organisms, increasing sediment load, and altering channel morphology. On the other hand, reduced flow during dry periods limits habitat availability and increases the concentration of pollutants, creating stressful conditions for aquatic life[9]. The Interaction between climate change and human activities further complicates the situation. While natural climatic variability plays a role, anthropogenic factors such as deforestation, urban expansion, and industrial activities have accelerated environmental changes. The emission of greenhouse gases from the burning of fossil fuels has contributed to global warming, while deforestation has reduced the capacity of ecosystems to absorb carbon dioxide. In urban areas, the expansion of infrastructure often disrupts natural drainage systems, leading to increased surface runoff and reduced groundwater recharge. These changes not only affect water availability but also influence the quality of river water[10].

Pollution and Declining Water Quality

Pollution remains one of the most critical challenges facing urban rivers. Climate change tends to amplify its effects in multiple ways. During periods of heavy rainfall, runoff carries a wide range of contaminants into rivers, including industrial effluents, agricultural chemicals, and domestic sewage. These pollutants degrade water quality and pose risks to both aquatic organisms and human health[11]. Conversely, during low-flow conditions, the reduced volume of water limits the river's ability to dilute pollutants, resulting in higher concentrations of harmful substances. This combination of increased pollutant input and reduced dilution capacity creates a highly stressful environment for aquatic ecosystems[12]. Water quality degradation has direct implications for aquatic biodiversity. Parameters such as dissolved oxygen, biochemical oxygen demand, nutrient concentrations, and pH are critical indicators of river health. Changes in these parameters can influence the survival and distribution of aquatic species. For example, low dissolved oxygen levels can be lethal to many fish species, while excessive nutrients can lead to eutrophication and algal blooms. These blooms not only reduce oxygen levels but may also release toxins that further harm aquatic life[13]. As environmental conditions become more challenging, sensitive species tend to decline, while pollution-tolerant species become more dominant, leading to shifts in community structure. Aquatic biodiversity is an essential component of river ecosystems, contributing to their stability and resilience. Each species plays a specific role in maintaining ecological balance[14]. Plankton form the base of the food chain, providing energy for higher trophic levels. Fish contribute to nutrient cycling and help regulate populations of other organisms. Aquatic plants provide habitat and oxygen, while microorganisms play a key role in decomposition and nutrient recycling. The loss or decline of any of these components can disrupt the entire ecosystem, highlighting the importance of conserving biodiversity in river systems[15].

Figure: Major source of pollution entering urban rivers

Habitat Degradation and Loss of Ecological Connectivity

Habitat degradation is another significant consequence of climate stress. Changes in temperature and flow patterns can alter the physical characteristics of river habitats, affecting their suitability for different species. Flooding can erode riverbanks and destroy breeding grounds, while droughts can shrink water bodies and reduce habitat availability. In some cases, changes in flow regimes may disconnect rivers from their floodplains, which are essential for nutrient exchange and habitat diversity. Floodplains act as natural buffers, storing excess water during floods and releasing it gradually over time. When this connectivity is lost, the ecological functioning of the river system is compromised[16]. The socio-economic implications of these changes are equally important. Many communities depend on rivers for their livelihoods, particularly through agriculture and fisheries. Changes in water availability and quality can directly affect agricultural productivity. Reduced water levels may limit irrigation, while polluted water can degrade soil quality and reduce crop yields. Similarly, declining fish populations can affect the income of fishermen, leading to economic instability. These impacts are often more severe in rural and semi-urban areas, where alternative sources of income are limited and communities are more directly dependent on natural resources[17]. Urbanization adds another layer of complexity to the challenges faced by river systems. The construction of roads, buildings, and drainage systems can alter natural water flow, affecting hydrological processes. Impermeable surfaces such as concrete prevent water from infiltrating the soil, increasing surface runoff and reducing groundwater recharge. This not only affects water availability but also increases the risk of flooding. Additionally, urban areas generate large amounts of waste, much of which eventually enters river systems, further degrading water quality and harming aquatic life. Sedimentation is another issue influenced by changing climatic conditions. Heavy rainfall can lead to increased soil erosion, resulting in higher sediment loads in rivers. Excessive sedimentation can reduce water clarity, affect photosynthesis in aquatic plants, and disrupt feeding and breeding patterns of aquatic organisms[18]. During dry periods, reduced flow may cause sediments to accumulate in certain areas, altering the shape and structure of the river channel. These physical changes can have long-term effects on habitat availability and ecosystem stability. Water quality concerns are further intensified by rising temperatures, which can promote the growth of harmful microorganisms, including algae that produce toxins. These algal blooms can deplete oxygen levels in the water, creating hypoxic conditions that are harmful to aquatic life. The presence of pollutants such as heavy metals and plastics adds to the problem, posing serious risks to both ecosystems and human health[19]. Since rivers often serve as sources of drinking water, maintaining their quality is of utmost importance. Beyond their ecological and economic roles, rivers also have significant cultural and recreational value. They are often central to local traditions, festivals, and social activities. In many regions, rivers attract tourists due to their natural beauty and biodiversity. However, environmental degradation can reduce their attractiveness, affect tourism and associate economic benefits. This highlights the need to consider social and cultural dimensions in addition to ecological factors when addressing the impacts of climate change. Given the complexity of these challenges, it is clear that traditional approaches to river management are no longer sufficient.

Need for Sustainable and Integrated River Management

Addressing the impacts of climate change requires an integrated and adaptive approach that considers multiple factors, including land use, pollution control, biodiversity conservation, and community involvement. Sustainable practices such as the restoration of wetlands, protection of riparian zones, and implementation of green infrastructure can help improve water quality and enhance ecosystem resilience. Scientific research plays a crucial role in understanding the interactions between climate change and river ecosystems[20]. Long-term monitoring and data analysis are essential for identifying trends and assessing impacts. At the same time, local knowledge and community participation are equally important. People who live near rivers often have valuable insights into environmental changes and can contribute to conservation efforts. Combining scientific and traditional knowledge can lead to more effective and sustainable solutions. Maintaining hydrological connectivity is another key aspect of river management. Ensuring the natural flow of rivers and their connection with floodplains is essential for ecosystem health. Efforts should be made to minimize disruptions caused by infrastructure and to restore natural flow patterns wherever possible. Such measures can enhance the resilience of river systems, enabling them to better adapt to changing environmental conditions[21]. Urban rivers are increasingly being shaped by the combined effects of climate change and human activities. Rising temperatures, changing precipitation patterns, and increasing pollution are altering their physical, chemical, and biological characteristics. These changes have significant implications for aquatic ecosystems, biodiversity, and human livelihoods. Protecting and restoring river systems requires a holistic approach that integrates environmental, social, and economic considerations[22]. By adopting sustainable management practices and promoting awareness, it is possible to reduce the impacts of climate change and ensure the long-term health and sustainability of urban river ecosystems.

Future Research Directions

Future studies should focus on long-term monitoring of climate variables and river health to better understand how rising temperatures and irregular rainfall patterns continue to influence flow regimes and water quality. There is a need for integrated assessments that link hydrological changes with biological responses, particularly shifts in fish diversity and the decline of sensitive species such as Catla catla and Labeo rohita. Further research should also explore the combined impact of urban discharge, agricultural runoff, and reduced dilution capacity on nutrient enrichment and oxygen depletion in river systems. Advanced tools like remote sensing and modeling can be used to predict future changes and identify vulnerable stretches of the river. In addition, studies on pollution-tolerant and invasive species are important to understand ecological imbalances and their long-term consequences for native biodiversity. Socio-economic research is equally necessary to assess how declining fish yield and water availability affect local communities and to develop sustainable livelihood alternatives. Future work should emphasize climate-resilient river management strategies, including restoration of flow, pollution control measures, and conservation of critical habitats, to ensure the long-term sustainability of urban river ecosystems.

Conclusion

Urban rivers today stand at a turning point, shaped by the combined impact of changing climate conditions and continuous human pressure. The gradual rise in temperature, uncertain rainfall patterns, and reduced flow levels are no longer isolated observations; they are now clearly influencing the overall health of these river systems. Declining water quality and visible changes in aquatic life, especially the replacement of sensitive species by more tolerant ones, reflect a system under stress. Addressing these challenges calls for a more coordinated and practical approach. Efforts from policymakers, researchers, and local communities need to come together, focusing not only on controlling pollution but also on improving water flow and protecting natural habitats. Measures that strengthen the resilience of rivers to climate variability will play an important role in their recovery. Ultimately, the protection of urban rivers goes beyond ecological concerns. These rivers support livelihoods, provide water for daily use, and hold cultural value for many communities. Ensuring their health is therefore essential, not just for biodiversity, but for sustaining the broader relationship between people and their environment.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 27 - 32 |

Quality Control and Food Safety Standards

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Article DOI Link: https://zenodo.org/uploads/20108941

DOI: 10.5281/zenodo.20108941

Abstract

Quality control and food safety standards are critical components of the global food industry, ensuring that food products are safe, nutritious, and fit for consumption. With increasing globalization, complex supply chains, and heightened consumer awareness, the need for robust quality management systems has intensified. This chapter provides a comprehensive overview of quality control principles, food safety frameworks, international standards, analytical methods, and regulatory requirements. Key systems such as Hazard Analysis and Critical Control Points (HACCP), ISO 22000, and Codex Alimentarius guidelines are discussed in detail. Emerging trends including digital traceability, artificial intelligence, and sustainability considerations are also explored. The chapter concludes by highlighting future challenges and the importance of integrated approaches in maintaining food safety and quality.

Keywords: Food safety, quality control, HACCP, ISO 22000, food standards, food quality assurance, traceability, food contamination, regulatory frameworks

Introduction

Food safety and quality are fundamental to public health and economic development. Unsafe food containing harmful bacteria, viruses, toxins, or chemical substances can lead to foodborne diseases, affecting millions globally. Quality control ensures that food products meet defined standards of safety, consistency, and consumer acceptability.

Modern food systems involve multiple stages — production, processing, packaging, storage, distribution, and consumption — each posing potential risks. Therefore, systematic control measures and internationally recognized standards are necessary to ensure safety across the entire supply chain.

Concepts of Quality Control in Food Industry

Quality control (QC) refers to operational techniques and activities used to fulfil quality requirements. It includes

- Raw material inspection
- Process monitoring
- Product testing
- Documentation and record keeping

Quality control is part of a broader system known as Quality Assurance (QA), which focuses on preventing defects rather than detecting them.

Objectives of Quality Control

- Ensure product safety and compliance
- Maintain consistency in product quality
- Minimize waste and production errors
- Enhance consumer confidence

Food Safety Hazards

Food safety hazards are categorized into

1. Biological Hazards

- Bacteria (Salmonella, E. coli)
- Viruses and parasites

2. Chemical Hazards

- Pesticide residues
- Food additives and toxins

3. Physical Hazards

- Glass, metal fragments
- Foreign particles

Effective food safety systems aim to identify, evaluate, and control these hazards at all stages.

Food Safety Management Systems

1. HACCP (Hazard Analysis and Critical Control Points)

HACCP is a preventive approach designed to identify and control hazards in food production. It is widely regarded as one of the most effective food safety systems.

Principles of HACCP

- Hazard analysis
- Identify critical control points (CCPs)
- Establish critical limits
- Monitoring procedures
- Corrective actions
- Verification
- Documentation

These principles provide a structured framework for managing risks in food production.

2. ISO 22000 Food Safety Management System

ISO 22000 integrates HACCP principles with a structured management system, ensuring continuous improvement and consistent implementation.

Key Features

- Combines HACCP with prerequisite programs (PRPs)
- Uses risk-based approach
- Ensures traceability and recall systems
- Follows Plan-Do-Check-Act (PDCA) cycle

ISO 22000 enhances hazard control by integrating systematic management practices with operational controls.

3. Prerequisite Programs (PRPs)

PRPs are basic conditions necessary for maintaining hygienic food production environments. These include

- Good Manufacturing Practices (GMP)
- Good Hygiene Practices (GHP)
- Sanitation procedures
- Pest control
- Personnel hygiene

These programs form the foundation for effective HACCP implementation.

International Food Safety Standards

1. Codex Alimentarius

Developed by FAO and WHO, Codex provides global food standards, guidelines, and codes of practice to ensure food safety and fair trade.

2. **ISO 22002 (Latest Updates)**

- Recent updates emphasize
- Food fraud prevention
- Digital traceability
- Sustainability
- Food defence

These improvements align food safety practices with modern global challenges.

3. **National Regulations**

Examples

- FSSAI (India)
- FDA (USA)
- EFSA (Europe)

These agencies enforce food laws and safety compliance.

Methods in Food Quality Control and Safety Analysis

1. **Microbiological Analysis**

- Detection of pathogens
- Culture methods and rapid tests

2. **Chemical Analysis**

- Chromatography (HPLC, GC)
- Spectroscopy

3. **Physical Analysis**

- Texture, colour, moisture content

4. **Sensory Evaluation**

- Taste, aroma, appearance

5. **Molecular Techniques**

- PCR-based detection
- DNA sequencing

Food Traceability Systems

Traceability ensures that food products can be tracked through the supply chain. Modern systems use

- RFID technology
- Blockchain
- IoT-based sensors

Advanced systems allow real-time monitoring of temperature, humidity, and location, improving transparency and safety.

Emerging Technologies in Food Safety

1. Artificial Intelligence (AI)

- Predicting contamination risks
- Data analysis for safety trends

2. Big Data and Digital Platforms

- Centralized safety databases
- Predictive analytics

Large-scale datasets are now used to analyse contamination trends and support regulatory decisions.

3. Smart Packaging

- Sensors for spoilage detection
- Indicator labels

Challenges in Food Safety and Quality Control

- Complex global supply chains
- Lack of awareness and training
- High implementation costs
- Emerging contaminants
- Climate change impacts

Ensuring compliance across diverse regions remains a major challenge.

Future Perspectives

Future food safety systems will focus on

- Integration of AI and automation
- Real-time monitoring systems
- Sustainable food production
- Global harmonization of standards

The transition toward digital and intelligent food systems will significantly enhance safety and quality.

Conclusion

Quality control and food safety standards are essential for protecting public health and ensuring consumer trust. Systems such as HACCP and ISO 22000 provide structured approaches to hazard identification, control, and continuous improvement. Advances in analytical techniques, digital technologies, and regulatory frameworks have strengthened food safety management. However, challenges such as globalization, emerging risks, and resource limitations persist. A multidisciplinary and integrated approach combining science, technology, and policy is necessary to achieve safe and sustainable food systems.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 33 - 40 |

CRISPR and Genetic Engineering in Aquaculture: Enhancing Growth, Disease Resistance, and Climate Resilience

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Article DOI Link: https://zenodo.org/uploads/20108975

DOI: 10.5281/zenodo.20108975

Abstract

Aquaculture is the fastest-growing sector of animal food production, contributing significantly to global food security and nutritional sustainability. However, its expansion is constrained by disease outbreaks, suboptimal growth performance, environmental stress, and the escalating impacts of climate change. Recent advances in genome editing, particularly CRISPR-Cas systems, have revolutionized genetic engineering by enabling precise, efficient, and scalable modification of fish genomes. This chapter provides a comprehensive overview of CRISPR-based genetic engineering in aquaculture, focusing on its applications in improving growth traits, enhancing disease resistance, and developing climate-resilient fish strains. Mechanistic insights, case studies across major aquaculture species, biosafety concerns, ethical considerations, and regulatory frameworks are critically discussed. The integration of CRISPR with omics technologies and precision aquaculture platforms is also explored as a pathway toward sustainable and resilient aquaculture systems.

Keywords: CRISPR-Cas9; aquaculture; genome editing; fish genetics; disease resistance; climate resilience; myostatin; hypoxia tolerance; sustainable fisheries

Introduction

Aquaculture currently supplies over half of the fish consumed globally and is projected to expand further to meet the protein demands of a growing population [1]. However, the sector faces major challenges, including infectious diseases, inefficient feed utilization, environmental degradation, and climate variability. Traditional selective breeding has improved aquaculture productivity, but it is limited by long generation times and low precision [2].

The emergence of genome-editing technologies has transformed biological research and agricultural innovation. Among these, CRISPR-Cas systems have gained prominence due to their simplicity, efficiency, and versatility [3]. Unlike earlier genome-editing tools such as zinc-finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs), CRISPR enables rapid and targeted modification of multiple genes simultaneously.

In aquaculture, CRISPR-based genetic engineering holds immense potential to accelerate genetic improvement, enhance disease resistance, and enable adaptation to environmental stressors. This chapter explores the molecular basis, applications, challenges, and future prospects of CRISPR technology in aquaculture.

Overview of CRISPR-Cas Systems

1. Historical Background

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) was first identified as part of the bacterial adaptive immune system. The discovery that CRISPR-associated (Cas) proteins can be programmed to target specific DNA sequences revolutionized genome editing [3].

2. Mechanism of CRISPR-Cas9

The CRISPR-Cas9 system consists of:

- Guide RNA (gRNA): directs Cas9 to a target DNA sequence
- Cas9 nuclease: introduces a double-strand break (DSB)

The DNA break is repaired via:

- Non-homologous end joining (NHEJ) → gene knockout
- Homology-directed repair (HDR) → precise gene insertion

This system allows precise manipulation of genes controlling economically important traits.

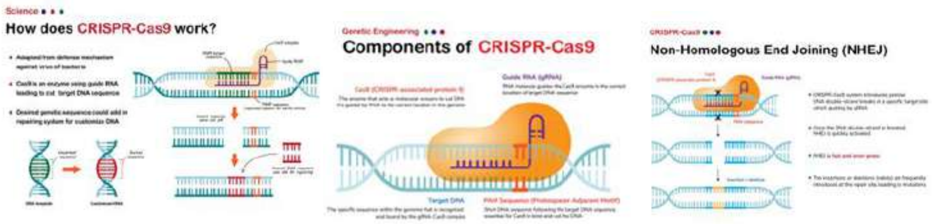

Fig. 1. Mechanism of CRISPR-Cas9 genome editing. The guide RNA (gRNA) directs the Cas9 nuclease to a specific DNA sequence, where a double-strand break is introduced. The break is repaired via non-homologous end joining (NHEJ), resulting in gene knockout, or homology-directed repair (HDR), enabling precise gene insertion or correction.

CRISPR-Cas9 consists of a guide RNA (gRNA) and Cas9 nuclease. The system enables targeted genome editing through DNA cleavage followed by cellular repair mechanisms [3,9].

Applications in Aquaculture Species

CRISPR has been successfully applied in multiple aquaculture species, including:

Species	**Application**
Zebrafish (*Danio rerio*)	Model organism for functional genomics
Nile tilapia (*Oreochromis niloticus*)	Growth and reproduction control
Common carp (*Cyprinus carpio*)	Disease resistance
Atlantic salmon (*Salmo salar*)	Growth enhancement
Channel catfish (*Ictalurus punctatus*)	Disease resistance

These applications demonstrate wide adaptability across aquaculture systems [4].

Growth Enhancement

1. Genetic Basis of Growth Regulation

Growth in fish is regulated by complex interactions among:

- Growth hormone (GH)
- Insulin-like growth factors (IGFs)
- Myostatin (MSTN)

Myostatin acts as a negative regulator of muscle growth, making it a prime target for genetic modification.

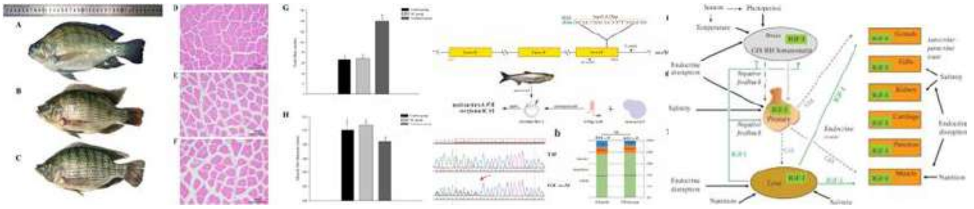

Fig. 2. Genetic regulation of growth in fish and CRISPR-mediated enhancement. The myostatin (MSTN) gene acts as a negative regulator of muscle growth; its disruption via CRISPR leads to muscle hypertrophy. The growth hormone (GH)–insulin-like growth factor (IGF) axis further regulates somatic growth and metabolic efficiency.

CRISPR-mediated editing of growth-related genes such as MSTN significantly enhances muscle mass and growth rate in aquaculture species [5].

2. Myostatin Gene Editing

CRISPR-mediated knockout of the MSTN gene has resulted in:

- Increased muscle mass
- Faster growth rates
- Improved feed efficiency

Studies in tilapia and carp have demonstrated significant enhancement in growth performance following MSTN disruption [4,5].

3. Feed Conversion Efficiency

Improving feed conversion ratio (FCR) is critical for economic and environmental sustainability. CRISPR can:

- Modify metabolic genes
- Enhance nutrient absorption
- Reduce feed waste

4. Reproductive Control and Sterility

Gene editing can induce sterility to prevent:

- Genetic contamination of wild populations
- Uncontrolled breeding

Knockout of reproductive genes such as GnRH has been explored for this purpose [2].

Table 1: Key Genes Targeted for Growth Enhancement

Gene	Function	Outcome of Editing
MSTN	Muscle growth inhibitor	Increased muscle mass
GH	Growth hormone	Accelerated growth
IGF	Growth regulation	Enhanced metabolism

Disease Resistance

1. Disease Challenges in Aquaculture

Disease outbreaks cause billions of dollars in losses annually. Pathogens include:

- Bacteria (e.g., Aeromonas, Vibrio)
- Viruses (e.g., ISA virus)
- Parasites

Traditional methods such as antibiotics and vaccines are insufficient and can lead to resistance [6].

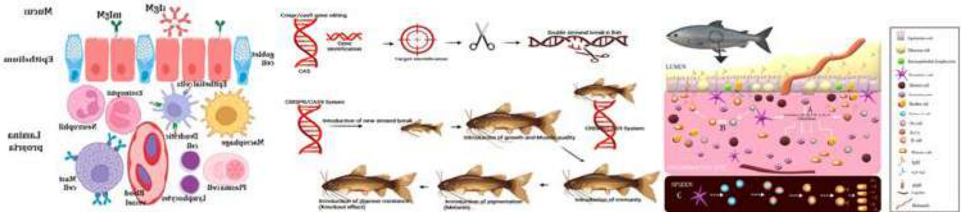

Fig. 3. Immune system pathways in fish and CRISPR-based genetic enhancement. Genome editing can target immune-related genes to strengthen innate and adaptive immunity, reduce pathogen susceptibility, and improve resistance to bacterial, viral, and parasitic infections.

CRISPR enables functional genomics approaches to identify and manipulate immune pathways, leading to enhanced disease resistance [6,7].

2. CRISPR-Based Disease Resistance

CRISPR can enhance immunity through:

- Knockout of susceptibility genes
- Overexpression of immune genes
- Modification of pathogen entry receptors

For example, editing immune-related genes has improved resistance to bacterial infections in fish models [7].

3. Functional Genomics in Disease Studies

CRISPR enables identification of genes involved in:

- Host-pathogen interactions
- Immune signalling pathways
- Antiviral responses

Zebrafish models have been extensively used to study immune gene functions [6].

4. Case Studies

- CRISPR-edited fish showing reduced mortality
- Enhanced resistance to viral infections
- Improved survival rates under pathogen exposure

Climate Resilience

1. Climate Change Impacts

Aquaculture is vulnerable to:

- Rising temperatures
- Hypoxia
- Salinity fluctuations
- Ocean acidification

These stressors affect fish physiology and productivity.

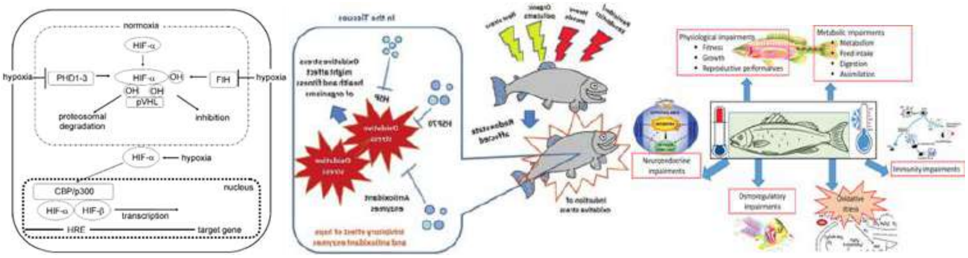

Fig. 4. Genetic pathways involved in climate resilience in fish. Hypoxia-inducible factor (HIF) regulates oxygen homeostasis under low oxygen conditions, while heat shock proteins (HSPs) protect against thermal stress. CRISPR-mediated editing of these pathways enhances tolerance to environmental stressors such as hypoxia, temperature fluctuations, and salinity changes.

Genetic modification of stress-response pathways improves survival and productivity under climate change conditions [8].

2. Genetic Basis of Stress Tolerance

Key genes involved include:

- Heat shock proteins (HSPs)
- Hypoxia-inducible factors (HIFs)
- Ion transporters

3. CRISPR for Climate Adaptation

CRISPR can:

- Enhance thermal tolerance
- Improve hypoxia resistance
- Modify osmoregulatory pathways

Editing HIF pathways has shown promise in improving oxygen utilization efficiency [8].

4. Sustainable Aquaculture

Genetic improvements can:

- Reduce environmental footprint
- Improve nitrogen utilization
- Enhance resilience to climate variability

Table 2: Genes Targeted for Climate Resilience

Gene	**Function**	**Trait Improved**
HIF	Hypoxia response	Oxygen tolerance
HSP	Heat stress response	Thermal resilience
Na^+/K^+ ATPase	Ion regulation	Salinity tolerance

Omics Integration

CRISPR is increasingly integrated with:

- Genomics (gene identification)
- Transcriptomics (gene expression profiling)
- Proteomics (functional proteins)

This integration enables:

- Precision breeding
- Trait prediction
- Smart aquaculture systems

Artificial intelligence and IoT further enhance monitoring and decision-making.

Ethical and Regulatory Issues

1. Off-Target Effects

Unintended mutations remain a concern. Advances in guide RNA design are improving specificity [6].

2. Ecological Risks

Potential risks include:

- Escape of genetically modified fish
- Impact on biodiversity
- Ecosystem imbalance

3. Ethical Issues

- Animal welfare
- Public acceptance
- Food safety concerns

4. Regulatory Frameworks

Regulations vary globally:

- **USA:** Product-based regulation
- **EU:** Strict GMO regulations
- **Asia:** Emerging frameworks

Harmonized policies are needed for global adoption.

Challenges and Limitations

- Limited genomic data for many aquaculture species
- Technical challenges in delivery systems (microinjection, electroporation)
- High costs of implementation
- Regulatory and ethical barriers

Despite these challenges, continuous advancements in CRISPR technology are addressing these limitations [9].

Future Perspectives

The integration of CRISPR with emerging technologies such as:

- Multi-omics (genomics, transcriptomics, proteomics)
- Artificial intelligence
- Precision aquaculture systems

will further enhance the efficiency and sustainability of aquaculture.

Future research should focus on:

- Developing climate-resilient fish strains
- Improving genome-editing precision
- Ensuring biosafety and regulatory compliance

Conclusion

CRISPR-Cas genome editing represents a paradigm shift in aquaculture, offering unprecedented opportunities to enhance growth, disease resistance, and climate resilience. While challenges related to ethics, regulation, and ecological safety remain, responsible application of this technology can significantly contribute to sustainable aquaculture and global food security.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 41 - 49 |

Small Size, Big Bang: A Review of the Snapping Mechanism in Pistol Shrimp

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Article DOI Link: https://zenodo.org/uploads/20109043

DOI: 10.5281/zenodo.20109043

Abstract

Pistol shrimp, belonging to the family Alpheidae, display one of the most extraordinary biomechanical phenomena found in the animal kingdom: an ultra-rapid snapping claw that can create powerful cavitation bubbles and subsequent powerful sound waves which are being used in predation, defense and intra-specific communication. This review consolidates existing knowledge regarding the morphology, kinematics, and fluid dynamics that support this snapping mechanism. In addition, it delves into recent innovations in experimental and computational strategies applied to model this phenomenon, as well as additional research opportunities in this area.

Keywords: Pistol shrimp; Snapping mechanism; Cavitation bubble; Vortex ring; Review

Introduction

The ocean, vast and tranquil, occasionally unveils astonishing secrets from its depths and one such finding is pistol shrimp (which is also known as snapping shrimp), a small but fascinating marine crustacean widely known for its powerful snapping claw. It belongs to the Alpheidae family, and there are over a thousand species of this family worldwide; of which Alpheus and Synalpheus are two special genera with over 330 and 160 species respectively. Numerous species belonging to Alpheidae family reside in shallow, warm tropical and temperate marine waters across the globe, especially within coral reefs and seagrass beds (Cato and Bell, 1992; Anker, 2001). Typically, pistol shrimps measure between 3 to 5 cm in length (Williams, 1984), and their body structure resembles that of various other shrimp species. However, the distinguishing feature that sets them apart is that one of their chelated claws (Figure 1), known as the snapper claw, is significantly larger than the other (small pincer claw), nearly reaching half of their body size (Schmitz and Herberholz, 1998; Versluis et al., 2000). They are allowed to possess just one snapper claw at a time. In the event that the large snapper claw is lost, the small pincer claw will change into a snapper, while the stump of the lost claw regenerates into a new pincer (McClure, 1996). This new claw is functional immediately, yet it takes about 1-3 molts to completely develop into its mature size and complexity, particularly for the specialized 'pistol' mechanism. This large chelated snapping claw is capable of generating high-velocity water jets and intense cavitation events. This unique mechanism allows pistol shrimps to produce one of the loudest biological sounds in the ocean, the power of which is around 190-210 dB (Schmitz, 2002) that significantly restricts the application of underwater acoustics for both active and passive sonar in scientific and naval contexts (Versluis et al., 2000) and is used by snapping shrimps for predation (Suzuki, 1986; Schultz et al., 1998), defense (Schein, 1977; Conover and Miller, 1978; Hughes, 1996) and intra-specific communication (Hughes, 1996; Herberholz and Schmitz, 1998). Pistol shrimp stands out as the sole species that has developed the ability to actively employ cavitation as a means to kill or incapacitate its prey (Herberholz and Schmitz, 1999; Koukouvinis et al., 2017).

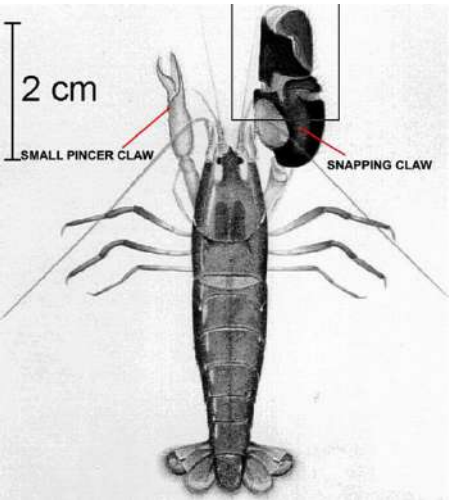

Figure 1: Pistol shrimp with snapping and small pincer claw (Reproduced from Versluis et al., 2000)

This review aims to synthesize current knowledge on the morphological structure, mechanical principles, and fluid dynamic consequences of the pistol shrimp's snapping mechanism. Additionally, it explores recent advances in experimental and computational approaches used to model this phenomenon, as well as further research scopes on this topic.

Literature Review

A comprehensive search of the literature pertaining to the snapping mechanism of pistol shrimp has been conducted across multiple sources including Google Scholar, ResearchGate, Science Direct, Academia, JStore, and Mendeley, and has been rigorously analyzed to convey the findings and prospective research opportunities related to this topic.

Snapping Mechanism and Sound Production

The narrative surrounding the discovery of the extraordinary ability of snapping shrimp represents a decade-long endeavor, characterized by extensive research conducted by numerous esteemed scientists.

This narrative traces its origins back to the 1940s, amidst the turmoil of World War II. U.S. Navy sonar operators were alarmed by an unusual, crackling sound emanating from the Pacific, which resembled the noise of "burning twigs" (Johnson et al., 1947). Initially, they suspected it to be a novel Japanese secret weapon designed to obscure the sounds of submarines. Subsequently, the Navy took the expertise of researchers from the University of California's war research division. These researchers identified the source of the sound as a colony comprising millions of these diminutive shrimps. Through their investigation, they determined that the sound was merely the mechanical "clicking" produced by the snapping claw of the shrimp. Even at that time, the researchers were unaware of the multitude of secrets concealed within this tiny shrimp's claw.

For the subsequent 50 years, the “mechanical click” theory was upheld in law. However, in the year 2000, this snapping theory underwent a significant restructuring. Versluis et al. (2000) chose to revisit the snapping mechanism and sound production of this enigmatic shrimp. The snapping sound produced by the shrimp is a result of the very rapid closure of its large snapper claw. Unlike typical crustacean claws that rely solely on muscular force, the pistol shrimp employs a latch-mediated spring actuation (LaMSA) system. The chelated claw of the pistol shrimp is composed of the dactyl and propus (Hess et al., 2013). The loud snapping sound is believed to result from the mechanical contact that occurs when the edges of the dactyl and propus collide as the claw closes. The claw features a protruding plunger on the dactyl and a corresponding socket in the propus (Figure 2). Prior to snapping, the claw is opened through the co-contraction of an opener and a closer muscle, which builds up tension until a second closer muscle contracts. This leads to an extremely rapid closure of the claw. A high-velocity water jet (velocity ~25 m/second) is created when the dactyl plunger is thrust into the propus socket, displacing water (Figure 3). The velocity of the water jet is so high that the resulting pressure falls below the vapor pressure of water. Seawater contains minute air bubbles. If such a micro-bubble is present between the dactyl and the propus of the snapper claw, it increases in size (cavitation bubble) when it passes through the low-pressure area generated by the water jet. Eventually, it collapses violently when the pressure increases again, producing the characteristic sound.

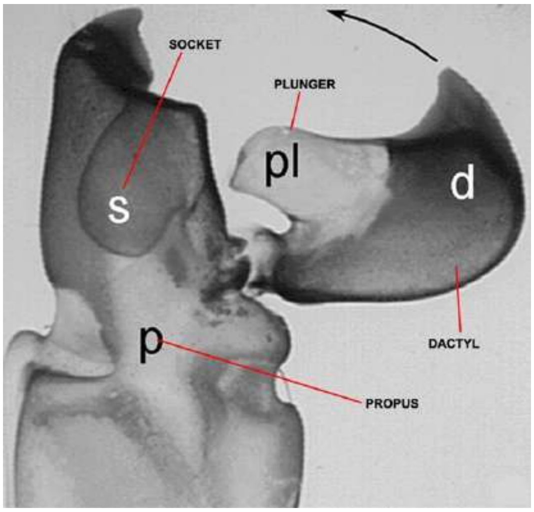

Figure 2: Structural components of the snapping claw (Reproduced from Versluis et al., 2000)

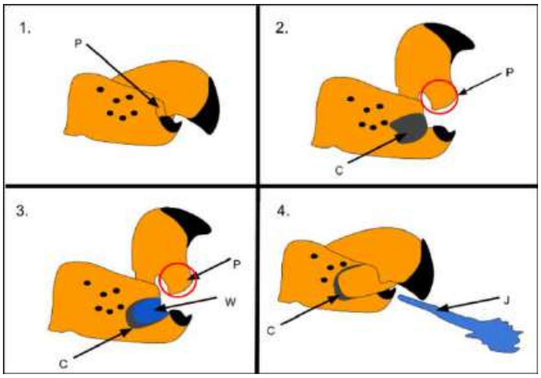

Figure 3: Snapping mechanism in pistol shrimp (Reproduced from IOA Facts and Details)
1) Closed claw with slightly hidden plunger (P); 2) Exposed plunger (P) and chamber (C) in open claw; 3) Water (W) in open chamber; 4) The closure of the claw results in the plunger being pushed into the chamber, which in turn produces a jet of water.

Although Versluis et al. (2000) provided a thorough explanation of the formation and collapse of cavitation bubbles, they did not, at that time, offer a detailed analysis of the flow field and pressure data surrounding the closing claw. Hess et al. (2013) elucidated these loopholes; they employed a Computer-Aided Design model, commonly referred to as a CAD model (Figure 4), to illustrate the power of this water jet. They stated that when the plunger strikes the water-filled socket and forces water out of the cavity, the water emerges through a narrow front groove that is created between the plunger and the socket. This process generates a vortex ring and a robust axial reentrant jet (a liquid flow produced by cavitation or cavity formation that moves from the rear of the vapor cavity in the opposite direction to the primary flow or into the cavity), which enhances the strength of the water jet.

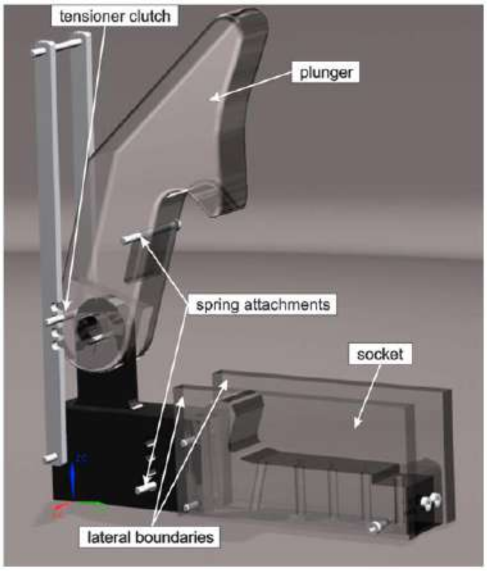

Figure 4: CAD model to assess the power of the water jet (Reproduced from Hess et al., 2013)

Subsequently, Koukouvinis et al. (2017) provided additional insights concerning the fluid mechanics involved in the processes of cavitation formation, growth, and collapse, by analyzing the flow field surrounding the claw through numerical simulations. Through computer simulations, it was demonstrated that as the claw closes, a high-velocity water jet of 25-30 meters per second is generated, which forms a vortex ring around it. If the closing speed is sufficiently high, the motion intensity of the vortex ring can lead to significant depressurization (a decrease in pressure or release of pressure) at the center of the vortex, resulting in the creation of a cavitation ring. This cavitation ring travels along the jet axis and collapses shortly after its formation, with the reaction being reversible, leading to a peak pressure of 80 bar. Notably, the research indicates that the cavitation ring rebounds after its initial collapse, causing it to pulse and emit multiple pressure waves that can stun or kill prey.

Further Yang et al. (2020) examined the motion properties and the cavitation mechanism of the snapper claw, along with the formation and structure of cavitation bubbles. They have reported that different species of snapping shrimps exhibit varying rotation speeds and motion characteristics. The snapping shrimp generates cavitation bubbles through the rapid closure of its snapper claw. The average pressure drop at the claw nozzle reaches about 2.5 atm, which is sufficient to trigger cavitation. When the cavitation number of the bubbles produced by the snapping shrimp is less than 0.2 an asymmetric cavitation vortex form. Under the influence of the flow jet, the cavitation bubble changes from an initial toroidal shape to a conical one. As it nears the point of bursting, the bubble compresses into a concave shape, with a micro jet directed towards the bubble's head.

Orbital Hood and Its Role in Reducing Snapping Shockwaves

Pistol shrimps utilize snapping shockwaves for communication within their species, but how do they safeguard their brains from such intense impacts? Kingston et al. (2022) identified the existence of an orbital hood in pistol shrimps (Figure 5) that effectively shields their brains from these shockwaves. The orbital hood is essentially a helmet-like extension of their exoskeleton (carapace). These helmet-like structures cover the eyes and brains of various snapping shrimp species. The orbital hoods of snapping shrimp represent the first biological armor system demonstrated to protect an organism from neurotrauma caused by blasts by dampening shock waves. Their development seems to be associated with the evolution of more robust snapping claws, indicating a co-evolution of offensive weaponry and defensive armor.

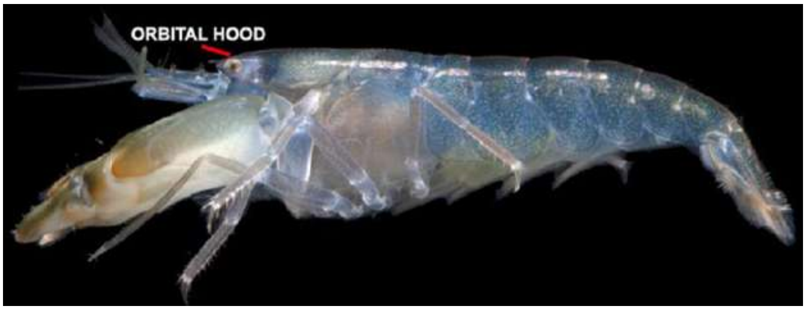

Figure 5: Orbital hood of pistol shrimp (Reproduced from Kingston et al., 2022)

Crustaceans construct their exoskeletons from chitin, a long-chain polysaccharide, with aligned chitin fibers organized into sheets known as lamellae. Orbital hoods possess nearly double the number of lamellae compared to carapaces, despite being only half as thick. The thinner and more numerous lamellae may contribute to a more elastic exoskeleton. The multiple interfaces within the orbital hood facilitate sliding between layers under stress, allowing them to absorb and dissipate transient shock waves, thereby protecting neural tissues. This helmet-like formation retains water internally and releases it externally. It can mitigate the shock wave by redirecting kinetic energy away from the shrimp's head, thus safeguarding the brain from potential harm. Ongoing research into the effectiveness and structure of this orbital hood may assist in the future development of helmets that provide enhanced protection for the human head against blast-induced neurotrauma.

Snapping and Shrimpoluminescence

Pistol shrimp not only generates sound through cavitation bubbles, but it also produces sparkles in water. Lohse et al. (2001) documented this astonishing phenomenon of flashing bubbles. They hypothesized that the collapse of the bubbles was so intense that it could emit light. Their research revealed that the shrimp indeed generates a flash of light, demonstrating that the bubble reaches temperatures exceeding 5,000 Kelvin. They termed this phenomenon shrimpoluminescence, a variant of sonoluminescence. This marked the first instance of sonoluminescence being observed in an animal. The flash of light signifies the extreme conditions present within the cavitation bubbles and the violent nature of their collapse.

Concluding Remarks

The study of this snapping mechanism has attracted interdisciplinary interest spanning biomechanics, fluid dynamics, and biomimetics. Researchers have investigated the kinematics of claw movement, the hydrodynamics of jet formation, and the physics of cavitation collapse. Beyond its biological significance, the pistol shrimp system has inspired engineering applications, particularly in the design of high-speed actuators and underwater propulsion systems (Murcek et al., 2025).

While research has revealed numerous aspects of this powerful shrimp, there is still much to uncover. Harrison and Patek (2023) have noted that juvenile shrimp can create cavitation even at the millimeter scale, yet the complete understanding of how fluid dynamics effectively scales down remains elusive. In the field of engineering, smaller pumps often lose efficiency due to 'viscous effects' (where water feels 'thicker' to small entities). How do juvenile shrimp manage to counteract water viscosity to achieve supersonic bubble collapse? Although it is known that the collapse of a cavitation bubble generates heat, there is ongoing debate regarding the condition of the gas inside that bubble. Brenner et al. (2002) have suggested it may briefly reach a plasma-like state. It is important to examine the chemical dissociation that occurs. Does the snap generate free radicals (like OH-) in the water? If so, could this 'chemical signature' fulfill a secondary role, such as sterilizing the vicinity or signaling to other organisms? The shrimp’s orbital hood serves as a biological helmet. While it is established that the hood reduces shock waves by about 20-30%, the long-term neurological consequences of repeated snapping are still unknown. Do older shrimp experience a form of biological 'CTE' (chronic traumatic encephalopathy) or fatigue? Cavitation is greatly influenced by water density, temperature, and salinity. As ocean temperatures increase and acidification modifies water chemistry, the physical 'threshold' for cavitation is likely to shift. Will the pistol shrimp's weapon become less effective in warmer, less dense water? This represents a significant area for a Fisheries Science student to investigate, as it involves forecasting the functional decline of a keystone species due to changing oceanic physics.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 50 - 59 |

Microplastics Pollution in Freshwater and Marine Fisheries: Sources, Bioaccumulation, Ecotoxicological Impacts, and Sustainable Mitigation Strategies

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Article DOI Link: https://zenodo.org/uploads/20109064

DOI: 10.5281/zenodo.20109064

Abstract

Microplastic pollution has emerged as a major threat to freshwater and marine fisheries because these particles are now widely detected in water, sediments, and aquatic organisms across both environments. Freshwater systems act both as sinks for land-based plastic waste and as transport corridors delivering microplastics to estuaries and coastal seas, linking inland pollution with marine fishery contamination. In fish and other fishery organisms, microplastics are most commonly reported in the gastrointestinal tract and gills, but experimental and review evidence also indicates translocation to other tissues under some exposure conditions, raising concerns for animal health, food safety, and ecosystem functioning. Ecotoxicological effects reported in the literature include oxidative stress, inflammation, metabolic disturbance, altered feeding and swimming behavior, impaired immunity, and neurotoxicity, particularly when exposure is chronic or combined with co-contaminants such as heavy metals, additives, and persistent organic pollutants. Sustainable mitigation requires interventions across the full plastic life cycle, including source reduction, wastewater control, fishing-gear management, standardized monitoring, circular economy policies, and fishery-specific best practices that reduce environmental inputs without shifting burdens elsewhere.

Keywords: Microplastic pollution, Freshwater systems, gastrointestinal tract, Ecotoxicological effects

Introduction

Microplastics are generally defined as plastic particles smaller than 5 mm, including fragments, fibers, films, foams, and beads generated either as primary microplastics intentionally manufactured at small size or as secondary microplastics formed by fragmentation of larger debris. Despite their scale, these materials endure for long periods, spreading via waterways thanks to varied chemical makeup, passing through streams, ponds, tidal zones, and deep ocean currents alike. Life within those waters - floating algae, bottom dwellers, finned animals, shelled creatures, farmed species - often encounters such particles during daily existence. Because fishing relies upon balanced underwater ecosystems, growing presence of these contaminants raises concerns about ecosystem function alongside harvest reliability. One reason stands out: inland and saltwater habitats link closely instead of operating independently. Water flow carries poorly handled synthetic refuse from towns, factories, farms, homes downstream, delivering it eventually to coastal regions. At the same time, edible aquatic species, whether caught offshore or upstream, may consume microscopic plastics, hold onto them internally, even pass them along feeding chains. Viewing pollution only by location misses key dynamics; understanding requires tracing material movement continuously - from terrain runoff into flowing channels then outward to open seas (Ghosh, 2024). This study looks into key origins of microplastics within fishing environments; it outlines how these particles enter and build up in marine life. Focus shifts toward documented toxic impacts on creatures central to fisheries, using current scientific consensus. Consideration extends to sustainability-focused approaches now recognized across studies. Emphasis rests equally on ecosystem outcomes and practical fishery considerations - covering market-important species, risks tied to consumption, alongside institutional reactions seen today.

Sources of Microplastics in Freshwater and Marine Fisheries

Land-Based and Urban Sources

The dominant share of aquatic microplastic pollution originates from land-based activities, especially mismanaged plastic waste, urban runoff, sewage discharges, wastewater treatment plant effluents, laundry-derived synthetic fibers, tire and road wear particles, and fragmentation of consumer plastics. Freshwater environments receive these inputs directly from populated catchments, making lakes and rivers important accumulation zones as well as transport pathways to estuarine and marine fisheries. Because a large proportion of marine plastic has terrestrial origins, reducing freshwater inputs is central to protecting coastal and offshore fishery resources.

Wastewater infrastructure plays a critical role because treatment plants can retain a substantial fraction of microplastics, yet large numbers still escape in effluents or are redistributed in sewage sludge. Textile washing is a particularly important source of microfibers, which are commonly reported among the dominant morphologies found in fish and environmental samples. Stormwater overflows, open dumping, and inadequate solid waste management further intensify loading in low-capacity or rapidly urbanizing regions (Patre, 2026).

Fishery and Aquaculture Sources

Floating remnants from worn equipment slowly enter waterways, releasing tiny particles as sunlight weakens their structure. Instead of vanishing, these fragments persist, breaking into smaller pieces due to constant wave motion. Nets left behind do not dissolve; they shed fibers that mix with surrounding sediments. Plastic parts used in holding tanks gradually degrade when exposed to outdoor conditions. Equipment meant for containment becomes a source of contamination over time. Materials stacked near ponds begin to crumble after repeated temperature shifts. Items like straps or covers lose integrity, scattering granules across wet surfaces. Even intact-looking containers contribute, leaching residues during routine handling. Structures submerged for long periods weaken at connection points. Sunlight intensifies surface fractures on floating markers. Debris accumulates where currents slow, trapping degraded bits near shorelines.

Farming aquatic species holds distinct significance since raised organisms can encounter microplastics from natural waters along with those originating within facilities through feeds or operational debris. Such conditions lead to cycles where efforts meant to offer sustainable protein might instead concentrate plastic contact if upgrades in material choices, runoff control, and filtration remain unaddressed (Jangid, 2025).

Environmental Fragmentation and Secondary Formation

Most tiny plastic pieces in water come from big thrown-away items breaking down slowly when exposed to sun, oxygen, rubbing actions, or living things’ activity. Though differing widely in form, material kind, weight level, hue, and outer layer traits, such fragments behave unpredictably across ecosystems. Their movement patterns shift due to how fast they sink, whether microbes coat them, or if sea life absorbs them easily. When organisms grow on these bits, floatation changes - what once stayed up high often drops toward the bottom layers. There, creatures living near or on the seabed might interact with the submerged remnants.

Smaller fragments emerge without pause, creating issues for fishing operations due to their resemblance in dimension to organic food sources - examples include plankton, decomposing matter, aquatic eggs, along with bottom-dwelling debris. Because of this likeness, unintended consumption rises, mistaken identity occurs more often, pathways through feeding networks grow more complex (Marcharla, 2024).

Bioaccumulation and Trophic Dynamics

Microplastics enter fishery organisms through ingestion, ventilation across gills, contact with contaminated sediments, and trophic transfer from prey. Reviews indicate that the gastrointestinal tract and gills are the most common sites of accumulation in fish, with subsequent movement to other tissues reported under certain experimental and field conditions. The extent of retention depends on particle size, shape, polymer type, dose, exposure duration, feeding behavior, habitat use, and species-specific physiology.

In freshwater fish, reported occurrence varies widely by species, watershed, and sampling design, but evidence now confirms ingestion in many taxa across lakes, rivers, reservoirs, and urban streams. Freshwater systems may be underreported compared with marine environments, even though they receive strong direct inputs and serve as conduits to the ocean. A study from Lake Titicaca detected microplastics in water and in stomach contents of commercially targeted fish species, although ingestion frequency in fish was relatively low in that case, illustrating that contamination patterns can differ substantially among fisheries (Varol, 2025).

Marine food webs show strong evidence for within-trophic-level bioaccumulation, but broad field evidence for biomagnification across an entire marine food web remains limited and inconsistent. A meta-analysis of marine data found support for bioaccumulation within trophic levels, while concluding that current field observations do not convincingly demonstrate general biomagnification across trophic levels. This distinction is important because trophic transfer clearly occurs, yet higher trophic position alone may not reliably predict higher microplastic body burden under natural conditions (Varol, 2025). Fishery products also differ in consumer relevance depending on whether contaminated organs are removed before consumption. In many finfish species, microplastics are more often detected in the digestive tract than in muscle, so evisceration can reduce direct dietary exposure. However, small pelagic fish eaten whole, bivalves, some crustaceans, and processed fishery products can still contribute to human intake because edible portions may retain particles or become contaminated during handling and processing.

Ecotoxicological Impacts on Fishery Organisms

Physiological and Cellular Effects

Experimental and review studies consistently identify oxidative stress as one of the major mechanisms of microplastic toxicity in aquatic organisms. Excess generation of reactive oxygen species can disrupt antioxidant defenses, damage lipids and proteins, and trigger downstream inflammation and cellular injury. Reported physiological responses in fish include altered hematological indices, impaired osmoregulation, tissue damage, inflammatory responses, and reduced overall condition when exposure is sufficiently intense or prolonged (Smith et al., 2018).

Microplastics can also interfere with metabolism, digestion, and energy allocation. By occupying gut space, reducing feeding efficiency, or inducing chronic stress, they may decrease nutrient assimilation and redirect energy from growth and reproduction toward maintenance and detoxification. Such sublethal effects are highly relevant to fisheries because they may reduce survival, body condition, recruitment, and stock productivity even when outright mortality is low (Miller et al., 2020).

Behavioral, Reproductive, and Immunological Effects

Behavioral impacts have been reported in fish exposed to microplastics, including altered feeding, reduced predatory performance, changes in swimming behavior, and predator-response impairment. These effects can weaken foraging success and anti-predator capacity, thereby increasing ecological vulnerability under natural conditions. In reproductive terms, chronic physiological stress, endocrine disruption from additives, and reduced energy availability may impair gonadal function, embryonic development, and larval fitness, though outcomes vary by species and exposure regime. Immune effects are another major concern because microplastics can alter inflammatory signaling and immune competence. Reviews describe immunomodulation, dysbiosis of the gut microbiota, and increased susceptibility to secondary stressors as plausible pathways of harm. In fisheries, these responses may interact with crowding, warming, hypoxia, pathogen load, and other production or environmental stressors, amplifying disease risk in both wild and cultured populations (Miller et al., 2020).

Combined Toxicity with Co-Contaminants

A central ecotoxicological issue is that microplastics rarely act alone in real environments. Their surfaces can adsorb metals, persistent organic pollutants, antibiotics, and other chemicals, and they can carry additives originally incorporated during manufacture such as bisphenol A, nonylphenol, or flame retardants. This means microplastics may function both as particles causing physical stress and as vectors that modify contaminant exposure, bioavailability, and mixture toxicity.

The significance of vector effects remains debated. Some reviews conclude that ingestion of microplastics is not yet proven to increase persistent toxic chemical exposure enough to explain all observed biological effects in marine animals, while other studies emphasize that localized conditions, biofilms, and particle chemistry may still make co-exposure ecologically important. For fisheries research, the most defensible interpretation is that particle toxicity and contaminant interactions should be studied together, especially in polluted estuaries, aquaculture zones, and urbanized inland waters (Cverenkárová et al., 2021).

Implications for Fisheries and Food Safety

Fisheries face disruption through microplastic presence across ecological and economic layers - habitat conditions shift, feeding networks weaken, market value wavers, consumer trust declines. In oceanic zones like the Atlantic, Mediterranean, Pacific, and Indian regions, alongside interior water bodies, commercial species such as fish, shellfish, and molluscs show traces of synthetic particles; however, measured amounts differ markedly between animal groups and research efforts. When entire creatures are eaten - including two-shelled filter feeders and midwater schooling types - people encounter these materials more directly compared to when internal organs are removed prior to consumption (Banaee, 2025) Although signs point to possible risks, proof of harm to people from microplastics in seafood stays unclear. Studies suggest these particles might lead to cellular damage, inflammation, or movement within body tissues; they could also bring chemical additives or pollutants along with them - still, today’s information lacks depth for solid numerical conclusions about danger levels. Because of this gap, handling the matter carefully makes sense - not through fear-driven statements, but via watchful tracking, lowering contact where feasible, and agreeing on uniform testing approaches across research efforts.

Much like shifting tides, microplastics influence both economy and policy in fishing oversight. When pollutants appear, trust in markets may decline - these ties into approval systems, trade rules, alongside public acceptance of fish farming and wild harvest alike. Visibility matters: once contamination reaches consumer awareness, it often aligns with deeper unease over food security and natural balance (Banaee, 2025).

Sustainable Mitigation Strategies

Source Reduction and Circular Material Policy

The most sustainable solution is to prevent plastic leakage before it reaches freshwater and marine systems. Policies that reduce unnecessary single-use plastics, improve product design, expand producer responsibility, and strengthen collection and recycling can cut the upstream burden that eventually enters fisheries. Because freshwater systems transport a major share of land-derived plastics to the sea, inland waste governance is also marine fisheries policy in practical terms.

Material substitution must be approached carefully. Replacing conventional polymers with alternatives can help only when life-cycle impacts, field durability, degradation pathways, and end-of-life management are clearly superior; otherwise, substitutions may simply shift environmental burdens or create new contamination problems. A circular economy approach that prioritizes reduction, reuse, repair, and responsible recovery is more defensible than relying on substitution alone (Alberghini et al., 2022).

Wastewater, Stormwater, and Catchment Controls

Purified water flows begin where waste systems grow more precise, stopping tiny plastics from drifting into fish-rich zones. Where homes release used water, advanced filters paired with careful residue handling reduce harmful outflows remarkably. Urban surfaces channel rain; here, engineered barriers hold back pollutants effectively. Along river edges packed with people, organized removal of debris limits what washes downstream slowly. Devices placed within flowing channels trap floating refuse before it spreads further. In regions tied closely to lakes, tidal areas, or shore-based fishing spots, oversight of illegal disposal becomes a quiet necessity. Structures designed to store excess flow during heavy rains also serve as buffers against contamination repeatedly.

Among particles found in water, microfibers rank high - making synthetic fabric release a key concern. Textile improvements stand alongside filter installation in laundry machines. Pretreatment at factories works together with shifts in how people wash clothes. Fewer fibers enter ecosystems when these steps combine.

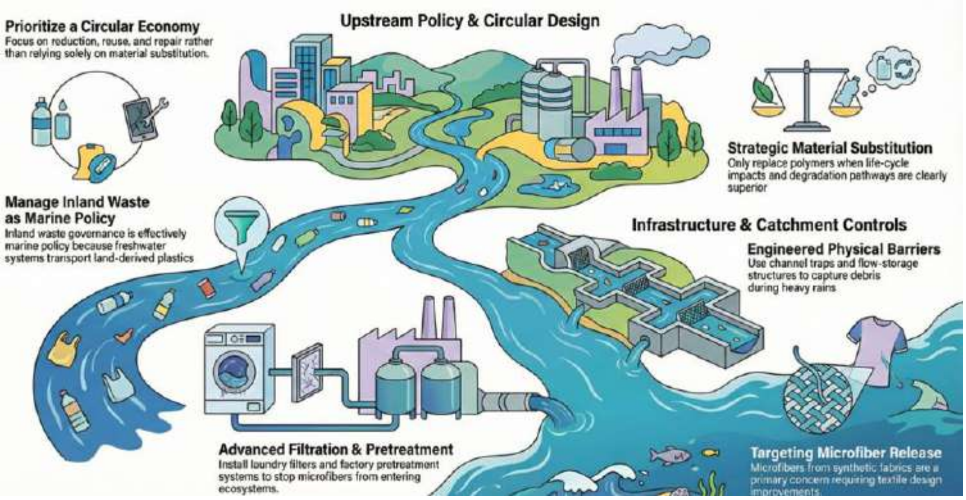

Figure 1: A strategy to stop plastic leakage

Fishery-Specific and Aquaculture Interventions

Beyond broad waste regulations, fishing industries require targeted strategies. Although common policies exist, specific steps prove more effective here. Marking equipment stands first among these efforts; recovering lost items follows closely behind. Instead of discarding old materials, return schemes for nets and lines reduce environmental release. Ports equipped to handle such waste enable consistent disposal practices. Scheduled updates for worn tools prevent fragmentation at sea. Procurement focused on long-lasting, retrievable designs shifts market behavior gradually. Accountability improves when each stage - from production to disposal - follows clear guidelines. Polymer loss declines where these approaches are applied systematically. Capture operations, including fish farming, show measurable change under structured oversight.

Water quality checks help lower contamination risks at fish farms. Through careful oversight of incoming supplies, sites limit contact with pollutants. Losses tied to plastic materials drop when structures are maintained properly. Feed must be stored securely to prevent environmental leaks. Management routines gain clarity once waste reviews become routine. Oversight programs may include measures targeting tiny plastics. Such standards encourage recordkeeping on safeguards taken. Progress tracking becomes part of normal operations under these frameworks (Smith et al., 2018).

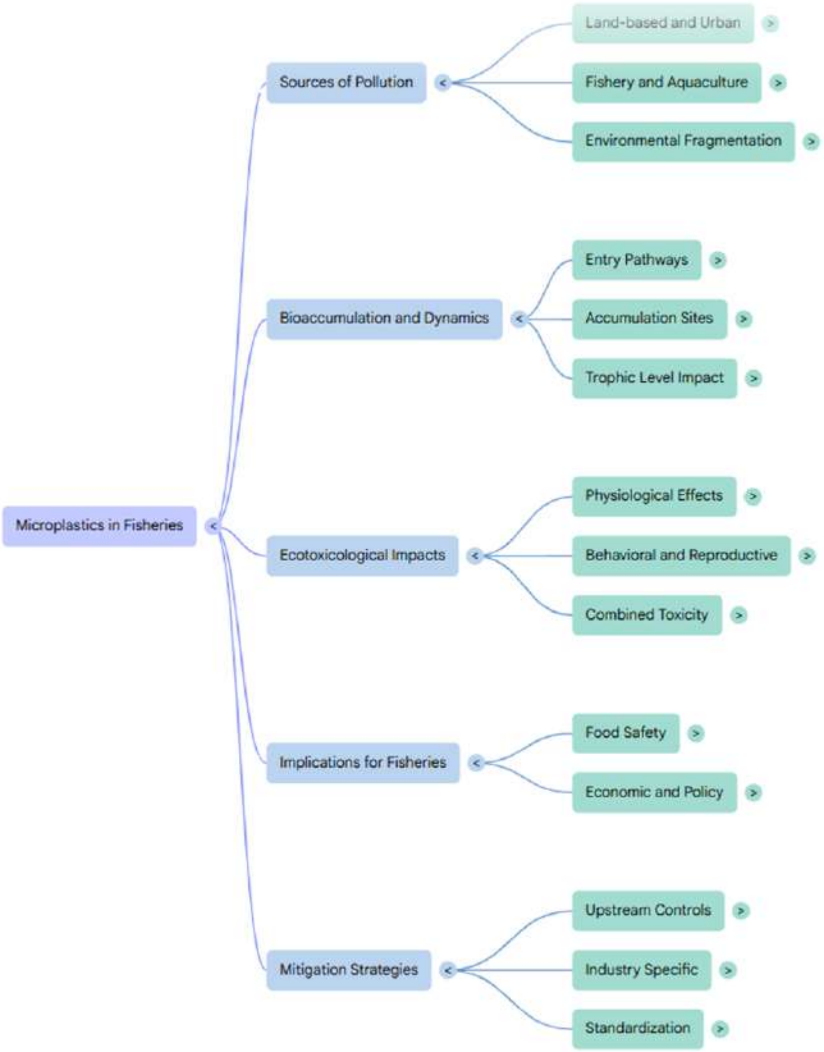

Figure 2: The Impact of Microplastics on Fisheries and Marine Ecosystems

CONTEXT

Microplastics (<5mm) flow from terrestrial sources into freshwater and marine environments, where they are ingested by aquatic life. This contamination threatens ecosystem health and food safety, requiring a shift toward circular material policies and improved fishery gear management.

WIDESPREAD INGESTION AND RETENTION

Particles accumulate primarily in the gastrointestinal tracts and gills of freshwater and marine fish.

CHRONIC PHYSIOLOGICAL STRESS

Exposure triggers oxidative stress, inflammation, and metabolic disturbances that reduce overall stock productivity.

TROPHIC TRANSFER TO HUMANS

Whole-consumed species like bivalves and small pelagic fish serve as direct dietary pathways.

SOURCE CATEGORY	PRIMARY CONTRIBUTORS
LAND-BASED	Urban runoff, wastewater effluent, and synthetic textile fibers.
FISHERY-BASED	Fragmented nets, aquaculture pond debris, and worn equipment.
SECONDARY	Breakdown of larger debris via sunlight, oxygen, and wave action.

UPSTREAM SOURCE REDUCTION

Implementing circular economy policies to prevent plastic leakage before it reaches waterways.

ADVANCED FILTRATION CONTROLS

Upgrading wastewater plants and laundry systems to capture high-volume synthetic microfibers.

GEAR STEWARDSHIP PROGRAMS

Establishing net recovery schemes and using retrievable designs to prevent equipment fragmentation at sea.

Figure 3: The Microplastic cycle, impact and solution in Fisheries

Conclusion

Microplastic pollution in freshwater and marine fisheries is now well established as a cross-ecosystem problem driven by land-based waste leakage, wastewater emissions, fragmentation of larger plastics, and fishery-related materials. In fishery organisms, the strongest evidence supports widespread ingestion, frequent accumulation in digestive tracts and gills, and diverse sublethal effects involving oxidative stress, inflammation, metabolic disruption, behavioral change, and immune dysfunction. Evidence for broad biomagnification across whole food webs remains weaker than evidence for localized bioaccumulation and trophic transfer, which means risk assessment must remain nuanced and habitat-specific.

The most sustainable response is preventive rather than reactive. Reducing plastic inputs at source, upgrading wastewater and stormwater controls, improving gear stewardship, standardizing monitoring, and embedding microplastic control into fisheries and aquaculture governance together offer the most credible pathway for protecting aquatic biodiversity, fishery productivity, and seafood safety in the long term.

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ISBN: 978-93-49938-76-2| Year: 2026 | pp: 60 - 84 |

Fish and Fishery: An Overview of Fish Farming and Aquaculture, Pollution, Microplastics and Habitat Degradation

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Article DOI Link: https://zenodo.org/uploads/20109183

DOI: 10.5281/zenodo.20109183

Abstract

Aquatic ecosystems are increasingly threatened by multiple anthropogenic stressors, among which pollution, microplastic contamination, and habitat degradation are of critical concern for fisheries and aquaculture sustainability. This chapter provides a comprehensive synthesis of the sources, distribution, and ecological consequences of these stressors in freshwater and marine environments. Special emphasis is placed on microplastics as emerging contaminants, detailing their origin, physicochemical characteristics, trophic transfer, and bioaccumulation in fish species. The chapter further explores how conventional pollutants such as heavy metals, pesticides, and industrial effluents interact synergistically with microplastics, exacerbating toxicity and ecological risks. Habitat degradation, including mangrove destruction, coral reef decline, eutrophication, and sedimentation, is discussed in relation to its impact on fish diversity, breeding grounds, and aquaculture productivity. The implications for fish health, growth performance, reproductive success, and food safety are critically evaluated. Finally, the chapter highlights mitigation strategies, including sustainable aquaculture practices, pollution control measures, habitat restoration, and policy interventions, providing a roadmap for enhancing ecosystem resilience and ensuring long-term fishery sustainability.

Keywords: Microplastics; Aquatic pollution; Habitat degradation; Fish health; Sustainable aquaculture; Ecosystem resilience

Introduction

Aquatic ecosystems, including rivers, lakes, estuaries, and oceans, provide essential ecological services such as water purification, nutrient cycling, carbon storage, and habitat for diverse organisms (Duarte et al., 2020; Halpern et al., 2019). These ecosystems also support human livelihoods by supplying fisheries, aquaculture products, recreation, and cultural benefits. Globally, fisheries provide nearly 20% of animal protein for over three billion people, while aquaculture has become increasingly important in meeting seafood demand, sometimes surpassing capture fisheries in production (FAO, 2022; Boyd et al., 2020). However, anthropogenic pressures, including urbanization, industrial effluents, agricultural runoff, and climate change, threaten aquatic biodiversity, fish health, and ecosystem productivity (Li et al., 2018; Wang et al., 2018). Water quality is a fundamental determinant of fish growth, reproduction, and survival. Poor water quality, characterized by low dissolved oxygen, elevated nutrient loads, or high concentrations of toxic chemicals, induces physiological stress, increases disease susceptibility, and reduces feed conversion efficiency in cultured fish (Ahmed & Thompson, 2019; Badiola et al., 2018; Jabeen et al., 2018).

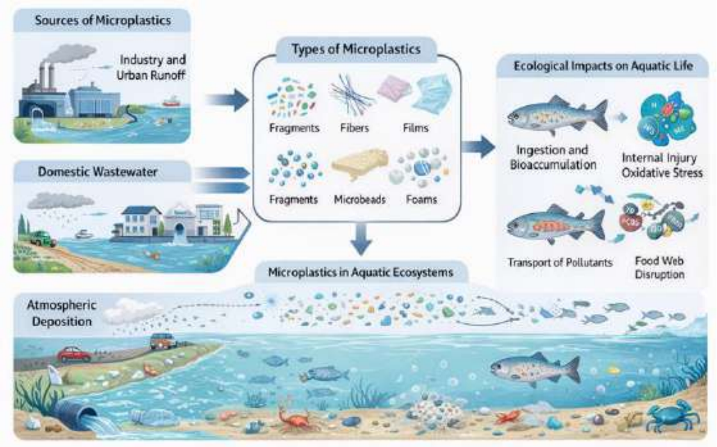

Figure 1: Sources, Types, and Ecological Impacts of Microplastics in Aquatic Ecosystems

Emerging contaminants, particularly microplastics, exacerbate these challenges. Microplastics can be ingested by fish, causing gut inflammation, oxidative stress, and immune dysfunction, and may act as vectors for harmful chemicals such as heavy metals and persistent organic pollutants (Lu et al., 2016; Jin et al., 2018; Guo & Wang, 2019). Their presence in aquatic ecosystems not only affects fish physiology and aquaculture productivity but also raises concerns for food safety and human health (EFSA, 2016). Given the cumulative impact of pollution, microplastic contamination, and habitat degradation, integrated approaches are essential to maintain ecosystem health, ensure sustainable fisheries, and optimize aquaculture production (Li et al., 2018; Rochman et al., 2019; Boyd et al., 2020). This review synthesizes current knowledge on the sources, distribution, and ecological consequences of these stressors, evaluates their effects on fish health and aquaculture performance, and discusses mitigation strategies for enhancing ecosystem resilience and long-term sustainability.

Aquatic Pollution: Sources and Types

1. **Point and Non-Point Sources of Pollution:** Aquatic pollution arises from both point and non-point sources, each contributing to the deterioration of water quality. Point sources originate from identifiable locations, such as industrial effluents, sewage discharges, and aquaculture runoff, and are relatively easier to manage (Ahmed & Thompson, 2019; Li et al., 2018). Non-point sources are diffuse and more difficult to control, including agricultural runoff, urban stormwater, and atmospheric deposition. These sources carry nutrients, sediments, pesticides, and increasingly, microplastics into rivers, lakes, and coastal areas (Blettler et al., 2018; Wang et al., 2018). The widespread use of plastics and synthetic fibers has introduced microplastics as a significant non-point pollutant in freshwater and marine environments, further complicating water quality management (Eerkes-Medrano et al., 2019; Dris et al., 2018). The combined effect of point and non-point pollution reduces ecosystem resilience, threatens biodiversity, and compromises the sustainability of fisheries and aquaculture.

2. **Chemical Pollutants (Heavy Metals, Pesticides, Industrial Effluents):** Chemical pollutants, including heavy metals, pesticides, and industrial effluents, are persistent and bioaccumulative, posing long-term threats to aquatic systems (Guo & Wang, 2019). Heavy metals such as cadmium, lead, mercury, and arsenic enter waterways through mining, industrial activities, and agricultural runoff. These metals accumulate in sediments and aquatic organisms, presenting risks to fish and human consumers (Wang et al., 2018; Pitt et al., 2018). Agricultural pesticides and herbicides exacerbate stress on aquatic life by promoting eutrophication and inducing oxidative stress in fish,

impairing growth, reproduction, and immune function (Lu et al., 2016; Jabeen et al., 2018). Industrial effluents, often complex mixtures of organic and inorganic chemicals, can interact synergistically with microplastics. Microplastics act as vectors, facilitating pollutant transport and increasing bioavailability to aquatic organisms (Wang et al., 2018; Guo & Wang, 2019). Studies demonstrate that co-exposure to microplastics and chemical pollutants intensifies physiological stress, alters gut microbiota, and suppresses immune responses in fish (Jin et al., 2018; Espinosa et al., 2018).

3. **Nutrient Pollution and Eutrophication:** Nutrient pollution, primarily from nitrogen and phosphorus, drives eutrophication in freshwater and coastal ecosystems (Duarte et al., 2020). Excessive nutrients stimulate algal blooms that deplete dissolved oxygen, creating hypoxic or anoxic conditions leading to fish kills, biodiversity loss, and ecosystem destabilization (Ahmed & Thompson, 2019). Nutrient inputs are amplified by agricultural runoff, untreated sewage, and poorly managed aquaculture operations (Badiola et al., 2018). Microplastics can exacerbate nutrient-related impacts by providing surfaces for microbial colonization. Microbial biofilms on plastics enhance organic matter decomposition and alter nutrient cycling, amplifying ecological risks (Eerkes-Medrano et al., 2019; Setälä et al., 2018). Together, chemical and nutrient pollution, along with microplastic contamination, represent complex threats to water quality, aquatic biodiversity, and fisheries and aquaculture productivity.

Table 1. Sources, Distribution, and Ecological Consequences of Aquatic Stressors

Stressor	**Sources**	**Distribution in Aquatic Systems**	**Ecological Consequences**	**References**
Chemical Pollution (Heavy metals, pesticides, industrial effluents)	Mining, industrial discharge, agriculture, sewage, and aquaculture	Found in the water column, sediments, and biota; persistent in freshwater and coastal areas	Bioaccumulation, oxidative stress, impaired growth/reproduction, trophic transfer, mortality	Wang et al. (2018); Pitt et al. (2018); Lu et al. (2016); Jabeen et al. (2018); Guo & Wang (2019)

Nutrient Pollution (Nitrogen, phosphorus)	Agricultural runoff, sewage, and aquaculture effluents	Rivers, lakes, estuaries, coastal waters; often spatially diffuse	Eutrophication, algal blooms, hypoxia/anoxia, fish kills, biodiversity loss	Duarte et al. (2020); Badiola et al. (2018); Ahmed & Thompson (2019)
Microplastics	Synthetic fibers, packaging, personal care products, textile runoff	Ubiquitous in freshwater and marine systems; sediments, water column, biota	Ingestion by fish and invertebrates, gut damage, bioaccumulation, trophic transfer, vector for chemicals	Li et al. (2018); Rochman et al. (2019); Eerkes-Medrano et al. (2019); Dris et al. (2018)
Organic Contaminants (POPs, pharmaceuticals, personal care products)	Wastewater, industrial effluents	Water, sediment, biota; sometimes widespread due to persistence	Endocrine disruption, reproductive impairment, bioaccumulation, and reduced fish fitness	Rochman et al. (2019); Koelmans et al. (2019)
Biological Contaminants (Bacteria, viruses, parasites)	Aquaculture, sewage, pollution-stressed environments	Water column, sediments, and farmed fish	Increased disease prevalence, reduced growth and survival, and food safety risk	Lafferty et al. (2018); Smith et al. (2018); Barboza et al. (2020)
Habitat Degradation (Mangroves, coral reefs, seagrass, sedimentation)	Deforestation, coastal development, dredging, and climate change	Localized to affected coastal and freshwater habitats	Loss of nursery grounds, reduced biodiversity, altered hydrology, decreased aquaculture productivity	Hughes et al. (2018); Alongi (2018); Duarte et al. (2020); Nagelkerken et al. (2015)

Microplastics in Aquatic Environments

Microplastics are plastic particles smaller than 5 mm that originate from primary sources, such as manufactured microbeads and industrial pellets, or secondary sources, including fragmentation of larger plastic debris (Li et al., 2018; Rochman et al., 2019). They are classified based on size, shape, polymer type, and origin.

Common shapes include fibers, fragments, films, foams, and spheres, while polymer types typically include polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) (Guo & Wang, 2019; Wang et al., 2018). Understanding these properties is essential, as they influence environmental persistence, mobility, and interactions with pollutants (Jin et al., 2018).

1. Sources and Pathways

Microplastics Enter Aquatic Ecosystems Through Multiple Pathways:

- **Wastewater Treatment Plants (WWTPs):** Fibers from laundry, microbeads from cosmetics, and industrial fragments can pass through conventional treatment systems (Liu et al., 2019).
- **Runoff and River Transport:** Urban and agricultural areas carry microplastics to lakes, rivers, and estuaries via surface runoff (Blettler et al., 2018; Dris et al., 2018).
- **Atmospheric Deposition:** Synthetic fibers from textiles and road dust settle into aquatic environments via precipitation or wind transport (Dris et al., 2018).
- **Direct Maritime Sources:** Fisheries, aquaculture equipment, and shipping activities introduce microplastics directly into coastal waters (Setälä et al., 2018).

These pathways result in widespread contamination, with microplastics now detected globally in rivers, lakes, estuaries, and open oceans (Eerkes-Medrano et al., 2019; Wang et al., 2018).

Table 2. Classification, Sources, and Environmental Impacts of Microplastics

Feature	Details	Typical Sources	Environmental Distribution	Ecological Consequences	References
Size	<5 mm	Primary (microbeads, industrial pellets), Secondary (fragmented plastics)	Surface water, sediments, biota	Small particles can penetrate tissues, facilitating bioaccumulation	Li et al., 2018; Rochman et al., 2019

Shape	Fibers, fragments, films, foams, spheres	Synthetic textiles, packaging, fishing gear	Fibers dominate freshwater; fragments/films dominate marine systems	Fibers can entangle organisms; fragments may cause gut obstruction	Blettler et al., 2018; Setälä et al., 2018
Polymer Type	PET: Polyethylene Terephthalate, PE: Polyethylene, HDPE/LDPE, , PP: Polypropylene), and PS**:** Polystyrene	Packaging, textiles, industrial products	Distributed in both freshwater and marine sediments and water columns	Chemically stable; adsorb hydrophobic pollutants	Guo & Wang, 2019; Wang et al., 2018
Pathways	Transport routes into ecosystems	WWTP effluent, runoff, atmospheric deposition, maritime sources	Rivers, lakes, estuaries, and coastal waters	Ingested by fish and invertebrates; facilitate trophic transfer of pollutants	Liu et al., 2019; Setälä et al., 2018; Dris et al., 2018
Environmental Persistence	High chemical stability, slow degradation	Weathered particles from all sources	Accumulate in sediments; remain suspended in water column	Long-term exposure causes gut damage, oxidative stress, immune disruption	Jin et al., 2018; Pitt et al., 2018; Espinosa et al., 2018

2. Physicochemical Properties and Environmental Persistence

The physicochemical properties of microplastics, ncluding polymer type, size, density, and surface characteristics determine their buoyancy, transport, and interactions with chemical pollutants (Guo & Wang, 2019; Jin et al., 2018). Weathered or aged particles develop rough surfaces that enhance adsorption of heavy metals and hydrophobic organic contaminants (Pitt et al., 2018). Once ingested by aquatic organisms, microplastics cause gut damage, oxidative stress, immune disruption, and can facilitate the trophic transfer of pollutants through food webs (Espinosa et al., 2018; Koelmans et al., 2019).

Microplastics are chemically stable and slow to degrade due to their polymer composition, which allows them to persist in aquatic systems for decades (Guo & Wang, 2019). Their low density, small size, and inert surface chemistry enable them to remain suspended in the water column or accumulate in sediments. Despite aging and surface weathering, which promote pollutant adsorption, these particles largely resist degradation, continually interacting with chemical and biological contaminants and entering aquatic food webs (Jin et al., 2018; Pitt et al., 2018).

Interaction of Microplastics with Pollutants

1. **Microplastics as Vectors for Toxic Chemicals:** Microplastics serve as carriers of chemical pollutants due to their large surface area, hydrophobic nature, and weathered surfaces, which enable them to adsorb heavy metals like cadmium and lead, as well as hydrophobic organic pollutants such as PCBs and PAHs (Guo & Wang, 2019; Rochman et al., 2019; Jin et al., 2018; Wang et al., 2018). They can also leach additives, including phthalates, bisphenol A (BPA), brominated flame retardants, and metal stabilizers, many of which act as endocrine disruptors or developmental toxicants (Rochman et al., 2013; Hermabessiere et al., 2017).

2. **Experimental Studies Highlight the Impact on Aquatic Species:** zebrafish (Danio rerio) exposed to BPA-laden microplastics show disrupted hormone levels, altered gene expression in the hypothalamic-pituitary-gonadal axis, and reduced reproduction. Meanwhile, tilapia (Oreochromis niloticus) fed microplastics containing phthalates exhibit oxidative stress, liver damage, and reduced growth performance (Espinosa et al., 2018; Jin et al., 2018). Laboratory experiments also demonstrate that aged polyethylene microplastics can transfer adsorbed metals directly to fish tissues, intensifying toxicity and causing histopathological damage (Guo & Wang, 2019; Wang et al., 2018). Overall, the ingestion of pollutant-laden microplastics amplifies bioaccumulation, oxidative stress, immune suppression, and ecological risk, beyond the effects of dissolved or sediment-bound contaminants alone (Espinosa et al., 2018; Barboza et al., 2020).

3. **Adsorption and Desorption Mechanisms:** The interactions between microplastics and pollutants involve both adsorption and desorption processes. Adsorption occurs through hydrophobic interactions, van der Waals forces, and electrostatic attractions between pollutants and microplastic surfaces (Guo & Wang, 2019). Environmental factors such as pH, salinity, and temperature influence the extent of these interactions (Wang et al., 2018). Once ingested by aquatic organisms, desorption can release the adsorbed pollutants directly into tissues, increasing internal exposure (Jin et al., 2018). Studies with zebrafish

and mussels indicate that microplastics facilitate the trophic transfer of contaminants, posing potential risks to higher trophic levels, including humans (Setälä et al., 2018; Rochman et al., 2019).

4. **Synergistic Toxic Effects:** Microplastics can magnify the toxicity of environmental pollutants through synergistic interactions, acting both as chemical carriers and physical stressors. When ingested, microplastics carrying heavy metals, plastic additives, or persistent organic pollutants cause effects more severe than exposure to either stressor alone (Rochman et al., 2013; Wang et al., 2018). For example, exposure to phthalate-containing microplastics increases oxidative stress in liver and gut tissues and impairs growth, showing that microplastics enhance the bioavailability and toxicity of associated pollutants (Jin et al., 2018; Barboza et al., 2020).The combined toxicity is not limited to fish. Microplastics contaminated with polycyclic aromatic hydrocarbons (PAHs) impair plankton growth, reduce photosynthesis, hinder reproduction, and decrease survival in zooplankton, disrupting energy transfer across trophic levels (Cole et al., 2016; Galloway et al., 2017). Additionally, microplastics can trigger immunotoxic effects, intestinal inflammation, and microbiota imbalance when co-exposed with pollutants, further amplifying ecological and health risks (Hirt & Body-Malapel, 2020; Jin et al., 2018; Espinosa et al., 2018). Together, these findings illustrate that microplastics act as multiplicative stressors, with combined physical and chemical effects exceeding the sum of individual exposures, highlighting their critical role in shaping the toxicity landscape in aquatic ecosystems.

Impact on Fish and Aquatic Organisms

1. **Ingestion and Bioaccumulation of Microplastics:** Fish are highly susceptible to microplastic ingestion through filter feeding, gill exposure, and consumption of contaminated prey. Studies show that microplastics accumulate in the gut, liver, and sometimes muscle tissues, with smaller particles more likely to move beyond the gastrointestinal tract (Jin et al., 2018; Espinosa et al., 2018; Lu et al., 2016). These particles can carry chemical pollutants such as heavy metals and hydrophobic organic compounds, increasing bioaccumulation and oxidative stress. This exposure impairs growth, reproduction, and immune function while causing histopathological damage in liver and gut tissues (Guo & Wang, 2019; Wang et al., 2018; Espinosa et al., 2018). Co-exposure with pollutants like cadmium amplifies toxicity, highlighting the significant ecological and aquaculture implications of microplastic ingestion.

2. **Physiological and Histopathological Effects:** Ingested microplastics and their associated chemical pollutants induce oxidative stress, inflammation, and tissue

damage in fish. Aquatic life forms exposed to polystyrene microplastics show intestinal epithelial disruption, hepatocyte vacuolation, and deformation of gill lamellae (Jin et al., 2018; Pitt et al., 2018). Such tissue alterations reduce nutrient absorption, metabolic efficiency, and immune competence, making fish more vulnerable to pathogens and other environmental stressors (Espinosa et al., 2018). Chronic exposure can lead to cumulative tissue damage, impaired growth, and higher mortality, especially in high-density aquaculture systems.

3. **Impacts on Growth, Reproduction, and Survival:** Microplastic exposure adversely affects fish growth, reproductive success, and survival, producing cascading effects throughout aquatic food webs. Studies report reduced body weight, stunted growth, and impaired larval development following ingestion of microplastics or microplastic-associated chemical pollutants (Espinosa et al., 2018; Jin et al., 2018; Lu et al., 2016). Larvae are particularly vulnerable, as microplastics interfere with yolk sac absorption, organ formation, and early skeletal development, leading to reduced survival rates and higher deformity incidence (Lu et al., 2016; Espinosa et al., 2018).

   Beyond fish, microplastics impact lower trophic levels. Phytoplankton can adsorb microplastics or their chemical additives, altering growth rates, reducing photosynthetic efficiency, and inducing oxidative stress (Hui et al., 2021). Zooplankton, including copepods and rotifers, ingest microplastics directly, which can cause gut blockage, lower feeding efficiency, and impaired reproduction, thereby limiting food availability for larval and juvenile fish (Barboza et al., 2020). This trophic transfer increases bioaccumulation of pollutants in higher-order species and contributes to population declines. Microplastic contamination thus compromises growth, reproduction, and survival across fish populations while altering plankton communities essential for larval nutrition, emphasizing multilevel ecological risks in freshwater and marine ecosystems with implications for aquaculture productivity, biodiversity, and food security (Espinosa et al., 2018; Guo & Wang, 2019; Hui et al., 2021).

4. **Trophic Transfer and Food Web Implications:** Microplastics readily move through aquatic food webs, from primary consumers such as zooplankton and bivalves to higher predators, including fish and ultimately humans, often carrying associated chemical contaminants (Farrell & Nelson, 2013; Galloway et al., 2017). At the base level, microplastics accumulate in the tissues or fecal pellets of primary consumers, making them available to predators (Cole et al., 2016; Gove et al., 2019). Predatory species then biomagnify these plastics and associated pollutants, increasing exposure at higher trophic levels and potentially causing inflammation, oxidative stress, behavioral changes, and reduced survival, which can alter population dynamics (Espinosa et al., 2018; Jin et al., 2018; Rochman et al., 2013). Human consumption of seafood

introduces another pathway for microplastic and chemical exposure, raising public health concerns (Rochman et al., 2019; Smith et al., 2018). Trophic transfer of microplastics disrupts predator-prey interactions, alters energy flow, reduces ecosystem resilience, and amplifies the ecological and health risks associated with persistent pollution (Barboza et al., 2020; Gove et al., 2019).

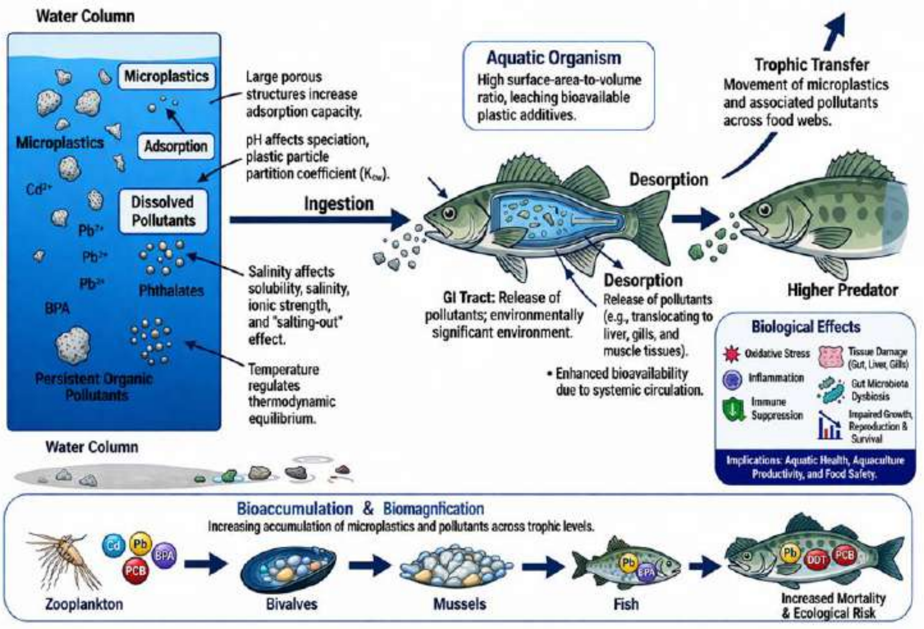

Figure 2: Mechanisms of Microplastic–Pollutant Interactions and Trophic Transfer in Aquatic Systems

Habitat Degradation and Its Consequences

1. **Types of Habitat Degradation:** Aquatic habitats are increasingly threatened by multiple stressors, including mangrove deforestation, coral reef loss, sedimentation, eutrophication, and the pervasive presence of microplastics. Globally, approximately 35% of mangroves and 30% of coral reefs have been lost over the past four decades due to coastal development, aquaculture, and urban expansion (Alongi, 2018; Burkepile et al., 2020). Sedimentation from river runoff and dredging smothers benthic organisms and reduces light penetration, negatively affecting seagrasses and algae, while eutrophication creates hypoxic zones with dissolved oxygen levels often below 2 mg/L, causing mass mortality of fish and invertebrates (Li et al., 2018; Wang et al., 2018). In the Pearl River Estuary, Zuo et al. (2020) recorded microplastic levels in mangrove sediments ranging from 200 to over 4,000 particles per kg. Primarily composed of fibers and fragments, these microplastics showed a significant correlation ($p < 0.05$) with halogenated flame retardants (HFRs). This relationship suggests that microplastics do not just coexist with chemical

pollutants but actively serve as carriers and indicators of HFR contamination within the ecosystem.

The accumulation of microplastics in these degraded habitats compounds these effects. Microplastics can accumulate in sediments and on benthic surfaces, altering substrate structure and reducing habitat complexity, which diminishes shelter and feeding grounds for benthic organisms (Guo & Wang, 2019; Wang et al., 2018). Studies have shown that filter-feeding and sediment-ingesting species, such as mussels and juvenile fish, ingest microplastics along with natural particles, leading to reduced growth, impaired reproduction, and increased mortality rates (Cole et al., 2016; Pitt et al., 2018). In estuarine and coastal nurseries, where juvenile fish depend on mangroves and seagrasses, microplastic ingestion can disrupt gut function, alter microbiota, and reduce survival by up to 30–40% in experimental studies (Espinosa et al., 2018; Mattsson et al., 2017). Furthermore, microplastics act as vectors for chemical pollutants, including heavy metals and hydrophobic organic compounds, which can accumulate in fish tissues, exacerbating the toxic impacts of degraded habitats (Koelmans et al., 2016; Rochman et al., 2013). For example, microplastics contaminated with bisphenol A or polychlorinated biphenyls can induce hepatic stress, neurotoxicity, and endocrine disruption in fish populations inhabiting coral reefs and seagrass meadows (Chen et al., 2024; Mattsson et al., 2017). This structural habitat loss and chemical exposure create a synergistic pressure that reduces biodiversity, compromises fish recruitment, and impairs the ecological resilience of aquatic ecosystems (Hirt & Body-Malapel, 2020; Galloway et al., 2017).

2. **Loss of Breeding and Nursery Grounds:** The destruction of habitats such as mangroves, seagrass beds, and estuarine wetlands leads to a significant loss of breeding and nursery grounds, directly affecting fish reproduction and population dynamics (Sheaves et al., 2015). Juvenile fish rely on structurally complex habitats to evade predators, forage effectively, and develop properly. Experimental studies show that removal of vegetation cover increases predation risk, reduces growth rates by up to 25–30%, and lowers recruitment success in commercially important species such as snapper and mullet (Aburto-Oropeza et al., 2008; Zuo et al., 2020). The presence of microplastics in these nursery areas further exacerbates these effects. Juvenile fish in estuaries and mangrove creeks ingest microplastics along with natural prey, leading to reduced feeding efficiency, gut obstruction, and impaired nutrient absorption (Espinosa et al., 2018; Mattsson et al., 2017). Laboratory experiments indicate that ingestion of microplastics can reduce survival of larvae and juveniles by 20–40%, depending on particle size and concentration (Pitt et al., 2018). Moreover, microplastics often carry adsorbed pollutants, including heavy metals and

endocrine-disrupting chemicals, which can interfere with hormone regulation, delay development, and reduce reproductive potential in later life stages (Rochman et al., 2013; Koelmans et al., 2016). Together, habitat loss and microplastic contamination create compounded pressures that threaten the sustainability of fish populations reliant on nursery habitats.

3. **Coral Reef and Mangrove Ecosystem Decline:** Coral reefs and mangroves are experiencing widespread decline due to climate change, pollution, sedimentation, and destructive human activities (Burkepile et al., 2020; Alongi, 2018). Coral bleaching, ocean acidification, and excess sediment reduce reef structural complexity, leading to a 40–60% decline in local fish abundance and decreased species richness in affected areas (Pratchett et al., 2011). Similarly, mangrove deforestation for aquaculture, urbanization, and agriculture diminishes coastal protection, nursery habitats, and nutrient cycling capacity (Barbier et al., 2019). Restoration experiments show that replanting mangroves can increase juvenile fish density by over 50%, enhancing growth rates and survival, highlighting the importance of habitat conservation (Nagelkerken et al., 2015).

   Microplastics compound these declines by infiltrating coral reefs and mangrove sediments. Filter-feeding invertebrates and juvenile fish ingest microplastics, which can alter gut microbiota, impair digestion, and reduce energy allocation for growth and reproduction (Cole et al., 2016; Espinosa et al., 2018). In coral reef fish, microplastic exposure has been shown to induce oxidative stress and hepatic damage, further reducing fitness in already stressed ecosystems (Mattsson et al., 2017; Hirt & Body-Malapel, 2020). Additionally, microplastics can adsorb and transport chemical pollutants, including pesticides and heavy metals, amplifying toxic effects in declining reef and mangrove habitats (Rochman et al., 2013; Chen et al., 2024). The combination of physical habitat loss, reduced structural complexity, and chemical stress from microplastics threatens both biodiversity and the resilience of coastal ecosystems.6.4 Sedimentation and Altered Hydrology Sedimentation from erosion, deforestation, and construction alters hydrology and water quality, negatively affecting aquatic habitats (Sheaves et al., 2015). Increased turbidity reduces light penetration, impairing photosynthesis in seagrasses and corals, while fine sediments smother benthic organisms and reduce oxygen availability (Alongi, 2018). Changes in water flow and hydrology disrupt spawning migration, feeding behavior, and nutrient cycling. Experimental evidence demonstrates that sediment-laden waters reduce fish growth and survival, particularly in estuarine and coastal nursery habitats (Zuo et al., 2020).

Implications for Aquaculture

1. **Water Quality Degradation and Fish Farming:** Water quality is a critical determinant of aquaculture productivity. Pollution, eutrophication, and microplastic contamination degrade water parameters by lowering dissolved oxygen, altering pH, and increasing turbidity, which collectively stress farmed fish and reduce growth rates (Ahmed & Thompson, 2019; Badiola et al., 2018).

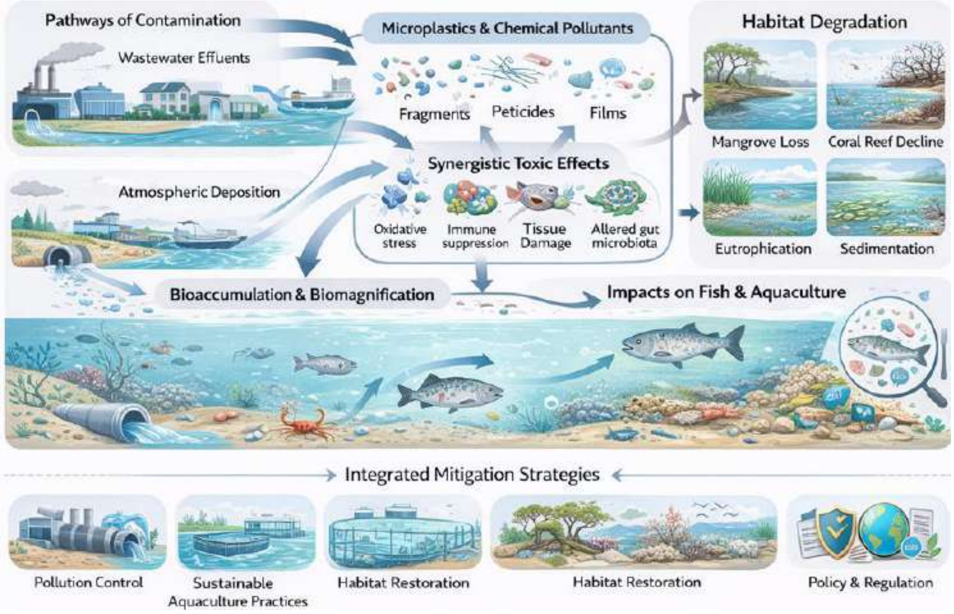

Figure 3: Integrated Effects of Microplastics, Pollution, and Habitat Degradation on Aquatic Ecosystems and Sustainable Aquaculture

Experimental studies demonstrate that microplastics accumulate in both feed and water, affecting feeding behavior and nutrient absorption. For instance, tilapia and carp exposed to microplastics show 15–25% reduction in growth rates, decreased feed conversion efficiency, and impaired lipid metabolism (Espinosa et al., 2018; Li et al., 2018). In addition, microplastics can act as vectors for chemical pollutants, such as heavy metals and persistent organic pollutants, which amplify water toxicity and compromise physiological functions (Koelmans et al., 2016; Chen et al., 2024). Consequently, water contamination with microplastics not only stresses fish but also diminishes farming efficiency, raising operational costs.

2. **Disease Susceptibility and Stress Responses:** Environmental stressors, including chemical pollutants, microplastics, and degraded habitats, increase susceptibility to disease in aquaculture species (Jabeen et al., 2018; Barboza et al., 2020). Pollutant-laden microplastics induce immunosuppression, oxidative stress, and gut inflammation, reducing resistance to bacterial, viral, and parasitic

infections (Espinosa et al., 2018; Pitt et al., 2018). Chronic exposure to microplastics also triggers stress responses, such as elevated cortisol levels, decreased feeding activity, and abnormal behavior, which can cumulatively impair growth, reproduction, and survival (Rochman et al., 2019). For example, zebrafish and tilapia exposed to combined microplastic and heavy metal contamination show 30–40% higher mortality under pathogenic challenge than unexposed controls (Wang et al., 2018; Jin et al., 2018). These findings emphasize that environmental contamination not only threatens fish health but also reduces the resilience of aquaculture systems.

3. **Economic and Productivity Impacts:** Pollution and habitat degradation directly undermine the economic viability of aquaculture. Reduced growth rates, elevated mortality, and disease outbreaks increase operational costs while lowering the quantity and quality of marketable fish (Badiola et al., 2018). Experimental aquaculture trials reveal that microplastic contamination in feed and water decreases feed conversion efficiency by 10–20%, reduces biomass production, and increases the need for veterinary interventions (Lu et al., 2016; Espinosa et al., 2018). These cumulative impacts, poor water quality, elevated disease risk, and stress-induced growth suppression can translate to substantial financial losses, particularly in small-scale or resource-limited aquaculture operations.

4. **Food Safety and Human Health Concerns:** The accumulation of microplastics and adsorbed pollutants in edible fish tissues raises food safety concerns (Barboza et al., 2020; Rochman et al., 2019). Consumption of contaminated seafood can introduce heavy metals, persistent organic pollutants, and microplastics into the human diet, with potential long-term health risks, including endocrine disruption and gastrointestinal inflammation. Studies have emphasized the need for monitoring and managing microplastic contamination in aquaculture to protect consumer health and maintain the sustainability of seafood production (Koelmans et al., 2019; Wang et al., 2018).

Monitoring and Assessment Techniques

1. **Sampling and Detection of Microplastics:** Accurate monitoring of microplastics is critical for assessing their distribution, sources, and ecological impacts. Sampling techniques are tailored to the environmental medium: surface water, sediment, or biota (Li et al., 2018; Koelmans et al., 2019). Surface water is often sampled using net trawls or filtration systems, while sediment samples rely on cores or grabs to assess benthic microplastic accumulation. For biota, dissection and tissue digestion allow the extraction of microplastics from gastrointestinal tracts, gills, or other organs, enabling quantification of ingestion levels. Detection of microplastics combines visual

identification with spectroscopic methods such as Fourier-transform infrared (FTIR) and Raman spectroscopy, which provide polymer-specific characterization (Prata et al., 2019; Lenz et al., 2016). Experimental evidence indicates that integrating visual sorting with spectroscopic confirmation reduces false positives by 15–25%, enhancing accuracy in both environmental and laboratory studies. These techniques also allow identification of microplastic size, shape, and chemical composition, which are crucial for assessing their biological uptake and ecological risks (Li et al., 2018).

2. **Biomonitoring Using Indicator Species:** Biomonitoring leverages the bioaccumulative properties of aquatic organisms to evaluate environmental microplastic exposure. Filter feeders such as mussels and clams, and small fish species like zebrafish and tilapia, are widely employed due to their high ingestion rates and trophic connectivity (Espinosa et al., 2018; Barboza et al., 2020). Experimental trials show that analyzing microplastic content in these species provides quantitative insights into environmental contamination and trophic transfer within aquatic food webs (Setälä et al., 2018). Fish accumulate microplastics by eating them directly or by consuming prey that is already contaminated. Research has identified these particles in the digestive systems of hundreds of species, ranging from surface-dwelling (pelagic) fish like Atlantic mackerel and horse mackerel to bottom-dwelling (demersal) species like Atlantic cod and whiting. These findings, specifically from the English Channel, highlight that microplastic exposure is a widespread issue across diverse marine habitats and commercially important fish stocks (Lusher et al., 2013). For example, mussels exposed to microplastic-laden water accumulate polymers in the range of 20–500 µm, often associated with adsorbed pollutants like heavy metals and persistent organic contaminants (Koelmans et al., 2016; Chen et al., 2024). Such biomonitoring not only identifies contamination hotspots but also informs potential human exposure via seafood consumption, supporting long-term ecosystem and food safety assessments.

3. **Toxicity Assessment Methods:** Ecological risk evaluation requires assessing both lethal and sub-lethal effects of microplastics and associated pollutants. Standard approaches include:
    - Acute and chronic exposure tests in laboratory fish and invertebrates, measuring mortality, growth, reproductive output, and behavioral changes (Jin et al., 2018; Lu et al., 2016). For instance, zebrafish exposed to polystyrene microplastics show 20–30% slower growth and reduced survival when combined with heavy metals.
    - Biochemical assays, including oxidative stress markers (ROS production, lipid peroxidation), enzymatic activity (acetylcholinesterase, catalase), and

immune responses, reveal sub-lethal impacts on metabolism and defense mechanisms (Espinosa et al., 2018).

- Histopathological studies examine tissue damage in gills, liver, and intestines, showing epithelial disruption, inflammatory cell infiltration, and vacuolation in microplastic-exposed fish (Pitt et al., 2018). Such data highlight the cumulative risk of microplastic ingestion, especially when particles are vectors for adsorbed chemicals, affecting both individual health and population-level resilience.

These monitoring and assessment techniques form a comprehensive framework for tracking microplastic pollution, evaluating ecological impacts, and guiding mitigation strategies in both freshwater and marine ecosystems. Experimental evidence emphasizes the importance of multi-level assessments, integrating molecular, physiological, and ecological endpoints to fully capture microplastic and pollutant impacts (Rochman et al., 2019; Wang et al., 2018).

Mitigation and Management Strategies

Mitigating aquatic pollution and safeguarding aquaculture productivity requires integrated approaches targeting both chemical pollutants and microplastics. Improving wastewater treatment through advanced filtration and membrane technologies can significantly reduce microplastic discharge into freshwater and coastal ecosystems, while reducing single-use plastics and promoting biodegradable alternatives, lowering long-term environmental contamination (Koelmans et al., 2019; Li et al., 2018; Ziajahromi et al., 2018). Sustainable aquaculture practices, including recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA), help maintain water quality, recycle nutrients, and minimize effluent impacts (Badiola et al., 2018; Ahmed & Thompson, 2019). Experimental evidence demonstrates that controlling microplastic contamination in feed and water enhances fish growth, immune function, and survival, directly improving food safety and economic outcomes (Espinosa et al., 2018; Lu et al., 2016; Pitt et al., 2018).

Restoration of degraded habitats and robust regulatory frameworks are essential for sustaining aquatic ecosystems and fisheries. Reforestation of mangroves, rehabilitation of coral reefs, and management of sediment dynamics improve juvenile fish density, species richness, and survival, enhancing ecosystem resilience and aquaculture productivity (Alongi, 2018; Nagelkerken et al., 2015; Aburto-Oropeza et al., 2008). Complementary policy measures regulating plastic production, effluent discharge, habitat protection, and aquaculture standards reduce anthropogenic pressures, while community engagement and public awareness campaigns reinforce compliance (Barboza et al., 2020; Rochman et al., 2019; Koelmans et al., 2019). The combined effect of restoration and governance strengthens ecological integrity, stabilizes trophic interactions, and supports sustainable fisheries and aquaculture development.

Table 3. Integrated Mitigation Strategies and Future Directions for Managing Microplastics and Aquatic PollutioN

Category	**Strategy/ Approach**	**Description**	**Expected Outcomes**	**References**
Pollution Control	Advanced Wastewater Treatment (WWTPs)	Use of membrane filtration, activated carbon, and tertiary treatments to remove microplastics and chemical contaminants	Reduced microplastic discharge into aquatic systems	Koelmans et al. (2019); Ziajahromi et al. (2018)
	Reduction of Single-Use Plastics	Policy-driven reduction and replacement with biodegradable materials	Decreased plastic input into ecosystems	Rochman et al. (2019); Li et al. (2018)
	Industrial Effluent Regulation	Strict discharge standards and monitoring of pollutants	Lower heavy metal and chemical contamination	Wang et al. (2018); Guo & Wang (2019)
Sustainable Aquaculture	Recirculating Aquaculture Systems (RAS)	Closed-loop systems that recycle water and reduce waste discharge	Improved water quality and reduced environmental impact	Badiola et al. (2018)
	Integrated Multi-Trophic Aquaculture (IMTA)	Co-culturing species to utilize waste nutrients efficiently	Enhanced nutrient recycling and ecosystem balance	Ahmed & Thompson (2019)
	Microplastic-Free Feed Management	Monitoring and reducing plastic contamination in feed	Improved fish health and growth performance	Espinosa et al. (2019)

Habitat Restoration	Mangrove Reforestation	Replanting degraded mangrove ecosystems	Increased nursery habitats and fish recruitment	Alongi (2018); Nagelkerken et al. (2015)
	Coral Reef Rehabilitation	Artificial reefs and coral transplantation	Enhanced biodiversity and ecosystem resilience	Burkepile et al. (2020)
	Sediment and Nutrient Management	Controlling runoff and erosion	Reduced eutrophication and habitat degradation	Duarte et al. (2020)
Monitoring & Technology	Microplastic Detection (FTIR, Raman)	Advanced spectroscopy for polymer identification	Improved accuracy in pollution assessment	Prata et al. (2019); Lenz et al. (2016)
	AI-Based Monitoring Systems	Automated detection and data analysis	Real-time tracking of pollution trends	.Elawady et al. (2025)
	Biomonitoring Using Indicator Species	Use of fish and bivalves to assess contamination	Early detection of ecological risks	Barboza et al. (2020)
Policy & Governance	Plastic Regulation Policies	Bans/restrictions on microbeads and single-use plastics	Long-term reduction in plastic pollution	Rochman et al. (2019)

Future Perspectives and Research Directions

Despite growing awareness of microplastics and chemical pollutants, critical knowledge gaps remain regarding their environmental distribution, long-term ecological effects, and human health implications (Koelmans et al., 2019; Barboza et al., 2020). Emerging contaminants, including nanoplastics, pharmaceuticals, and personal care products, are increasingly detected in aquatic systems but remain poorly understood in terms of toxicity, bioaccumulation, and interactions with existing stressors (Prata et al., 2019; Elawady et al., 2025). Research is urgently needed to elucidate synergistic effects between multiple stressors pollutants, microplastics, and habitat degradation and quantify their cumulative impacts on aquatic biodiversity and aquaculture productivity (Wang et al., 2018; Rochman et al., 2019).

Technological innovations are enhancing the detection, monitoring, and remediation of contaminants. High-resolution spectroscopic techniques (FTIR, Raman) enable precise microplastic identification, while automated image analysis and machine learning improve quantification efficiency (Lenz et al., 2016; Prata et al., 2019). Bioremediation strategies and advanced filtration systems can effectively remove microplastics and chemical pollutants from aquaculture and natural waters, optimizing water quality and fish health (Ziajahromi et al., 2018; Ahmed & Thompson, 2019). Integrated ecosystem management represents a forward-looking approach to sustain aquatic systems. Combining habitat restoration, pollution control, sustainable aquaculture practices, and policy measures builds resilience and supports adaptive management (Alongi, 2018; Nagelkerken et al., 2015). Coordinated restoration of mangroves, seagrass beds, and coral reefs, alongside pollutant reduction, enhances biodiversity, ecosystem services, and aquaculture productivity (Aburto-Oropeza et al., 2008; Burkepile et al., 2020). This holistic perspective is essential for ensuring the long-term sustainability of fisheries and aquaculture under mounting anthropogenic pressures and climate change.

Conclusion

Microplastics, chemical pollution, and habitat degradation collectively pose a serious threat to aquatic ecosystems and sustainable aquaculture. Microplastics act as carriers of toxic pollutants, enhancing their bioavailability and leading to oxidative stress, tissue damage, and impaired growth and reproduction in aquatic organisms. These effects extend through bioaccumulation and trophic transfer, disrupting food webs and ecosystem stability. At the same time, habitat loss and declining water quality further reduce biodiversity and fish productivity, directly impacting aquaculture performance and food security. Addressing these challenges requires integrated strategies, including pollution control, sustainable aquaculture practices, and habitat restoration. Ensuring the future of aquatic resources depends on coordinated scientific, technological, and policy efforts to reduce pollution, restore ecosystems, and enhance resilience.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 85 - 98 |

Antibiotic Resistance in Fish Aquaculture: Challenges, Trends Analysis, and Alternative Approaches

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Article DOI Link: https://zenodo.org/uploads/20109229

DOI: 10.5281/zenodo.20109229

Abstract

Aquatic animal health, environmental sustainability, and public health are all at risk due to antibiotic resistance in fish aquaculture, which has become a major worldwide concern. The selection of resistant bacterial strains and the spread of antibiotic resistance genes (ARGs) have been accelerated by the extensive use of antibiotics in aquaculture systems for disease prevention, treatment, and growth promotion. By boosting the persistence of multidrug-resistant infections in aquatic environments and raising the danger of transmission to humans through the food chain, these genes can spread quickly among microbial communities through horizontal gene transfer. Over the past 20 years, there has been a notable increase in scientific study on antibiotic resistance in aquaculture, with large contributions from nations like China, India, and the United States, according to trend assessments. The identification of multidrug-resistant bacteria, Meta genomic profiling of ARGs, and the ecological effects of antibiotic residues are current research hotspots. Despite greater awareness, a number of issues still exist, such as the uncontrolled use of antibiotics, the absence of efficient surveillance systems, the buildup of drug residues in the environment, and the scant application of biosecurity procedures. Alternative strategies are becoming more popular to reduce antibiotic resistance. Probiotics, prebiotics, vaccinations, phytotherapeutics, and better farm management techniques like increased hygiene, stocking density control, and biosecurity measures are some of these. In conclusion, combating antibiotic resistance in fish aquaculture necessitates an integrated, multidisciplinary approach that includes the creation of efficient non-antibiotic disease control techniques, worldwide monitoring frameworks, and sustainable farming methods. These methods are crucial for maintaining aquaculture's long-term viability and protecting the environment and public health.

Keywords: Alternative therapies, Aquaculture, Challenges, Disease prevention, Pathogens, Antibiotic resistance.

Introduction

One of the fastest-growing food production industries in the world is aquaculture, which is defined as the farming of aquatic organisms such as fish, crustaceans, mollusks, and aquatic plants. Due to population increase, the stagnation of catch fisheries, and the growing worldwide demand for foods high in protein, aquaculture has grown significantly during the past 50 years.

Globally, total fisheries and aquaculture production reached 223.2 million tons in 2022, marking a significant increase compared to previous decades. For the first time in history, aquaculture production alone hit a record 130.9 million tones, accounting for more than half of all aquatic animal production. Aquaculture has surpassed catch fisheries as the main source of fish for human consumption, marking a structural change in the world's seafood supply. Aquaculture production is focused in certain areas. Asia accounts for almost 70% of the world's output, with nations like China, India, Indonesia, and Vietnam at the forefront. Actually, approximately 90% of the world's aquaculture production comes from the top 10 producing nations, suggesting an uneven worldwide distribution and substantial room for growth in neglected areas like Africa (1). Therefore, it is anticipated that aquaculture will be the main source of future growth in the world's fish supply. By 2033, aquaculture might account for more than 55% of the world's fish production, according to projections (2).

A vital component of the world's food and nutritional security, fish is universally acknowledged as one of the most significant sources of high-quality animal protein. Because it is comparable to proteins from meat, eggs, and milk and includes all essential amino acids in the proper amounts, fish protein is regarded as high-quality. Furthermore, fish protein has a high digestion rate of about 85–95%, which improves the body's ability to absorb nutrients (1). For vulnerable groups including children, pregnant women, and the elderly, fish is particularly crucial. In addition to aiding in the prevention of malnutrition and micronutrient deficiencies, which are sometimes referred to as "hidden hunger," the minerals in fish promote cognitive development in newborns and children (4). Furthermore, compared to other animal protein sources like beef and pork, fish has a comparatively smaller environmental impact, making it a more sustainable choice for satisfying the protein needs of an expanding world population (OECD/FAO, 2024). It is anticipated that fish will become even more important in tackling future issues related to food security as aquaculture continues to grow (5).

Antibiotics are primarily used in aquaculture to treat bacterial infections in fish and other aquatic animals. In aquaculture systems, common bacterial infections including vibriosis, furunculosis, and columnar is can result in considerable mortality. Antibiotics aid in containing these epidemics and lowering financial losses. Research shows that antibiotics are useful in preventing or eliminating harmful microorganisms, which improves fish health (6). Antibiotics are frequently used preventively to stop illnesses from developing, particularly in stressful situations like handling, transit, or environmental changes. In intensive farming systems, where disease can spread quickly, this prophylactic use can lower the risk of infection (7). Antibiotics are occasionally used metaphylactically in aquaculture, which means they are given to a group of fish while some of them are already infected. This strategy reduces widespread outbreaks and aids in the management of disease transmission within the populace (8). Antibiotics have been employed as growth boosters in certain aquaculture systems. By lowering subclinical infections and altering gut microbial flora, they increase feed efficiency and growth rates. However, because it contributes to antibiotic resistance, this practice is being opposed more and more (9). Antibiotics indirectly increase aquaculture productivity and profitability by reducing illness and increasing survival rates. In the near run, using antibiotics is economically advantageous since healthy fish populations expand more quickly and use less resources (10).

The extensive and frequently careless use of antimicrobial drugs in fish farming has made the evolution of antibiotic resistance in aquaculture a serious global problem. When antibiotics are used in aquaculture systems, resistant populations of bacteria survive and multiply while vulnerable strains are eradicated. Antibiotic-resistant bacteria eventually take over fish, water, and sediments as a result of this (11). Through horizontal gene transfer (HGT) processes as transformation, transduction, and conjugation, antibiotic resistance can spread quickly among bacterial populations. Plasmids, transposons, and integrons have resistance genes that can spread from aquatic bacteria to human infections. Because of this, aquaculture settings are significant sources of resistance genes (12). In intensive aquaculture systems, high stocking densities, poor water quality, and stressful situations encourage disease outbreaks, which raise the need for antibiotics. These conditions promote bacterial contact and mutation rates, which hastens the emergence of resistance (13). The development of resistance has been greatly aided by the use of antibiotics as prophylactics and growth boosters. Constant low-dose exposure creates the perfect environment for bacteria to evolve resistance mechanisms (14). Antibiotic resistance genes (ARGs) are on the rise in aquaculture systems across the globe, according to recent studies. Due to increased antibiotic use, areas with intensive aquaculture operations, especially in Asia, have higher levels of resistance (15).

Objectives of the Review

This research review's goal is to critically analyze the development and dissemination of antibiotic resistance in fish farming, with an emphasis on comprehending its root causes, present difficulties, and worldwide ramifications. The review's objective is to examine current patterns of antibiotic use and resistance in aquaculture systems, emphasizing their effects on public health, aquatic animal health, and environmental sustainability. In order to identify gaps and restrictions in the management of antibiotic resistance, the study also aims to assess current regulatory frameworks and management methods. Investigating and evaluating substitute methods—such as probiotics, vaccinations, phytotherapeutics, and better husbandry techniques—as long-term tactics to lessen aquaculture's need on antibiotics is another important goal. In order to reduce antibiotic resistance in fish farming systems, the review aims to offer a thorough synthesis of current knowledge and suggest future research and policy initiatives.

Use of Antibiotics in Fish Aquaculture

In fish aquaculture, antibiotics are frequently used to prevent illness, boost output, and guarantee food supply. But their use also brings up important issues with food safety, environmental effects, and antibiotic resistance.

Numerous antibiotics from various chemical classes are employed in aquaculture systems to improve productivity and manage bacterial infections. These antibiotics, which include tetracyclines, sulfonamides, quinolones, β-lactams, macrolides, and aminoglycosides, can be generally classified according to their chemical structure and method of action, according to research investigations. These groups represent the foundation of antimicrobial therapy in fish farming and are extensively documented in aquaculture settings worldwide (16). Because of their broad-spectrum effectiveness against both Gram-positive and Gram-negative bacteria, tetracyclines are among the most commonly utilized classes among these. Infections brought on by pathogens like Aeromonas and Vibrio are frequently treated with drugs like oxytetracycline, doxycycline, and chlortetracycline. They are widely used because they are inexpensive and effective, but because of their high affinity with tissues and sediments, they often endure in aquatic environments (17). Sulfonamides are another significant class that is frequently used either by themselves or in conjunction with trimethoprim. By preventing bacteria from synthesizing folic acid, medications including sulfadiazine, sulfamethoxazole, and sulfamethazine function as bacteriostatic agents. Due to their high solubility, affordability, and ease of administration through water or feed, these antibiotics are frequently employed in finfish farming (18). Because of their potent antibacterial activity and quick action, quinolones and fluoroquinolones (such as ciprofloxacin and enrofloxacin) are also frequently utilized. They are especially useful in intensive aquaculture settings where disease outbreaks can spread swiftly because they target the replication of bacterial DNA. Similar to this, β-lactam antibiotics like amoxicillin and penicillin are used to prevent the formation of bacterial cell walls, albeit their application may be restricted because of the emergence of resistance (19). Furthermore, reports of phenicols (like florfenicol) and macrolides (like erythromycin) in aquaculture techniques are common. Because of its efficacy and comparatively lower toxicity as compared to previous medications like chloramphenicol, florfenicol in particular is regarded as one of the most widely used antibiotics globally. Antibiotics including oxytetracycline, florfenicol, and sulfadiazine are among the most often used in aquaculture operations worldwide, according to studies (20).

Antibiotic Class	**Examples**	**Mode of Action**	**Usage in Aquaculture**	**Key Issues**
Tetracyclines	Oxytetracycline, Doxycycline, Chlortetracycline	Inhibit protein synthesis (bind to 30S ribosome)	Widely used for bacterial infections like *Aeromonas* and *Vibrio*	Persistence in environment, resistance development
Sulfonamides	Sulfadiazine, Sulfamethoxazole, Sulfamethazine	Inhibit folic acid synthesis (bacteriostatic)	Used alone or with trimethoprim in fish farming	Residue accumulation, resistance risk
Quinolones / Fluoroquinolones	Ciprofloxacin, Enrofloxacin	Inhibit DNA gyrase and topoisomerase IV	Effective in intensive aquaculture systems	High risk of resistance, regulatory restrictions
β-lactams	Amoxicillin, Penicillin	Inhibit bacterial cell wall synthesis	Used for Gram-positive bacterial infections	Reduced effectiveness due to resistance
Phenicols	Florfenicol, Chloramphenicol	Inhibit protein synthesis (50S ribosome)	Broad-spectrum antibiotic, widely used globally	Toxicity concerns (chloramphenicol banned in many

				countries)
Macrolides	Erythromycin	Inhibit protein synthesis (50S ribosome)	Used for specific bacterial infections	Limited use, resistance issues
Aminoglycosides	Streptomycin, Gentamicin	Inhibit protein synthesis (30S ribosome)	Used in some aquaculture treatments	Toxicity and environmental impact

Challenges of Antibiotic Resistance

The emergence and dissemination of antibiotic resistance genes (ARGs) in aquatic environments is one of the main issues. Research shows that resistance genes can be passed from one bacterium to another via horizontal gene transfer, which includes plasmids and mobile genetic elements. Even in the absence of antibiotics, this strategy allows resistance characteristics to spread quickly among many bacterial species. Because biofilms, sediments, and high organic loads create the perfect environment for bacterial interaction and gene exchange, such gene transfer is especially boosted in aquaculture systems (21). The environmental pollution and durability of antibiotic use is another serious problem. When antibiotics are added to aquaculture systems, they are frequently not completely digested and are discharged into nearby bodies of water, where they continue to put native microbial communities under selective pressure. As a result, resistant bacteria build up in sediments and water, impacting aquatic ecosystems and possibly making their way into the human food chain. There are growing reports of multidrug-resistant (MDR) bacteria in aquaculture settings, which raises grave issues for public health and environmental sustainability (22). Antibiotic resistance also poses a serious threat to aquaculture's economic viability and disease control. Antibiotics that were once effective becoming less dependable as resistance rises, increasing disease outbreaks, mortality rates, and financial losses for fish farmers. This makes farmers use stronger antibiotics or greater dosages, which exacerbates the resistance issue. Furthermore, antibiotic abuse and overuse are exacerbated by inadequate regulatory frameworks and ignorance in many poor nations, which makes managing resistance much more challenging (23).

Trends Analysis

Global Trends in Antibiotic Consumption in Aquaculture

Due in major part to the aquaculture industry's explosive growth, the use of antibiotics in aquaculture has grown dramatically worldwide during the past few decades. The need for antimicrobial medicines to prevent bacterial illnesses has increased as fish farming has emerged as one of the fastest-growing food production industries. According to studies, the amount of antimicrobials used worldwide in aquaculture reached over 10,259 tons in 2017, demonstrating the extent of antibiotic reliance in this industry. The expansion of aquaculture practices, especially in developing nations, and the rising worldwide fish consumption are intimately associated with this increase (24) Antibiotic use in aquaculture is predicted to rise by almost 33% by 2030, to almost 13,600 tons per year under existing methods. This increasing trend is indicative of the aquaculture industry's ongoing growth, particularly in low- and middle-income nations with laxer regulations. The intensification of farming systems, where high stocking densities foster disease outbreaks and increase the demand for antimicrobial interventions, is linked to the growing dependence on antibiotics (25). The geographical concentration of antibiotic use, with the Asia-Pacific area dominating consumption, is a significant global trend. According to research, this region uses over 93% of all antibiotics used in aquaculture worldwide, with nations like China accounting for the largest portion because of their enormous production quantities. The size of aquaculture enterprises and variations in management techniques, such as antibiotic stewardship and regulatory enforcement, are both reflected in this regional supremacy (26).

Increasing Resistance Patterns

The table illustrates how the main bacterial infections in fish aquaculture are becoming more resistant to antibiotics. It demonstrates that popular antibiotics like tetracyclines, sulfonamides, and β-lactams are causing bacteria like Aeromonas, Vibrio, and Pseudomonas to become highly resistant. The emergence of multidrug-resistant (MDR) strains, which complicates and reduces the efficacy of illness therapy, is a noteworthy finding.

Bacterial Pathogens	**Antibiotic Classes**	**Observed Resistance Pattern**	**Key Findings from Research**	**References**
Aeromonas spp.	Tetracyclines, Sulfonamides	High resistance (>50% in many studies)	Common fish pathogen showing multidrug resistance due to frequent antibiotic exposure	Schar et al., 2021
Vibrio spp.	Quinolones, β-	Increasing	Resistance	Mohammed

	lactams	resistance trends over time	linked to intensive aquaculture practices and antibiotic misuse	et al., 2025
Escherichia coli	Multiple classes (MDR)	Emergence of multidrug-resistant (MDR) strains	Environmental factors (temperature, pH) influence resistance proliferation	El Badawy et al., 2025
Pseudomonas spp.	β-lactams, Aminoglycosides	High intrinsic and acquired resistance	Resistant strains persist in water and sediments, acting as reservoirs	Yuan et al., 2023
Salmonella spp.	Sulfonamides, Quinolones	Moderate to high resistance	Resistance genes transferable through food chain and environment	Yuan et al., 2023
Mixed aquatic bacteria	Multiple antibiotic classes	~33% antibiotics show >50% resistance (Asia data)	Long-term data (2000–2018) show plateau but persistently high resistance levels	Schar et al., 2021
Diverse bacteria (aquaculture environment)	Ampicillin, Tetracycline, Chloramphenicol	High multidrug resistance prevalence	Antibiotic use creates selective pressure leading to resistant bacterial reservoirs	Kathleen et al., 2016

Alternative Approaches to Antibiotics

Probiotics and Prebiotics

Use sufficient quantities, probiotics—beneficial living microbes including Bacillus, Saccharomyces, and Lactobacillus—improve the host's health. By preventing the growth of dangerous pathogens through competitive exclusion, the synthesis of antimicrobial compounds, and the stimulation of digestive enzyme activity, probiotics aid in maintaining a balanced gut microbiota in aquaculture. As a result, fish have better gut health overall, greater growth performance, and better nutrient absorption (31). Conversely, prebiotics are indigestible food components (such inulin, fructo-oligosaccharides, and mannan-oligosaccharides) that specifically promote the development and functioning of good gut flora. Prebiotics support a healthy intestinal environment and increase microbial diversity in the gut by acting as a food source for probiotics (32).

Vaccination

In fish farming, vaccination is a sustainable and successful substitute for antibiotics since it boosts the fish immune system, preventing illness. It lowers mortality and the need for antibiotics by reducing infections brought on by organisms like Vibrio and Aeromonas. Depending on the species and agricultural conditions, a variety of techniques, including injectable, oral, and immersion vaccines, are employed. Vaccination is essential for encouraging environmentally friendly and disease-resistant aquaculture methods, despite obstacles such high cost and scarcity (33).

Phytochemicals (Plant-based compounds)

Herbal Extracts and Natural Antimicrobials

Phytochemicals exhibit strong antibacterial, antiviral, antifungal, and antiparasitic properties, making them direct substitutes for antibiotics. Compounds like terpenes, phenolics, and alkaloids disrupt microbial cell walls, inhibit enzyme activity, and prevent pathogen proliferation. Effective against both Gram-positive and Gram-negative fish pathogens such as Aeromonas, Vibrio, and Edwardsiella. Some plant extracts show significant inhibitory effects with low minimum inhibitory concentrations (MICs) (34).

Immunostimulants

Enhancing Fish Immune Response

Fish innate and adaptive immune responses are strengthened by phytochemicals. Boost immune cell activity (macrophages, lymphocytes). Encourage the synthesis of complement proteins, antibodies, and lysozyme. Instead of eliminating germs directly, increase resistance to diseases (35).

Improved Farm Management

Among the best non-antibiotic methods for stopping disease outbreaks in aquaculture are better farm management techniques. Fish health, pathogen burden, and overall production are all directly impacted by biosecurity protocols and water quality control.

Biosecurity Measures

Use of verified disease-free brood stock and seed. New fish stocks must be quarantined before being introduced. disinfection of workers, vehicles, and equipment (36). Tanks, ponds, and nets should be cleaned and disinfected on a regular basis. Fish that are sick or dead should be removed right away. Usage of restricted access areas and footbaths (37). Preserving ideal stocking densities to lower susceptibility to illness and stress (36). Preventing rodents, birds, and other carriers from entering. Management of potential pathogen-introducing water sources (38).

Water Quality Management

Because inadequate circumstances stress fish and encourage the growth of pathogens, water quality is a crucial factor in determining fish health. Preventing disease requires maintaining ideal water parameters. Breathing and metabolic functions depend on dissolved oxygen (DO). Low DO (< 3 mg/L) inhibits respiration, decreases energy availability, weakens the immune system, and increases fish susceptibility to illnesses, all of which contribute to stress and an increased risk of infection (40). Fish metabolism, immunological response, and disease pathogenicity are all impacted by temperature. Abrupt temperature changes have the potential to start illness outbreaks, particularly bacterial diseases (41). While excessive pH levels can damage gill tissues and impair the immune system, an ideal pH range of 6.5–8.5 is necessary for fish to sustain normal physiological functioning (42). Nitrite interferes with oxygen transmission in the blood, causing "brown blood disease," whereas ammonia (NH_3) is extremely poisonous and can seriously harm fish gills (43). While biofilters are essential for preserving the system's nitrogen balance, routine water exchange aids in the removal of waste and lowers the pathogen load (44).

Future Perspectives

An interdisciplinary, technology-driven, and sustainable approach to disease management is emphasized in future perspectives on antibiotic resistance in fish aquaculture. Growing worry over the emergence of multidrug-resistant bacteria and antibiotic resistance genes (ARGs) in aquatic settings is reflected in the rapid global expansion in research on antimicrobial resistance (AMR) (8). The creation of substitute tactics that boost fish immunity and lessen reliance on antibiotics, such as probiotics, phytochemicals, vaccinations, and immunostimulants, is one important avenue. Furthermore, precise detection, monitoring, and comprehension of resistance mechanisms and gene transfer channels are made possible by developments in genomic and molecular tools, including as metagenomics, whole-genome sequencing, and CRISPR-based technologies (43). The deployment of global surveillance systems and One Health strategies, which integrate environmental, animal, and human health to prevent the development of resistance across ecosystems, is another crucial future priority. Preventing disease outbreaks is also anticipated to be greatly aided by improved farm management, biosecurity, and environmental monitoring. Additionally, to control the use of antibiotics and encourage ethical aquaculture techniques, more international cooperation and policy development are required (8)

Conclusion

The review emphasizes that although antibiotics have been essential for maintaining fish aquaculture productivity and disease control, their overuse and careless use has caused antibiotic-resistant bacteria and resistance genes to quickly proliferate in aquatic habitats. Due to the spread of resistant infections via the food chain, this increasing resistance poses major concerns to public health and environmental sustainability in addition to endangering fish health and agricultural profitability. The use of antibiotics is still fueled by the growing demand for fish around the world as well as more intensive farming methods, which over time accelerates the development of resistance and reduces the efficacy of traditional therapies.

The study highlights the critical need for sustainable and integrated approaches to aquaculture disease management in order to solve these issues. Probiotics, vaccines, phytochemicals, and better farm management techniques are examples of alternatives that show promise for lowering the need for antibiotics. To mitigate resistance, it is crucial to strengthen regulatory frameworks, encourage ethical antibiotic use, and implement cutting-edge technologies for monitoring and surveillance. The aquaculture industry's long-term sustainability, safety, and productivity will depend on a concerted worldwide effort bolstered by the One Health strategy.

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Fish and Fisheries: An Overview of Fish Farming and Aquaculture

ISBN: 978-93-49938-76-2| Year: 2026 | pp: 99 - 105 |

Emerging Applications of Nanotechnology in Fisheries: A Comprehensive Review

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Article DOI Link: https://zenodo.org/uploads/20109380

DOI: 10.5281/zenodo.20109380

Abstract

Nano technology is currently one of the technologies that has made breakthroughs and been applied in various areas of science like aquaculture and fisheries. The current chapter presents a review on some of the latest developments of nano technology in fisheries where it could be applied in order to improve fish production sustainably without any harm to the environment. The use of nano particles nanoemulsion and nanosensors have been commonly used for better fish health management, water quality management, and efficient feed conversion ratios.

Introduction

Generally, nanomaterials have structured components with at least. One dimensional less than 100nm (1nm= 10-9) and distinctly different physical and chemical properties in comparison to their micron size counterpart. In nanoparticles the various material properties such as electrical, Mechanical, optical magnetic etc, can be selectively controlled by engineering the size, morphology materials, using a variety of synthesis methods, in the various forms like thin films, powder quantum wires , quantum wells , quantum dots etc[1].In fact, there are many sectors where this kind of technology will contribute to their effectiveness significantly owing to its applicability in different fields that are engaged in aquaculture. Moreover, another latest advancement in the field is concerned with creating material for cleaning water from different contaminants [2]. In addition, a fish feed based on minerals will enhance fish production greatly. The global fishing sector has been of great importance in guaranteeing food and nutrition security and economic growth especially in the developing nations. Some of the problems associated with the fishing sector include water pollution, diseases, poor feed management, and post-harvest loss among others. Conventional approaches may not be successful in tackling such complex problems. It is here that the application of nanotechnology comes into play through its ability to enhance fisheries via boosting production.

The effects of nanotechnology in relation to nutrition, medication, and vaccines of fish are explored. From observation, it is evident that if nanotechnology and biological systems are taken into account, there are developments that can make it possible to focus on the development of nanoparticles that are economical and also very important. The manufacturing of nanoparticles is a complex one. It should also be noted that at the moment, it is evolving at a fast rate due to its economic benefits [3].

The instances where there is usage of nanotechnology in the generation of nanomaterials are the nanoparticle, nanocomposite, nano emulsion, and the nano sensor. Currently, there are numerous applications of the nanomaterials in not only the drug delivery system of the aquatic animals but also in improving the efficiency of the fish feed through the process of nanoencapsulation technology. With regards to the process of disease identification, the use of nano sensors ensures fast tests, provision of clean water through nanofiltration, and also in antimicrobial treatments [4].

Nanotechnology Applications in Fisheries

Fig.1: Nanotechnology Applications in Fisheries

Although there are advantages to using nanotechnology in the fisheries industry, there are also problems that come with this technology. These include environmental safety, bioaccumulation, and toxicity concerns. Therefore, it is essential to find an equilibrium between the two for sustainable growth. This paper attempts to provide a complete analysis of nanotechnology and its novel use in the fisheries industry [5].

The Role of Nanotechnology in Fisheries and Aquaculture Industries It is imperative to mention that nanotechnology plays an important role in fisheries and aquaculture industries through rapid disease detection and improvement in ability of fish to absorb chemicals, hormones, and injections. With respect to the projections made by the National Science Foundation of America regarding the growth and development of the nanotechnology market the value of nanotechnology in the global market would have reached one trillion dollars as a result of extensive uses of nanotechnology in different areas such as electronics products, material sciences, household and agriculture industries[6] related to fish farming, biological sciences to detect biomolecules, cure cancer patients, develop non-viral vectors to enable the transfer of DNA, deliver medication to specified areas, surgeries and others even though more researches are required regarding the usage of nanotechnology in fish farming. Fish meat is considered as the number one option of getting nutrition for people living in poverty as a result of the fact that nutritional requirements for those people mainly include the availability of proper food and fish meat with appropriate amounts of protein. There is no doubt that consumption of fish meat, especially fatty fish meat, contributes to lowering mortality from coronary heart diseases (CHD). Nevertheless, the production of fish meat faces several problems related to sustainability, as water pollution in aquacultures negatively impacts productivity and ecology [7]. Conversely, nanotechnology becomes an increasingly important area of skills and technologies for innovation and aquaculture direct application as fish growth, fish feed, reproduction and gonadal, fish disease management in fig.1.

Nanomaterials have been regarded as an antimicrobial to viruses, bacteria, parasitic infections, and fungi. In addition to this, the use of poly lactic glycolic acid nanoparticle plays an important role for the field of medicine, hormones, and vaccines. It is correct to say that nano vaccines have more benefits than traditional vaccines because of their stability, availability, and sustainability. But the most important advantage of nanotechnology for the fishing industry is that through nanotechnology it will be possible for them to detect the presence of any type of pathogenic infection in the fish. The growth rate of fish is highly necessary to earn money from the fishing industry. The fishing industry always finds ways and means to increase the growth rate of the fishes. Nanotechnology may be useful for increasing the immunity of the fish [8].

1. Metal Oxide Nanoparticles Application in Treating Diseases in Aquaculture

There have been many experiments conducted on treating diseases using metal oxide nanoparticles. From the reviewed literature, it can be noted that the application of metal oxide nanoparticles, including zinc oxide nanoparticles (ZnO-NPs), copper oxide nanoparticles (CuO-NPs), gold nanoparticles (Au-NPs), silver nanoparticles (Ag-NPs), and titanium dioxide nanoparticles (TiO2-NPs) in curing pathogens is not uncommon. Zinc oxide nanoparticles have proven to be effective in inhibiting the growth of various bacteria. Copper oxide nanoparticles have been observed to be highly effective in removing fungi. Silver, zinc oxide, and copper nanoparticles exhibit antimicrobial properties that prevent any growth of bacteria in fish tanks and ponds. The use of these nanoparticles is beneficial as they are used in paints, coatings and water purification systems for disease prevention [9].

2. Removal of Heavy Metals from the Water

Ligand-centered nano-coating can be utilized to remove heavy metals because it can be restored by handling the bi-functional self-assembling ligand with the nano-coating medium that was used before. This process can be done in the same place where the ligand. Nanoparticles of metal oxides, such as nanosized FeO, AlO2, MnO, CeO2, MgO and TiO, having increased surface area and affinity for metal adsorption are currently preferred nanotechnology for wastewater treatment. For testing how well they can remove metals under different conditions, mathematical models and analytical techniques like XAS and NMM have become very important for developing new technologies and better applications for making metal oxide nanoparticles. For heavy metal removal, ligand-based nanocoating can be used due to its high absorption potential and low cost. Using crystal clear technology for water purification, several metal layers are bonded to one substrate. The high reactivity and large surface area of nanomaterials make them ideal for heavy metal removal from water and waste [10]. Heavy metal adsorption is specific to metal oxide nanoparticles such as nanosized FeO, AlO2, MnO, CeO2, MgO and TiO with high surface area and affinity for aqueous systems. It is essential to ensure the quality of water in aquaculture. Metal oxide nanoparticles, carbon nanotubes, and nano filters can be employed to eliminate heavy metals, ammonia, pathogens, and organics from the water [11].

3. Fish Feeds through Nanotechnology

By utilizing nanotechnology, nutrient efficiency is enhanced through the encapsulation of nutrients, vitamins, and bioactive ingredients in fish feed in fig.2. Encapsulation enhances the efficiency of nutrient uptake, reduces feed wastage, and promotes faster growth of aquatic organisms [12].

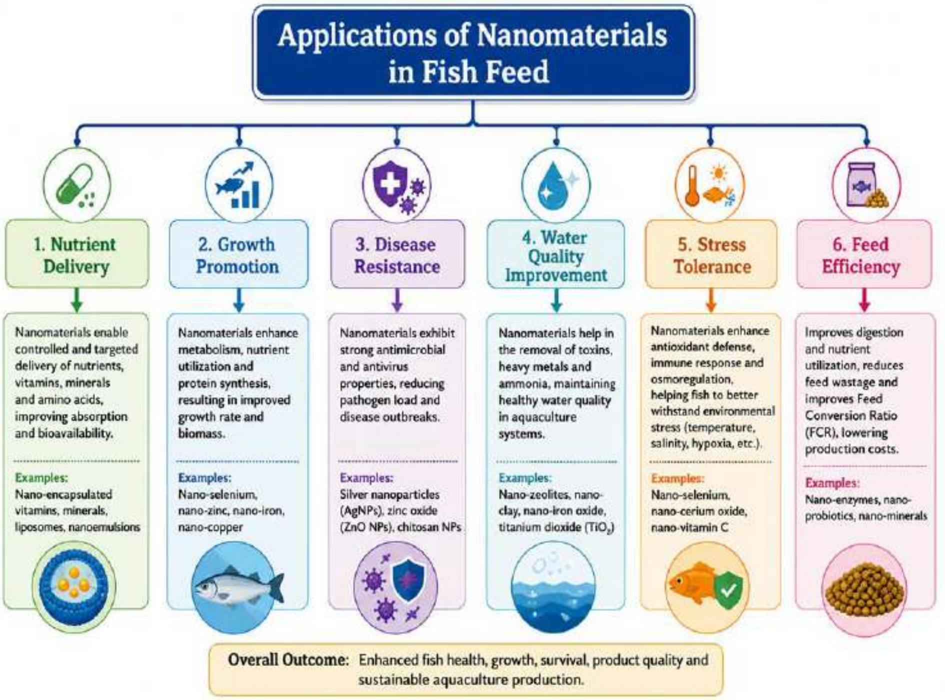

Fig.2: Applications of Nanomaterials in Fish Feed

Nanoparticles play a central role in the effective supply of nutrients, vitamins and trace minerals as nano-feed additives e.g., selenium, iron and vitamin C. Fish feed comprising nanosized nutrients help in their assimilation and passage in the intestine, to increase their development, reproduction and immunity of fish. The services of nanotechnology in controlling fish illnesses are more effective as compared to chemicals that exert numerous harmful effects like aquatic pollution, resistant bacterial strains and deposition of chemical remains [13].

4. Fish Immune System

The use of additives and vaccination through the application of nano technology has greatly contributed to improving the fish immune system. The benefits associated with the application of nano technology in fish health include the ability to boost their stress tolerance and overall good health [14].

5. Disposal of Waste in Aquatic Ecosystem

Nano technology has proven useful in addressing the issue of disposing of waste generated during fish farming in aquatic ecosystems.

6. Monitoring and Smart Management

The advent of nano sensors has made it possible to monitor environmental parameters such as pH, temperature, oxygen content, and toxins. This has proven useful in the management of the fish farm environment. Continuous monitoring is increasingly important for proactive health management.

- **Nano-Sensors:** Nano sensors integrated within the Internet of Things will allow constant monitoring of water parameters such as temperature, dissolved oxygen, pH, concentration of biomarkers, nutrients, and contaminations. This information will enable instant responses to issues related to water quality and feed intake of aquatic animals [15].

Conclusion

It is evident that the implementation of nanotechnology technology has been extremely essential in the improvement of the efficiency of fisheries and aquaculture owing to its ability to overcome various challenges experienced in fisheries management in these past. Different uses of nanotechnology ranging from feeding the fishes to treating diseases as well as collecting water prove that nanotechnology is going to be a promising technology for the future because it will bring about a great revolution in modern fisheries.

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ISBN: 978-93-49938-76-2| Year: 2026 | pp: 106 - 111 |

Impact of Exotic Fish Species on Indian Fishery: A Review

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Article DOI Link: https://zenodo.org/uploads/20109426

DOI: 10.5281/zenodo.20109426

Introduction

Indian fishery is a vital pillar of the national economy, positioning India as the second-largest aquaculture producer and the third-largest fish producer globally. Contributing approximately 1.1% to the country's GDP and over 7% to the agricultural GVA, the sector provides a primary source of livelihood and nutritional security for over 30 million people, particularly within marginalized coastal and rural communities. In recent years, the industry has undergone a massive transformation through the "Blue Revolution," shifting from traditional marine capture to a dominant inland aquaculture model, which now accounts for nearly 75% of total production. Despite this growth, the sector faces modern challenges such as climate change, overfishing, and the ecological threat of invasive exotic species, necessitating a shift toward sustainable practices and technological modernization to maintain its upward trajectory.

The Indian subcontinent, with its vast network of rivers, canals, lakes, and reservoirs, is one of the world's most significant hotspots for aquatic biodiversity. However, this diversity is currently facing an unprecedented challenge: the invasion of exotic fish species. An exotic species is defined as a non-native organism introduced into an ecosystem where it does not naturally occur. In India, the introduction of these species began in the mid-19th century, initially driven by colonial interests in sport fishing and later by the government's push to enhance food security through the "Blue Revolution."

While species like the Silver Carp and Grass Carp were introduced to fill specific ecological niches in aquaculture ponds, the lack of containment has led to their escape into open water bodies. Today, nearly 13.6% of India's fish diversity is comprised of exotic species. While they have undeniably boosted production figures, their presence in natural ecosystems often transitions from "introduced" to "invasive," leading to the displacement of indigenous fauna, habitat alteration, and significant economic losses for traditional fishing communities.

Current Status of Indian Fishery

The Indian fishery sector is a sunrise industry, showing a double-digit annual growth rate over the last decade. It serves as a primary source of livelihood for over 30 million people, particularly in coastal and rural inland areas. India is currently the second-largest aquaculture producer and the third-largest fish producer in the world. In the 2023-24 fiscal year, total fish production reached an all-time high of approximately 17.5 million metric tonnes. The sector is bifurcated into Marine and Inland fisheries, with the Inland sector (including aquaculture) contributing nearly 75% of the total production.

The Indian fisheries sector is currently at its highest historical peak, serving as a critical "sunrise sector" for the national economy. As of May 2026, India is the world's second-largest fish producer, contributing approximately 8% to global output.

Production and Growth

- **Record Output:** Total fish production surged to 197.75 lakh tonnes (provisional) in FY 2024–25, a 106% increase from 95.79 lakh tonnes in 2013–14.
- **Inland Dominance:** The inland sector, primarily driven by aquaculture, now accounts for nearly 75% of total production. Inland output expanded by 142% over the last decade.
- **Productivity:** Average aquaculture productivity improved significantly from 3 tonnes per hectare (pre-2020) to 4.77 tonnes per hectare by early 2025.

Economic Contribution: GDP & GVA: The sector contributes 1.1% to India's total GDP and roughly 7.43% to the Agricultural Gross Value Added (GVA)—the highest share among all agriculture and allied sectors.

- **Record Exports:** India is the 4th largest exporter of fish products globally. Seafood exports reached an all-time high of ₹62,408 crore in FY 2024–25, with frozen shrimp remaining the dominant commodity.
- **Employment:** The sector provides direct and indirect livelihoods to approximately 2.8 to 3 crore people.

Government Initiatives: The government has invested over ₹38,572 crore since 2015 to modernise the sector through major flagship schemes:

- **PMMSY:** The Pradhan Mantri Matsya Sampada Yojana (2020–2025) is the primary driver, with an investment of ₹20,050 crore targeted at infrastructure, credit access, and sustainable farming.
- **Financial Inclusion:** Over 4.76 lakh Kisan Credit Cards (KCC) have been issued to fishers as of June 2025, providing easy access to working capital.

- **Technology & Infrastructure:** Initiatives include the installation of artificial reefs (937 approved as of Sept 2024), satellite-based vessel communication systems, and the rollout of the National Fisheries Digital Platform.

Major Exotic Fish Species in India

Here is the list of major exotic fish species found in India, categorized by their primary use and ecological status:

Category	**Common Name**	**Scientific Name**	**Status / Impact**
Major Food Fish	**Common Carp**	*Cyprinus carpio*	Widespread; outcompetes native carps.
	Nile Tilapia	*Oreochromis niloticus*	Highly invasive; dominates river ecosystems.
	Silver Carp	*Hypophthalmichthys molitrix*	Surface feeder; competes with native Catla.
	Grass Carp	*Ctenopharyngodon idella*	Used for weed control; alters habitats.
	Pangas / Basa	*Pangasianodon hypophthalmus*	Major commercial species; huge market presence.
Banned / Invasive	**African Catfish**	*Clarias gariepinus*	**Legally Banned**; highly predatory to native fish.
	Suckermouth Catfish	*Pterygoplichthys spp.*	Invasive; damages nets and breeding grounds.
	Red-bellied Pacu	*Piaractus brachypomus*	Often sold as "Piranha"; invasive in open waters.
	Bighead Carp	*Hypophthalmichthys nobilis*	Unauthorized; competes for plankton resources.
Ornamental	**Goldfish**	*Carassius auratus*	Common pet; survives well in local climates.
	Alligator Gar	*Atractosteus spatula*	Growing threat; top predator escaped from

			tanks.
	Arowana	*Osteoglossum spp.*	High-value trade; strictly for aquariums.
Bio-Control	**Mosquito Fish**	*Gambusia affinis*	Introduced for malaria control; eats native fry.
	Guppy	*Poecilia reticulata*	Widespread in urban drains and wetlands.
Coldwater / Sport	**Rainbow Trout**	*Oncorhynchus mykiss*	Cultured in Himalayas for food and tourism.
	Brown Trout	*Salmo trutta fario*	Found in high-altitude streams for angling.

Characteristic Features of Exotic Fish Species Over Native Species

Exotic fish species often outcompete native Indian fish because they possess specific "superior" biological traits that allow them to dominate new environments. The following are the key characteristic features that give exotic species an advantage over native species:

1. **High Physiological Tolerance**

- **Extreme Resilience:** Many exotics, like Tilapia, can survive in highly polluted or "stressed" water bodies with very low dissolved oxygen (hypoxia) where native species like Rohu or Catla would perish.
- **Temperature & Salinity Range:** They often have a wider "ecological amplitude," meaning they can thrive in varying water temperatures and salinity levels, making them better suited for changing climates and degraded habitats.

2. **Prolific Breeding & Parental Care**

- **Year-round Spawning:** Unlike native Indian Major Carps (IMC), which generally require specific monsoon conditions and riverine flow to breed, many exotics are perennial breeders.
- **Mouth Brooding:** Species like Tilapia exhibit parental care (carrying eggs/fry in their mouths), ensuring a significantly higher survival rate for their offspring compared to the "broadcast spawning" (laying eggs and leaving) method of native fish.

3. **Generalist Feeding Habits**

- **Opportunistic Feeders:** While native fish are often "specialists" (e.g., Catla eats surface plankton, Mrigal eats bottom detritus), exotics are typically omnivorous generalists.

- **Efficient Conversion:** They are highly efficient at converting low-quality feed into body mass, allowing them to grow faster even when high-quality food is scarce.

4. Rapid Growth Rates

- **Short Doubling Time:** Species like Pangas and Common Carp reach marketable size much faster than native varieties. This rapid growth allows them to quickly outsize native competitors, reducing the risk of being eaten while increasing their own predatory potential.

5. Aggressive & Territorial Behaviour

- **Competition for Space:** Many exotic species are highly aggressive. The African Catfish, for instance, is a voracious predator that actively hunts the fry of native species.
- **Habitat Alteration:** The Common Carp uses a "rooting" behavior—digging into the bottom mud for food—which increases water turbidity. This muddies the water, destroying the clear-water habitat and spawning grounds required by native fish.

6. Resistance to Local Pathogens

- **Invader's Advantage:** Exotic species often lack natural predators in Indian waters and may be resistant to local parasites. Conversely, they can act as "asymptomatic carriers" of new diseases that can devastate vulnerable native populations.

Summary and Conclusion

India’s fisheries sector, a key economic driver, has achieved record-breaking production through the "Blue Revolution" but faces significant ecological threats from invasive exotic fish species. While non-native species like Tilapia and Carp have boosted aquaculture output, their dominance, driven by high environmental tolerance and rapid reproduction, is displacing indigenous biodiversity and altering ecosystems. To ensure long-term sustainability, a shift toward a "Responsible Blue Revolution" is required, balancing high commercial output with strict conservation measures to protect native fish populations.

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Nature- 91

ISBN: 978-93-49938-76-2
9 789349 938762
Price- 750/-