



Sewage-Fed Aquaculture: Issues and Opportunities

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Abstract

Sewage-fed aquaculture is an innovative technique for utilising nutrient-rich sewage water for sustainable fish farming. In this article, the advantages, disadvantages and opportunities associated with nutrient recycling, present problem of reduced supply of waste water in the East Kolkata Wetlands and providing affordable protein for low-income communities are discussed. Despite the beneficial effects on livelihoods and natural wastewater treatment, this practice is severely affected by serious issues, including health risks of the fishes caused by pathogens, degradation of the environment and an unreliable policy framework. This article also explores new opportunities that involve developments in technology to treat wastewater, techniques of bioremediation, as well as the application of aquaculture within the circular economy framework. This can be accomplished through innovation, effective policymaking and enhanced monitoring. In this regard, the sewage-fed aquaculture system can emerge as a sustainable model for aquaculture around the world.

Keywords: East Kolkata wetlands, Environmental conservation, Environmental risk, Food security, Sewage-fed aquaculture

Introduction

The productivity of aquaculture systems is significantly higher than that of terrestrial agriculture and they can increase protein production to the levels comparable to those of cereal crops utilized during the Green Revolution. Wastewater is now considered a resource that can be repurposed for fish farming rather than disposed of. The reuse of untreated or treated wastewater for aquaculture has recently been advocated because of the scarcity of water resources (Keraita *et al.*, 2008). In India, for example, in East Kolkata Wetlands, approximately 260 bheries produce over 20,000 tons of fish year⁻¹ using sewage effluent, well known for sewage-fed aquaculture (EKWMA, 2021). For millions of people in developing nations, especially in South, Southeast and East Asia, fish and other aquatic organisms, particularly fish grown in wastewater-fed systems, are significant sources of food and employment (Ninawe, 1999). Traditional practices of recycling sewage through agriculture, horticulture and aquaculture, which are biological processes, have been in use in several countries, including Germany,

Russia, Poland, Hungary, China and Indonesia (Bunting *et al.*, 2010).

Sewage can be defined as a cloudy fluid containing mineral and organic matter, in solution or as particles of solid material floating, suspended or in colloidal or pseudo-colloidal form. The main organisms of sewage are bacteria and protozoa. Sewage may be classified according to biological oxygen demand (BOD) or solid content as strong (BOD, 400 mg L⁻¹; solid content, 1200 mg L⁻¹), medium (BOD, 200 mg L⁻¹; solid content, 720 mg L⁻¹) and weak (BOD, 110 mg L⁻¹; solid content, 350 mg L⁻¹). Aquaculture is very useful, with domestic sewage having a relatively lower C: N ratio (3:1) than industrial sewage. The quantity of sewage used to fertilize a fish pond is determined by the characteristics of the sewage, climatic conditions, physical features of the pond and the species to be cultured. The transfer of sewage to aquaculture facilities involves a considerable reduction of the organic and BOD loads of the sewage. Raw domestic sewage BOD load usually ranges between 120-400 mg L⁻¹ and primary treatment by sedimentation may bring down BOD by 33%. Anaerobic

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bacteria and pathogens are greatly reduced in oxidation ponds (Jana and Jana, 2002).

Sewage-fed aquaculture is a natural treatment system that can offer effective wastewater treatment, economic returns and employment opportunities in rural and peri-urban areas (Kumar et al., 2014; Kumar et al., 2015). The system is largely based on domestic sewage and is an extensive or semi-intensive aquaculture system. Farmers often grow organisms in treated sewage water. No fertilization and feeding are practiced in the culture pond as the raw sewage is nutrient rich and can increase the production of plankton. Sewage water feeds ponds improving natural food sources for phytoplankton, zooplankton and benthic fish. Sewage fed fish culture is a cost-effective method of fish production which does not require manure and supplemental feeding as sewage has high nutritional value. Sewage water use is effective in reducing the organic load in river systems. Recycling waste and promoting the environment, urban areas are practicing aquaculture fed by sewage. Sewage-fed aquaculture is attractive and unique for wastewater treatment and resource recovery because of the many benefits it provides (Paul and Chanda, 2015). Nutrient addition to fish culture ponds using sewage increases the water productivity and makes the aquatic systems more vibrant (Ghosh et al., 1980). The water quality of a sewage fed fish pond was compared with that of a regularly fertilized pond and the results showed that the sewage pond had considerably higher levels of BOD, N, P and Cl^{-1} and its early morning pH value was lower. CIFA, with its long experience in domestic sewage, calculates that one litre of sewage may produce an average of 0.05 g of nutrients (N and P) and save 99% of water. It has been reported that the consumption of 1.0 litre of sewage effluent gives an average amount of 0.03 g biomass in the form of fish reared in such sewage water bodies (Mandal et al., 2015; Mandal and Nandi, 2015).

The major classes of fish in sewage-fed aquaculture are selected on the basis of their feeding habits; they are herbivores, detritivores, carnivores and omnivores. Herbivores eat microalgae such as phytoplankton and are the most efficient users of energy because they are eating the producers directly. Detritus feeders that feed on dead organisms and organic, decayed matter found at the bottom of the pond. Detritus is organic material from plants and animals. Carnivorous fish eat small animals like crustaceans, insect larvae, annelid larvae and molluscs. Among the fish species, some are omnivores and consume both plant and animal matter (Mandal et al., 2015; Mandal and Nandi, 2015). Farmers' culture exotic and Indian carps but they prefer the Indian Major Carps including catla (*Labeo catla*), rohu (*Labeo rohita*) and mrigal (*Cirrhinus mrigala*). Indian minor carps such as bata (*Labeo bata*) and Reba carp (*Cirrhinus reba*) and minnows such as morala (*Amblypharyngodon mola*) have also been reared in sewage-fed systems with intake of low concentrations of primary-treated sewage. Exotic fish like grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*) and common carp (*Cyprinus carpio*) are stocked at a small percentage (Paul and Chanda,

2015). However, the tilapia (*Oreochromis mossambicus* and *O. niloticus*) have become popular and represent 5-30% of the species stocked in different ponds, since they tolerate a considerable range of sewage concentrations. Some farmers stock pangas (*Pangasianodon hypophthalmus*) in relatively high organic load water because they are biologically hardy and can survive at low DO levels even as low as 3.0 mg L^{-1} . As part of integrated culture practices in paddy cum fish culture systems, Indian catfish, such as *Clarias magur* and *Heteropneustes fossilis* are also standardized for growth in sewage-fed aquaculture systems of shallow water bodies during the rainy season to keep in view the rising prices and consumers' preferences. Some are attempting to culture high value species such as the giant freshwater prawn, *Macrobrachium rosenbergii* and their impressive yields in this system may be attractive to farmers (Mandal et al., 2015).

Sewage-fed aquaculture has been practiced for decades and has great value in terms of wastewater treatment, nutrient recycling, fish production and livelihood generation. Its long-term sustainability is, however, a matter of debate. Existing studies are often fragmented, focusing on specific aspects such as production, water quality or environmental impacts and with limited integration of public health, food safety, emerging contaminants, socioeconomic and policy perspectives. The aim of this review is to synthesise the existing knowledge on opportunities and challenges of sewage-fed aquaculture, identify key knowledge gaps and discuss future research and policy directions towards its safe, sustainable and climate-resilient development.

History of Sewage-Fed Aquaculture

Sewage-fed aquaculture has a long and dynamic history, serving as an epitome of how old knowledge can fuse with ideas of modern ecology and sustainable practices. The origin of this concept can be traced to the most ancient civilizations of the world, such as China, as early as 1100 BC, where nutrient-rich water from humans and animals was used to fertilize rice paddies that held fish such as carp. During the medieval period, untreated wastewater was opportunistically used for irrigation and, in turn, supported wetlands that facilitated fish growth, particularly in Europe (Angelakis et al., 2018). With the growth of urbanization in the 19th century due to the Industrial Revolution, European cities began exploring systematic ways to use treated sewage for aquaculture and Germany and Austria pioneered early scientific approaches to constructed fishponds (Prein, 1988). One landmark example is the East Kolkata Wetlands in India, a large pond network that uses urban wastewater for massive fish farming, providing low-cost protein to the people of Kolkata and sustaining the livelihoods of the local communities (Vansintjan, 2021). The mid 20th century marked the beginning of rigorous scientific research on the nutrient cycle, as well as the twin benefits of using the waste products in aquaculture in terms of producing food, as well as water purification. This made way for the application in underdeveloped areas like Southeast Asia and Africa, through which Vietnam, Thailand and

China implemented integrated wastewater management techniques for food security (Prein, 1988). But after it came to light that there were increased threats of health hazards due to the improper treatment of waste products, the late 20th century was characterized by stringent regulations as well as improvements in wastewater treatments. Presently, sewage-fed aquaculture is advancing and demonstrating the combined aspects of historical genius and modern technology that address significant global challenges in food security, environmental conservation and wastewater management (Table 1).

Wastewater Treatment and Management

Wastewater treatment (Figure 1) is an important process which is divided into three stages, namely primary treatment, secondary treatment and tertiary treatment (Nourmohammadi *et al.*, 2013; Islam, 2025). These are meant to gradually remove pollutants and improve the quality of water. Mechanical processes are involved in primary treatment which includes screening and sedimentation for physical separation of large solids and debris 50-60% of total suspended solids are removed during this treatment stage. Meanwhile, the biochemical oxygen demand (BOD) reduction is around 25-35% (Tsamoutsoglou *et al.*, 2024). The primary effluent contains dissolved organic material and nutrients. Secondary treatment is a biological process which employs methods such as activated sludge

process, trickling filters or lagooning to decompose organic pollutants and nutrients that are present in dissolved form. This is usually able to reduce residual organic pollutants to 85-95% levels with secondary effluent that is cleaner but may still contain residual nutrients and microorganisms (Das *et al.*, 2022; Jahan *et al.*, 2022). Tertiary treatment consists of filtration, chemical treatment, nutrient removal and disinfection with chlorine, UV light or ozone (Islam, 2025). This process removes virtually all suspended solids, pathogens and nutrients, producing a high-quality tertiary effluent suitable for discharge into sensitive environments or reuse in applications such as irrigation, industrial processes or, after further treatment, potable water supply.



Figure 1: Step-wise demonstration of wastewater treatment

Table 1: Sewage-fed aquaculture systems worldwide

Country	Region/City	Major Fish Species Cultured	Key Details	References
India	Kolkata (East Kolkata Wetlands)	<i>Labeo rohita</i> , <i>Labeo catla</i> , <i>Cirrhinus mrigala</i> , <i>Oreochromis niloticus</i> , <i>Cyprinus carpio</i>	Largest sewage-fed aquaculture system; uses partially treated wastewater in integrated fish-paddy systems.	Paul and Chanda (2015)
Bangladesh	Dhaka, Narayanganj	<i>Hypophthalmichthys molitrix</i> , <i>Ctenopharyngodon idella</i> , <i>Pangasianodon hypophthalmus</i>	Informal use of diluted sewage in peri-urban ponds; risks of contamination.	Edwards (2005)
China	Beijing, Wuhan & Guangdong	Common carp, <i>Hypophthalmichthys nobilis</i> , <i>Carassius carassius</i>	Treated wastewater is used in rural-urban fringe areas.	Zhou and Wong (2000)
Vietnam	Hanoi, Ho Chi Minh City	Nile tilapia, Common carp, Catfish (<i>Clarias</i> spp.)	Wastewater-fed ponds are often combined with rice fields.	Van and de Pauw (2005)
Egypt	Cairo, Nile Delta	Nile tilapia, Mullet (<i>Mugil cephalus</i>), African catfish (<i>Clarias gariepinus</i>)	Treated sewage is used due to water scarcity; it is government-regulated.	Khalil and Hussein (1997)
Mexico	Mezquital Valley	Tilapia, Common carp	One of the world's largest wastewater reuse systems for irrigation and aquaculture.	Jimenez and Chavez (2004)
Ghana	Accra, Kumasi	Tilapia, African catfish (<i>Clarias gariepinus</i>)	Informal sewage-fed ponds; high contamination risks.	Tenkorang <i>et al.</i> (2012)
Peru	Lima	<i>Nile tilapia</i>	Sewage-fed ponds in arid regions; limited treatment.	Prein (1998)
Germany	Berlin	Common carp	Abandoned system; treated sewage was used in the early 20 th century.	Prein (1996)

Table 2: Composition and characteristics of sewage water

Category	Parameter	Description	References
Water content	Water proportion	Sewage typically comprises 98-99.9% water.	Mandal <i>et al.</i> (2015)
Solid matter	Organic and inorganic solids	Around 0.01% solids, mainly faecal residues and other organic content.	Mandal <i>et al.</i> (2015)
Organic fraction	Composition	Mostly proteins (about 60%), followed by carbohydrates (20%) and fats (10%).	Mandal <i>et al.</i> (2015)
Inorganic fraction	Mineral content	Includes sand, grit, salts, trace metals and other dissolved minerals.	Brown <i>et al.</i> (1973)
Organic compounds	Nitrogenous and non-nitrogenous	Comprises nitrogen-based substances and other compounds like fats, sugars.	Mandal <i>et al.</i> (2015)
Agricultural impact	Suspended solids effects	High solids can lead to soil saturation and reduced permeability in farmlands.	Yan <i>et al.</i> (2013)
Chemical profile	Site-dependent parameters	Properties vary with local industrial input; includes changes in pH, EC, bicarbonates, CO ₂ , Ca ²⁺ , Mg ²⁺ .	Dutta <i>et al.</i> (2017)
Heavy metals	Geographic differences	Elevated metal concentrations reported in Haryana and West Bengal vs. Punjab.	Dutta <i>et al.</i> (2017)
Microorganisms	Microbial presence	Sewage contains various bacteria and protozoans.	Datta and Pal (2005)
Nutrients	Organic carbon and nitrogen content	Generally, holds 250-400 mg L ⁻¹ organic C and 80-120 mg L ⁻¹ nitrogen; C:N ratio ~3:1.	Datta and Pal (2005)
Effluent contaminants	Common pollutants	Contains nutrients, heavy metals (Fe, Cu, Zn, Pb, etc.) and pathogens.	Dutta <i>et al.</i> (2017)

Process Adopted for Sewage Treatment before Releasing into the Fish Pond

Pre-treatment of sewage includes sedimentation, dilution and storage, which reduce pollutant concentrations and prepare the sewage for further treatment. Sedimentation is the process in which heavier particles in sewage settle in a settling tank, removing up to 50-60% of suspended solids while leaving dissolved pollutants and nutrients in the sewage. Dilution adds freshwater to sewage to reduce pollutant concentrations in water, so that toxicity levels can be temporarily decreased but not necessarily removed. Storage breaks down organic matter in diluted sewage under aerobic conditions, reducing BOD and stabilizing the water. However, these treatments do not address nutrient or hazardous chemical issues, although they dramatically improve the quality of the produced water. However, such water must typically undergo treatment to remove remaining pollutants.

Systems and Practices

Types of Sewage-Fed Aquaculture Systems

Sewage-fed aquaculture systems can be categorized by design, scale and level of wastewater treatment. The primary types of systems commonly utilized are as follows.

a) Wetland-based Systems: Wetland-based aquaculture provides wastewater treatment, where natural or constructed wetlands, with the help of aquatic plants' biological activity, with microorganisms' and fish contribution, break the

organic matter present in wastewater through the absorption of various nutrients. Perhaps the most spectacular example of global recognition is in India, where the East Kolkata Wetlands feature fish farming and wastewater collection simultaneously in the same facilities.

b) Pond-based Systems: Pond-based systems involve the direct use of untreated or partially treated sewage in fish ponds. Nutrient-rich wastewater enhances phytoplankton growth, which serves as a natural food source for fish. Although they are cheaper to implement, they require monitoring to ensure that no harmful pollutants and pathogens accumulate.

c) Integrated Systems: Integrated systems merge aquaculture with agriculture to reuse wastewater from fish farming for crop irrigation. This means that resource use is optimized while supporting diversified livelihoods. In some cases, the same field used for rice irrigation is also used for fish farming.

d) Advanced Treatment Systems with Aquaculture Integration: In modern systems, wastewater undergoes advanced treatment procedures, such as sedimentation, filtration and disinfection, before being used for aquaculture. Such systems promote public health and environmental safety and can be used on a large scale for urban applications.

e) Aquaponics with Treated Wastewater: Aquaponics integrates treated wastewater with aquaculture and hydroponics, producing a controlled environment for both fish and plants. These systems are usually closed-loop,

minimizing water use and the risk of contamination. They are technologically advanced but require higher capital investment and technical requirements.

Examples of Implementation in Different Regions

Sewage-fed aquaculture is an innovative method of sustainable food production and wastewater recycling that is practiced worldwide in countries such as India, Bangladesh, China and parts of Africa. One such example is the East Kolkata Wetlands in India, where untreated municipal wastewater supports both fish farming and agriculture and acts as a natural sewage-treatment system. In Zimbabwe, treated wastewater from Harare is discharged into Lake Chivero, where aquaculture takes place, although the nutrient load poses challenges. Traditional rice-fish farming in China combines village wastewater with irrigation of rice paddies and fish culture to increase productivity with minimal environmental impact. Urban wastewater-fed ponds are used for catfish and tilapia farming in Thailand, although more stringent food safety regulations have been introduced in recent years. More advanced aquaponics systems are in Australia, where treated wastewater is combined with aquaculture and hydroponics in a closed-loop system for efficient food production. These diverse practices show how sewage-fed aquaculture can adapt to meet different regional waste-management and food-security needs.

East Kolkata Wetlands

The East Kolkata Wetlands (EKW) located on the eastern outskirts of Kolkata support one of the world's largest integrated resource recovery systems combining aquaculture, agriculture and horticulture (Figure 2). The Government of India declared EKW as Wetland of International Importance under the Ramsar Convention in 2002 (as an example of Wetland wise-use). EKW is also among the few natural habitats offering recreational opportunities to urban and peri-urban populations. The EKW has the world's largest sewage-fed aquaculture system.

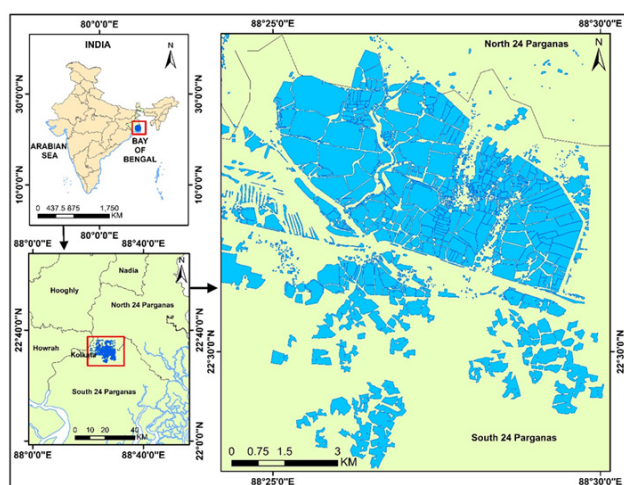


Figure 2: Map of East Kolkata wetlands

The EKW encompasses 12,500 ha area. Pre-settled sewage (~900 MLD) is being discharged daily into more than 260 shallow wetlands of Kolkata metropolitan region (EKWMA, 2021). EKW is the 'Kidneys of Kolkata' and saves

almost Rs. 468 crore year⁻¹ in terms of treatment cost saving (65% sewage of Kolkata) and reduces release of damaging greenhouse gases trapping over 60% of carbon in wastewater. The fish farms (6,100 ha total water spread area) depend on the nutrients in the wastewater and the agricultural practices (3,335 ha) produced 20,000 MT of fish and 50,000 MT of vegetables year⁻¹ (EKWMA, 2021). The EKW system offers livelihood opportunities for a large economically disadvantaged population of 1,50,000, of which 20,000 people depend on fisheries. The commonly cultured fish species are *Labeo rohita*, *L. catla*, *Cirrhinus mrigala*, *L. bata*, *Hypophthalmichthys molitrix*, *Ctenopharyngodon idella*, *Cyprinus carpio* and *Oreochromis niloticus*. Tilapia accounted for the highest share of about 30-35%, followed by Bata and IMC.

Benefits of Sewage-Fed Aquaculture

Several benefits are associated with sewage-fed aquaculture, mainly due to the integration of wastewater treatment, economic activities and environmental sustainability in the systems (Bunting *et al.*, 2010). The main benefit that comes from this is associated with the treatment of wastewater and recovery of resources. In such systems, sewage or partially treated waste water undergoes sedimentation for precipitation of suspended solids in the aquaculture ponds. The nutrient-enriched water containing nitrogen and phosphorus acts as the source of nutrition for the growth of planktons which serve as the primary diet for fish. Bacteria facilitates degradation of organic matter. This results in reduction in the levels of BOD and COD in water bodies. Fish consume plankton that recycles nutrients in the water (Jana, 1998). In India, for instance, the East Kolkata Wetland treats around 980 million litres of urban sewage per day, which is recycled for fish culture and agriculture (Chatterjee *et al.*, 2025). In addition, in Thailand, plankton feeder fish like tilapia are cultured using sewage, through appropriate processes of settling and nutrient removal (Edwards, 1985). Sewage-fed aquaculture is one of the economically viable methods in fish farming because it is non-expensive. Use of sewage minimises dependence on fertilizers and hence lowers costs of operation. Income generation occurs through fish farming, where water may be used to irrigate crops and cultivate vegetables. In China, rice-fish farming integrates by irrigating rice fields using village sewage while culturing fish and enhancing rice productivity (Angelakis *et al.*, 2018). The ventures ensure employment opportunities in farming, fishing and marketing to maintain food security. Economic benefits for cities are obtained from avoidance of costs of construction and maintenance of waste water treatment facilities. Aquaponics technology in Australia shows that reused water can generate revenue from sale of valuable fish and vegetables in urban centres (Cifuentes-Torres *et al.*, 2021). From an environmental perspective, sewage-fed aquaculture serves as a model of the circular economy as resources from waste products can be recycled back to life. Nutrients contained in sewage will be recycled for aquaculture and agricultural purposes. This will help avoid water pollution and eutrophication in natural waters since there would be no nutrients from sewage left in these

waters. Photosynthesizing plants and algae can help absorb carbon dioxide that contributes to mitigating the problem of greenhouse gases (Shitu *et al.*, 2024). In addition, sewage-fed aquaculture helps avoid transmission of diseases from contaminated water. Since there is no need to discharge untreated sewage into waterways, the system helps preserve aquatic biodiversity. The East Kolkata Wetlands is home to migratory birds and aquatic species; therefore, the ecological impact of such a sewage-fed aquaculture system will also be positive (Kundu *et al.*, 2008). This is a system that will allow saving energy and money on treating sewage. Overall, sewage-fed aquaculture systems have proven their effectiveness by helping communities generate profit and protecting ecosystems. Sewage-fed aquaculture is especially helpful for developing countries. It has proved successful in regions like India, Vietnam, Australia and China.

Challenges and Issues in Sewage-Fed Aquaculture

Although there are a number of benefits associated with the utilization of wastewater in fish farming, there are also various obstacles which need to be overcome. Some of the obstacles associated with wastewater fish culture include the threat to human health, environmental impact, regulatory and societal objections.

1. Public Health Concerns and Food Safety

Public health and food safety are the main concerns of sewage-fed aquaculture as the wastewater contains pathogens, heavy metals and chemical pollutants. Wastewater may contain harmful microorganisms such as *Salmonella*, *Escherichia coli* and a number of viruses, which may bioaccumulate in fish, thus posing a potential health risk to humans who consume them. Heavy metals like mercury, lead and cadmium may also be found in wastewater and after bioaccumulation can reach aquatic organisms and ultimately humans, causing long term health effects. Also, the presence of pharmaceuticals and antibiotics in sewage could promote the development of antibiotic resistance in bacteria, thereby aggravating potential public health risks (Roy *et al.*, 2025). In Zimbabwe, algal blooms have been reported in Lake Chivero which relies on treated sewage from Harare (Nhapi *et al.*, 2006; Manjengwa *et al.*, 2019). These blooms produce toxins that bioaccumulate in fish and cause health problems for consumers. In China, there are concerns over pesticide residues and heavy metal contamination of fish due to improper wastewater management in integrated rice-fish farming systems, which affect consumer confidence and marketability. Similar threats are also faced by the wastewater-fed aquaculture systems in Bangkok, where sewage inputs sometimes introduce contaminants into the aquaculture ponds, which need to be regulated properly and monitored and controlled strictly.

2. Environmental Risks: Pollution and Biodiversity Impact

Sewage-fed aquaculture does carry risks, such as pollution, nutrient overloading and possible loss of biodiversity. Many untreated or partially treated sewage contains high concentrations of nutrients that can cause eutrophication (Figure 3) and subsequent undesirable algal blooms that

reduce oxygen levels, negatively affecting other aquatic organisms. Diseases, invasive species or chemicals that can disrupt regional biodiversity and ecosystems are also encountered. Lake Chivero in Zimbabwe is severely eutrophied from nutrient rich sewage inflows which pose a threat to fish species and the whole ecosystem (Magadza, 2008). In East Kolkata Wetlands, unregulated industrial effluents mixing with urban sewage degrade water quality and thus adversely affect aquatic biodiversity and the ecosystem's efficiency. The nutrients from the city's waste-fed ponds sometimes cause pollution in the natural water bodies surrounding the city of Bangkok. Additionally, uncontrolled systems, including some prototype aquaponics systems in Australia, present the risk of invasive species entering the region's natural ecosystems if the discharge of wastewater is uncontrolled.



Figures 3: Image of the major concern of the sewage-fed system of East Kolkata Wetlands: (A, B) canal siltation and solid waste dumping; (C, D) weed choking

3. Regulatory and Policy Barriers

Lack or inconsistency in regulatory policies presents a major challenge in the widespread implementation of sewage-fed aquaculture (Schellenberg *et al.*, 2020). The majority of countries fail to provide policy guidelines on the application of sewage in aquaculture, which covers the regulation of treatment measures, permissible contaminants and safety of aquaculture produce. Additionally, lack of enforcement of regulations makes it possible for untreated wastewater to find its way into aquaculture. Moreover, inadequate financial resources and infrastructure in the monitoring and treatment of waste water reduce its feasibility.

Similarly, the lack of enforcement of land use regulations has posed serious challenges to the sustainable practice of sewage-fed aquaculture in the East Kolkata Wetlands of India. The strict enforcement of food safety and hygiene policies in Thailand comes at the expense of the development of wastewater-fed aquaculture, which significantly impacts small farmers' production capabilities due to their inability to comply with the regulations. As a result, the advanced technological state of Australia's aquaponics farms is not enough due to regulations prohibiting the reuse of wastewater for agriculture purposes.

4. Social Perceptions and Cultural Challenges

It faces challenges of social acceptance; many people dislike sewage-fed aquaculture because it goes against their cultural beliefs and wastewater-based production is perceived as unsafe and low in quality. Negative perceptions of wastewater-fed fish being “dirty” or unsafe for consumption reduce market demand and lower the economic feasibility of such systems. Cultural beliefs about purity and contamination often discourage the use of treated wastewater in aquaculture and agriculture (Verhoest *et al.*, 2022). Public awareness campaigns are inadequate, leaving consumers unaware of the safety and benefits of properly managed systems. In China, fish produced in integrated rice-fish farming systems irrigated with village wastewater often face scepticism from local communities, even though they are safe. Similarly, in Peru, concerns about contamination limit consumer acceptance of fish from sewage-fed systems, even when rigorous wastewater management practices are in place (Danzo *et al.*, 2022). In Palmas, Brazil, cultural resistance has made it difficult for farmers to market fish from wastewater-fed systems to urban consumers (Faria and Naval, 2022). Public awareness activities on Australian aquaponics projects have been successful and often indicate how education and transparency can improve the acceptance of wastewater-fed systems (Lennard, 2004).

5. Health Response of Fish in Sewage-fed Aquaculture

Sewage-fed aquaculture is a novel and resource-efficient method of fish culture, primarily practiced under conditions of water scarcity and nutrient demand. By utilizing domestic and industrial effluents rich in nutrients, these systems enhance primary productivity and promote fish growth at minimal external input costs. However, this method exposes fish to a variety of environmental pollutants, making fish health a central concern for the sustainability of sewage-fed aquaculture. The applied effluents, often wholly or partially untreated, introduce a complex mixture of stressors, including heavy metals, ammonia, nitrates, pharmaceuticals, endocrine disruptors and pathogenic microorganisms. These stressors can lead to various physiological, biochemical, immunological and pathological changes in fish. Compared to controlled aquaculture settings, sewage-fed systems expose fish to prolonged, low-dose contaminant exposure, which is unlikely to cause immediate death but may lead to sub-lethal effects such as immune suppression, reduced reproductive capacity, tissue deterioration and increased susceptibility to disease. High-profile case studies, like India’s East Kolkata Wetlands (EKW), serve as both efficient sewage treatment and aquatic ecosystems and fish cultivating areas, making them ideal experimental models for observing the delicate balance between productivity and fish well-being under pollutant stress.

Examination of the health responses of fish in such systems is significant for ecological risk assessment, mitigation design and food safety for consumers. In this section, the physiological adaptation or deterioration of fish in response to sewage is examined, identifying indicators such as oxidative stress, immunological alterations, metabolic

disorders and histopathological indicators, providing data on the environmental stresses and coping mechanisms prevailing in sewage-fed aquaculture.

6. Immunological Responses of Fish in Sewage-Fed Aquaculture

Fish immunity comprises two major arms: innate (nonspecific) and adaptive (specific) immunity. Innate defences respond quickly through physical barriers (skin, mucus, gills), cellular responses (phagocytes, granulocytes, natural cytotoxic cells) and humoral factors (lysozyme, complement, antimicrobial peptides, cytokines). Innate responses identify conserved pathogen-associated molecular patterns (PAMPs) and induce instant killing (*e.g.*, phagocytosis, respiratory burst) but do not establish long-term memory. Adaptive immunity entails B and T lymphocytes, antigen-specific receptors (MHC, immunoglobulins) and immunological memory. The adaptive system is present in teleost fish but is comparatively slower and frequently less intricate than in mammals. Innate responses predominate early defence, with adaptive IgM or cell-mediated responses augmenting protection on longer timescales. In experimental research, typical innate biomarkers are lysozyme and complement activity, phagocytic and respiratory-burst assays and levels of cytokine or acute-phase proteins, while adaptive responses are measured by lymphocyte proliferation, specific antibody titers (predominantly IgM) and B/T cell function markers.

6.1. Innate Immune Response of Fish in Sewage-Fed Aquaculture Systems

Fish in sewage-fed aquaculture are subjected to a complex and often chronic mixture of environmental stressors such as chemicals (heavy metals and organic toxins), hypoxia, fluctuating nutrient load and pathogenic microorganisms. The stressors induce a complex innate immune response, the initial and immediate defence against environmental stress. The fish’s innate immune system comprises several components, such as physical barriers, immune cells (*e.g.*, neutrophils, macrophages) and soluble components such as lysozymes, complement proteins and pro-inflammatory cytokines. Acute stress, usually from short-term exposure to sewage-borne stressors, induces a temporary increase in nonspecific immunity. During this phase, increased levels of stress hormones such as cortisol and catecholamines induce leukocytosis, an increased number of circulating leukocytes (Dhabhar, 2002; Wojtaszek *et al.*, 2002). This is followed by enhanced expression of genes of innate immunity like those encoding for complement component C3, lysozyme G and $\beta 2$ microglobulin, which enhance the capacity of the fish to rapidly clear pathogens (Sunyer and Tort, 1995; Kar *et al.*, 2015).

In addition, oxidative stress is a common response to exposure to sewage due to the content of reactive oxygen species (ROS) and this leads to the activation of antioxidant enzyme activity such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx) (Hossain *et al.*, 2022). The enzymes act synergistically to inactivate ROS and counteract cellular injury. The research conducted by Hossain *et al.* (2022) revealed much higher levels of these

antioxidant enzymes in Nile tilapia treated with Buriganga River water contaminated with pollutants and higher levels of malondialdehyde (MDA), a lipid peroxidation and oxidative damage marker. Interestingly, tissue-specific responses are reflected in gene expression profiles. For instance, Kar *et al.* (2015) identified that immune genes like NKEF-B and MnSOD were upregulated in the skin, suggesting innate immune defense activation; whereas, genes like TNF- α and TLR22 were downregulated in the early phase of infection, suggesting potential immunosuppressive effects. This indicates that immune responses might be stimulatory and suppressive depending on the timing and tissue in question.

Nonetheless, chronic exposure to sewage tends to lead to a downregulation of the innate immune response, most commonly when pollutant concentrations overwhelm the physiological tolerance capacity of the fish. Chronic stress disables immune cell viability and results in chronically elevated cortisol, which inhibits immune gene expression. It has been shown through studies that defense against oxidative stress and protection of cells, such as hsp70, SOD, GPx and metallothionein (MT), are expressed to a very minimal degree in fish from East Kolkata Wetlands, i.e., even when stress signals can be detected, they may not be of the intensity required to initiate complete activation of immunity (Anupama *et al.*, 2017). Moreover, a study by Zahran *et al.* (2021) emphasizes that liver-specific expression of pro-inflammatory cytokines such as IL-8 and TNF- α rises with the level of wastewater pollution, suggesting localized inflammation and a direct correlation between pollutant load and innate immune activation.

6.2. Adaptive Immune Response of Fish in Sewage-Fed Aquaculture Systems

The fish's adaptive immune system, while evolutionarily simpler than in mammals, is functionally robust and is responsible for long-term and antigen-specific responses to environmental pathogens. In sewage-fed aquaculture systems, where fish are chronically exposed to a mixture of stressors, such as heavy metals, organic pollutants and microbial agents, the adaptive immune system is substantially modulated. These changes are also mostly mediated through hormonal signalling pathways (e.g., cortisol), cytokine ratio and mechanisms of gene regulation that promote or inhibit immune effectors. Among the pivotal mechanisms involved in suppressing the adaptive immune response under chronic stress are prolonged HPI axis activation, leading to increased levels of cortisol. Chronic cortisol exposure has a direct detrimental effect on B-cell proliferation, suppresses immunoglobulin M (IgM) gene expression, a critical molecule in humoral immunity and interferes with T-cell-mediated responses (Montero *et al.*, 1999; Varsamos *et al.*, 2005). This immunosuppressive action manifests in the downregulation of cytokines like interleukin-1 β (IL-1 β), interferon-gamma (IFN- γ) and tumour necrosis factor-alpha (TNF- α)-all of which play a key role in the coordination of adaptive immunity (Elenkov and Chrousos, 1999; Kemenade *et al.*, 2009). Rather, anti-inflammatory cytokines such as IL-10 and TGF- β are typically upregulated, which suppresses inflammatory

and cell-mediated responses, directing the immune system to a Th2-predominant state that is conducive to immune tolerance rather than resistance.

Tissue-specific gene expression studies further deepen the knowledge of adaptive responses. For example, Kar *et al.* (2015) noted a divergence of immune gene expression between tissues: whereas the head kidney exhibited repression of various immune-related genes, other tissues such as spleen and liver evidenced upregulation of adaptive immune genes such as IgM and β 2-microglobulin at specific time points post-infection. This spatial and temporal modulation indicates that fish allocate adaptive immune resources as a response to pathogen exposure and environmental stress, potentially setting priorities for defending some organ systems. Effluent composition is also crucial. El-Shafai *et al.* (2013) deduced that septic tank effluent exposure to fish led to upregulation of immune gene expression in the brain and liver, indicating a localized immune challenge. Exposure of fathead minnows to municipal effluent, however, led to downregulation of innate and adaptive immune genes, as predicted by the hypothesis that adaptive responses are very sensitive to concentration and type of pollutant. Probiotic therapy is further augmented through adaptive immunity enhancement. Hou *et al.* (2025) reported that aquaculture supplementation with *Bacillus subtilis* triggered upregulation of the genes IgM and complement component C3 and at the same time downregulation of pro-inflammatory cytokines like TNF- α and IL-1 β , which enhanced immune homeostasis in sewage-stressed fish.

Interestingly, in the East Kolkata Wetlands (EKW) with relatively well controlled levels of contaminants, Anupama *et al.* (2017) observed weak and statistically nonsignificant upregulation of the essential stress-response genes such as hsp70, GPx, SOD and MT showing minimal activation of the adaptive immunity. These results agree with previous research conducted by Chatterjee *et al.* (2007), in which it was ascertained that fish in EKW were not immunologically stressed to a notable degree, implying adaptive immune function is preserved in properly managed sewage-fed systems. In total, the adaptive immune response in sewage-fed aquaculture systems is in context and a balance between stimulation and suppression. Acute or moderate exposure may transiently enhance adaptive immunity, whereas chronic and high-level exposure results in immunosuppression by cytokine shifts, antibody inhibition and B/T-cell dysfunction. The complexity of such responses highlights the need to utilize adaptive immune gene expression profiles as sensitive biomarkers for long-term ecological risk assessment and aquaculture health management.

7. Histopathological Evidence of Organ Damage in Fish from Polluted Waters

Aquatic habitats are increasingly threatened by human activities, by an extensive variety of pollutants released into water bodies. These range from agricultural runoff and industrial effluents to sewage discharge, heavy metals and persistent organic pollutants. These pollutants are

not only endangering the health of aquatic animals and the integrity of aquatic food chains, but the increasing contamination of the water is also harming biodiversity and posing threats to ecosystem services critical to human well-being, including fisheries and drinking water (Venkataraman *et al.*, 2007; Shahid *et al.*, 2022). Among all aquatic animals, fish are particularly renowned as suitable bioindicators of environmental health due to their ecological importance, susceptibility to chemical changes and the ability to accumulate pollutants. Histopathology of fish organs is a useful and sensitive method to estimate sub-lethal impacts of environmental pollutants, typically before any visible disease and death signs occur. In contrast to the physicochemical analysis of water that yields transient momentary snapshots, histological studies reflect the long-term, cumulative and integrated effects of exposures (Shahid *et al.*, 2022). This review outlines the histopathological changes found in fish obtained from contaminated aquatic habitats based on an integration of new and existing studies. Highlighting organ-level injury, most notably in the gills, liver, kidneys and muscles, this effort is meant to illustrate how organ-based pathology is associated with the types and levels of the pollutants. These are biologically important organs as these are critical physiological functions: gills for breathing and osmoregulation, liver for detoxification and metabolism, kidneys for the excretion and ionic homeostasis and the muscle tissue as an energy reservoir and site of nutritional and functional integrity (Saxena and Saxena, 2008; Shahid *et al.*, 2022). A study conducted by Sultana *et al.* (2016) also recorded histopathological changes in gills, liver and intestine tissue of *Labeo rohita*, which are induced by industrial waste-contaminated water of River Ravi, Pakistan.

Fish gills are multifunctional, highly specialized organs that are involved in functions beyond the exchange of gas, such as osmoregulation and acid-base balance and the elimination of nitrogenous wastes. The gills are made up of gill filaments covered with lamellae, which are thin, vascular lamellae that enhance the surface area for optimal oxygen and carbon dioxide diffusion. The gills are, however, prone to extensive histopathological impairment with the exposure to toxins such as heavy metals (cadmium, lead, chromium and mercury). The notable effects include lamellar fusion, hyperplasia and the occurrence of oedema, which all impair respiratory performance. Fusion of lamellae is an adaptive mechanism to minimize the surface area of gills to restrict the absorption of toxins while incurring an oxygen intake cost. Hyperplasia, which results in thickening of the gill epithelium, also hinders gas exchange. Oedema is a build-up of fluid between the connective tissue, marking an increase in vascular permeability and is the most frequent toxicant effect on the gills, especially among fish exposed to polluted freshwater bodies like river regions impacted by industrial or agricultural effluents (Shahid *et al.*, 2022). Attendant injury to the gills depresses respiratory efficiency to induce hypoxia, which is accompanied by behavioural alterations such as lethargy and surface gulping. Moreover, metal ions interfere with the regulation of ions and acid-base balance, further compromising the general well-being and immune

defence of the fish. Kaur and Dua (2015) studied the gill morphological alterations in *Channa punctatus* exposed to Tung Dhab drain wastewater at various concentrations for 15 and 30 days. The results described numerous circulatory deficiencies, including epithelial lifting, intraepithelial oedema, haemorrhages and hyperemia at the principal lamellae and breaking of the pillar cell system and aneurysms at the secondary lamellae. Furthermore, they noted regressive changes like necrosis, loss and damage to the secondary lamellae, cartilage breakdown in the primary lamellae and diminishment of both the mean length of the primary and secondary lamellae. Progressive changes were also observed, such as the merging of secondary lamellae between primary lamellae, hypertrophy and hyperplasia of gill lamellae resulting in total merging, bending of lamellae, balloon-like dilations within secondary lamellae and enhanced proliferation of chloride and mucous cells at the base of secondary lamellae.

The liver is an essential organ involved in detoxification and metabolism in fish and is one of the primary heavy metal storage areas. The structural modifications of the liver as a result of exposure to pollutants consist of vacuolization of hepatocytes, cytoplasmic degeneration and necrosis, all reflecting the compromised detoxification function of the liver (Saxena and Saxena, 2008). Vacuolization is often the first detectable sign of injury, representing disturbances in metabolism and excessive toxicity results in degeneration of hepatocytes, karyolysis and focal necrosis, which are the signs of acute or chronic toxicity. Such liver pathologies inhibit the function of the liver and excessive conditions may affect the reproductive function by disrupting the process of vitellogenin synthesis in females. Histopathological markers such as nucleus pyknosis, loss of cell membrane boundaries and the presence of infiltrative inflammation can act as markers of toxic effects of metals (Shahid *et al.*, 2022). Oxidative stress produced by heavy metals can also induce lipid peroxidation, which injures the membranes of the liver and impairs cell function, including mitochondrial and endoplasmic reticulum dysfunction.

The kidney is yet another organ very susceptible to environmental pollutants, such as heavy metals cadmium and mercury, which induce tubular degeneration, glomerular injury and inflammation of the interstitium (Venkataraman *et al.*, 2007). These histopathological alterations impair osmoregulation and excretion of waste products, resulting in fluid imbalance and compromised renal function. Tubular dilation and degeneration indicate disturbance in the production of the urine and the electrolyte balance and glomerular atrophy or necrosis compromises the glomerular function. Chronic contamination may cause irreversible renal damage, nephron loss and intra-renal haemorrhaging, extensively affecting the overall health and growth of the fish. Kidney histopathology plays a central role in ecotoxicological bioassays to detect the health of the water and assess sub-lethal toxicities.

8. Bacterial Load of Fish in Sewage-Fed Aquaculture

Microbial safety in aquaculture systems that use sewage as

a source of nutrients remains a serious concern due to the direct impact it has on the microbial content of fish in the systems. It has been observed that the microbial population in pond water tends to mirror the microbial content in the fish tissues and may affect their safety for human consumption. Exposure to sewage has long been identified as a major driver of gut microbial dysbiosis and elevated microbial load in fish. Kakakhel *et al.* (2023) noted that newly emerging aquatic pollutants that are frequent in treated as well as untreated sewage, such as heavy metals, nanoparticles, medicines and microplastics, have the potential to impact significantly the gut microbiota of many fish. In addition, more elevated levels of heterotrophic aerobic bacteria in pond water and more so elevated levels of over 10^4 Colony-Forming Units (CFU) per mL, can help promote invasion of disease-causing microorganisms into the muscle tissues of fish, hence a health threat to consumers (Mara *et al.*, 1989). For the assessment of microbial wastewater quality in aquaculture, traditional faecal contamination markers such as enterococci and total coliforms are typically used. The markers are a good indication of the hygienic nature of the water as well as the probability of the presence of the pathogen. Based on recommendations by the World Health Organisation (WHO, 2006), faecal coliform numbers in water used in aquaculture must not exceed 10^3 CFU per 100 millilitres to provide negligible risks to health. Studies in temperate climate zones, more so in fish farmed in ponds supplied on a regular basis only with treated sewage activated sludge, have found high levels of microbial contamination in fish tissues. These comprised total viable bacteria, coliforms, faecal coliforms and *Streptococcus faecalis*, showing a high microbial load involved in the practice (Niewolak and Tucholski, 2000). Surprisingly, a study found that post-harvest handling activities, like putting fish in clean water for depuration, were very effective in reducing fish tissue microbial loads in a relatively short time, underlining the need for post-harvest management to enhance fish quality and safety. These results emphasize the important need for frequent microbial monitoring within sewage-fed aquaculture systems and in fish tissues and highlight the significance of adopting proper post-harvest sanitation protocols to counter potential threats to human health posed by microbial contamination.

Sewage-based aquaculture ponds in the East Kolkata Wetlands use domestic wastewater to facilitate primary production and fish growth in a cost-effective and nutrient-dense medium. Domestic wastewater in these systems also poses food safety risks when it transfers microbial contaminants to the fish. Balasubramanian *et al.* (1992) performed a seminal work evaluating the fish cultured in sewage ponds in terms of their microbial quality and the role played by microbial colonization. Their analysis determined that the total viable bacterial count in the gut contents of fish reared in sewage-fed systems varied between 10^5 and 10^7 colony-forming units (CFU) per gram. The most common bacterial flora found were species of *Aeromonas*, *Pseudomonas*, *Proteus*, *Escherichia coli*, *Enterobacter* and *Staphylococcus*. The occurrence of *E. coli* and other coliforms in high numbers was an indicator of faecal contamination,

Table 3: Fish microbiota dynamics in sewage-fed aquaculture systems, based on the findings of Kakakhel *et al.* (2023)

Parameter	Observation in sewage exposure	Implication
Total plate count (TPC)	Increase in TPC significantly.	Shows the growth of microbial populations.
Microbial density	Increased.	Increased microbial load in the gut.
Community structure	Direction of opportunistic/ pathogenic taxa.	Dominance by <i>Aeromonas</i> , <i>Pseudomonas</i> , <i>Enterobacter</i> .
Beneficial microbes	Decrease in <i>Lactobacillus</i> , <i>Bifidobacterium</i> .	Decreased gut health and immune defence.
Microbial richness and diversity	Reduced.	Compromised gut microbiome functionality and gut resilience.
Enzyme activity	Decreased.	Linked to defective digestion and nutrient processing.
Hematological profile	Abnormal.	Associated with physiological impairment and enhanced disease susceptibility.
Pollutant type and impact	Nanoparticles (AgNPs), heavy metals (Cd) decrease diversity, elevate pathogens.	Contaminant-specific microbiota responses.
Health implications	Inflammation, oxidative stress, impairment of metabolism and death.	Long-term negative consequences.

which is of primary concern in wastewater-fed aquaculture systems. In addition, the study showed that fish gill and skin surfaces contained considerable microbial loads, but these tended to be lower on average than the gut loads. Interestingly, the authors reported that despite the high bacterial loads, the fish themselves were healthy and suggested there was some adaptation or resistance to the microbial environment. Nonetheless, the risk to human health if the fish is eaten raw or undercooked remains a consideration. Balasubramanian *et al.* (1992) highlighted the requirement for post-harvest treatments using depuration (storage of fish in clean water) and cooking to minimize risks from microorganisms. Their results provide a basis for understanding microbial activities in sewage-fed aquaculture

and highlight the significance of microbiological surveillance and hygienic handling in these systems.

Bacterial detection in aquaculture is based on both culture-based and molecular approaches. Conventional methods include phenotypic identification and biochemical analysis (Buller, 2022; Duman *et al.*, 2022). Molecular techniques are, however, increasing in use because of their efficiency and rapidity. Some of these are 16S rRNA sequencing, PCR-dependent techniques such as AFLP, FISH, RAPD and RFLP (Chatterjee and Haldar, 2012). The detection of fish pathogens is challenging because of their psychrophilic nature and they have to be grown on specific media with reduced incubation temperatures (Duman *et al.*, 2022). Correct detection mostly involves a combination of phenotypic and genotypic methods. The routine application of antibiotics in aquaculture has increased antibiotic resistance, resulting in the search for other alternative biocontrol approaches for the control of bacterial diseases in a sustainable manner (Defoirdt *et al.*, 2011).

8.1. Pathogenic Bacteria in Sewage-Fed Fish

Pathogenicity and survivability tests are important in aquaculture research to evaluate the bacterial virulence and its effect on fish health. Environmental conditions such as temperature, pH and the level of ammonia greatly affect the virulence of pathogens like *Aeromonas hydrophila* (Abdella *et al.*, 2024). Some bacterial species like *Vibrio* spp., *Photobacterium damsela* and *Aeromonas salmonicida* have varying levels of pathogenicity in fish, with *A. salmonicida* with isolate-specific virulence (Bowden *et al.*, 2018). Mechanisms of bacterial adhesion and host-pathogen interactions are critical in disease development (Hamed *et al.*, 2018). Toxins and other virulence determinants, including adhesins, capsular polysaccharides and lipopolysaccharides, are essential in bacterial pathogenesis and host immune response (Sarkar *et al.*, 2021). Knowledge of these factors is critical to designing effective disease prevention and control strategies in aquaculture, towards integrating the pathogen, host and environment (Hamed *et al.*, 2018).

9. Antimicrobial Resistance in Sewage-fed Aquaculture Systems

Antimicrobial resistance (AMR) is when the microorganisms (bacteria, viruses, fungi or parasites) adapt and become resistant to the medications (e.g., antibiotics, antivirals or antifungals) used to kill or stop their growth. This resistance renders the usual treatments useless, heightening the threat of ongoing infections, severe disease and transmission of diseases (WHO, 2021). AMR is becoming a global public health issue in aquaculture because of the widespread and largely uncontrolled application of antibiotics in fish and shellfish culture. In most developing and Asian nations with poor regulatory control, excessive use of antimicrobials has been associated with the frequent appearance of resistant bacterial strains like *Aeromonas*, *Vibrio* and *Escherichia coli* from aquatic animals. Resistance to critically valuable antibiotics such as tetracyclines, sulfonamides and quinolones has frequently been reported and some areas report it as “frequent” or “almost always” within

certain bacterial populations. International aquaculture product trade, such as shrimp and fish, complicates the likelihood of cross-border transmission of resistant bacteria. This is exacerbated by the absence of coordinated global monitoring systems in, particularly, lower-income countries and the difficulty of properly assessing the extent of the issue or taking effective action. Since the World Health Organization has also listed many of the antibiotics applied in aquaculture as critically important in human medicine, the occurrence of AMR in aquaculture systems has profound consequences for both aquatic animal and human health. There is thus a critical need to enhance surveillance systems, ensure responsible antibiotic stewardship and develop extensive regulatory policies to regulate the amplification of AMR in aquaculture ecosystems throughout the world (Preena *et al.* 2020; Caputo *et al.* 2022; Hossain *et al.* 2022). The same trends have followed in India, which is among the top freshwater fish-producing nations in the world. Repetitive employment of antibiotics, including oxytetracycline, enrofloxacin, sulfonamides and florfenicol in the case of species such as carp and tilapia, under sometimes inadequate veterinary management, has favoured the growth of multidrug-resistant strains of the pathogens, including *Aeromonas*, *Edwardsiella* and *Vibrio* (Preena *et al.*, 2020). The aforementioned concerns are being magnified due to low farmers’ awareness, a lack of diagnostic centres and lack of aquaculture-targeted surveillance. While India has identified AMR as a priority through its National Action Plan, aquaculture is still underrepresented in AMR governance structures. As a result, there is a pressing need to establish aquaculture-specific guidelines and adopt monitoring measures to counter the threat of AMR risks in India within an overarching One Health framework (Caputo *et al.*, 2022).

Antimicrobial resistance (AMR) in the aquaculture system is an issue due to the extensive use of antibiotics for disease prevention and treatment of infected fish in aquaculture. Aquatic environmental bacteria can pick up the resistance genes from the antibiotics during the extended exposure of aquatic organisms to antibiotics (Nallaiah *et al.*, 2022). This is a critical risk to human health, since the aquatic ecosystem can be a reservoir of resistant bacteria (Milijasevic *et al.*, 2024). Fascinatingly, the aquaculture system is also a “genetic hotspot” for gene transfer, with high bacterial populations of diverse species and previous and ongoing use of antibiotics, probiotics and other treatment protocols. This provides an optimal environment for the generation of AMR. However, it should be noted that in certain areas, including Asia, there has been a reduction in the proportion of antimicrobial substances with resistance higher than 50% in aquaculture from 52% to 22% over two decades (Milijasevic *et al.*, 2024). To meet this challenge, a One Health approach is paramount, acknowledging human, animal and environmental interconnection (Milijasevic *et al.*, 2024). Some of the strategies to minimize AMR in aquaculture are the practice of strict antimicrobial use regulations, encouraging alternatives to disease management such as more stringent biosecurity practices and immunization and

the use of alternatives to antibiotics such as phage therapy, prebiotics and probiotics (Lubis *et al.*, 2024; Milijasevic *et al.*, 2024). Ongoing surveillance programs, early detection of resistant pathogens and the use of high-throughput genomic technologies for metagenomic surveillance are required to prevent the spread of AMR in aquaculture systems (Preena *et al.*, 2020; Nallaiah *et al.*, 2022).

East Kolkata Wetlands (EKW), which is a Ramsar-protected area, constitutes one of the world's biggest integrated sewage-fed aquaculture systems. This model may be economically and environmentally sustainable on a theoretical level, but currently stands as a source of hotspot for antimicrobial resistance (AMR) as it experiences heavy inflow of sewage, inefficient regulation of drugs and heavy fish farming. Some of the most recent studies have revealed multidrug-resistant (MDR) bacteria, like *Escherichia coli*, *Pseudomonas aeruginosa*, *Vibrio* spp. and *Aeromonas* spp., in fish species raised in EKW directly. Not only are these bacteria harmful to fish production and health, but they also hold zoonotic significance for human health via the handling and consumption of fish. A comprehensive study by Sanyal and Banerjee (2013) investigated the prevalence and pattern of antibiotic resistance among thermotolerant faecal coliforms from three major aquaculture species *Labeo rohita*, *Cirrhinus mrigala* and *Oreochromis niloticus*, raised in sewage-fed ponds. The bacteriological tests showed there was a high percentage of isolates from pond water and fish tissues that were resistant to ampicillin, chloramphenicol and tetracycline, *Cirrhinus mrigala* being partially an exception for tetracycline resistance. However, resistance to kanamycin, streptomycin and co-trimoxazole occurred less often and was largely species-dependent (e.g., some kanamycin resistance in *Oreochromis*). Most strikingly, all isolates were still sensitive to gentamicin and amikacin, indicating that these antibiotics remain unchallenged in this environment. Most notably, ampicillin resistance was the most common and was single or exclusive; whereas, resistance to other antibiotics was typically linked with multidrug resistance (MDR) patterns, predominantly with co-resistance to ampicillin and tetracycline. They highlight the selective pressure of sewage pollution and illustrate the potential for transmissible resistance traits in aquatic microbial communities.

Technological Innovations

Sewage-fed aquaculture systems are confronted with several common challenges and the development of technological innovations is essential to improve efficiency, sustainability and safety. New technologies for wastewater treatment, such as membrane bioreactors (Figure 4), constructed wetlands and biofiltration systems, have improved the quality of wastewater used in aquaculture (Zhang *et al.*, 2022; Chao *et al.*, 2025). These techniques extract contaminants such as pathogens, heavy metals and organic pollutants from water, making it safe for fish and consumers.

It has, in turn, revolutionised the field by combining aquaponics with sewage-fed aquaculture. Aquaponics is the process of growing plants using fish waste as a nutrient



Figure 4: Membrane bioreactors used in wastewater treatment

(Rana *et al.*, 2011; Stoyanova *et al.*, 2024). This allows a symbiotic relationship and efficient use of resources without any residue. The combination of fish farming with closed-loop plant cultivation reduces waste and increases overall productivity. The monitoring and automation tools developed have also greatly improved the management of sewage-fed aquaculture systems. Advanced sensors and IoT technologies that monitor water quality, fish health and nutrient levels in real time are currently used. Real-time, precise data improve management decisions (Shete *et al.*, 2025). Automation tools, including automated feeding systems and water filtration controls, make aquaculture system operations smoother, less dependent on manual intervention and allow for better use of resources (Maharmi *et al.*, 2025). This makes the technology used in sewage-fed aquaculture more efficient, sustainable and economically viable and ensures the safety and quality of the fish and plants produced (Flores-Iwasaki *et al.*, 2025).

Policy and Governance

Effective policy and governance are most critical to the success and sustainability of sewage-fed aquaculture systems (Li *et al.*, 2026). Current policies and regulations regarding the use of wastewater in aquaculture vary with region; many countries lack clear guidelines or a full-fledged framework for wastewater management, water quality standards or the use of sewage in food production (Shoushtarian and Negahban-Azar, 2020). In some cases, regulations exist, but enforcement is not rigorous, resulting in inconsistent water quality and food safety. Government and NGOs play a role in establishing and enforcing regulations, raising financial support and technical requirements and promoting research and innovation in sustainable wastewater management. Governments can make the uptake of sewage-fed aquaculture easier by providing subsidies or grants to farmers for the adoption of advanced treatment technologies, while NGOs can contribute in many ways through sensitisation, capacity building and better governance. This entails policy recommendations: the creation of clear, standardised regulations for wastewater treatment and reuse in aquaculture and strong mechanisms

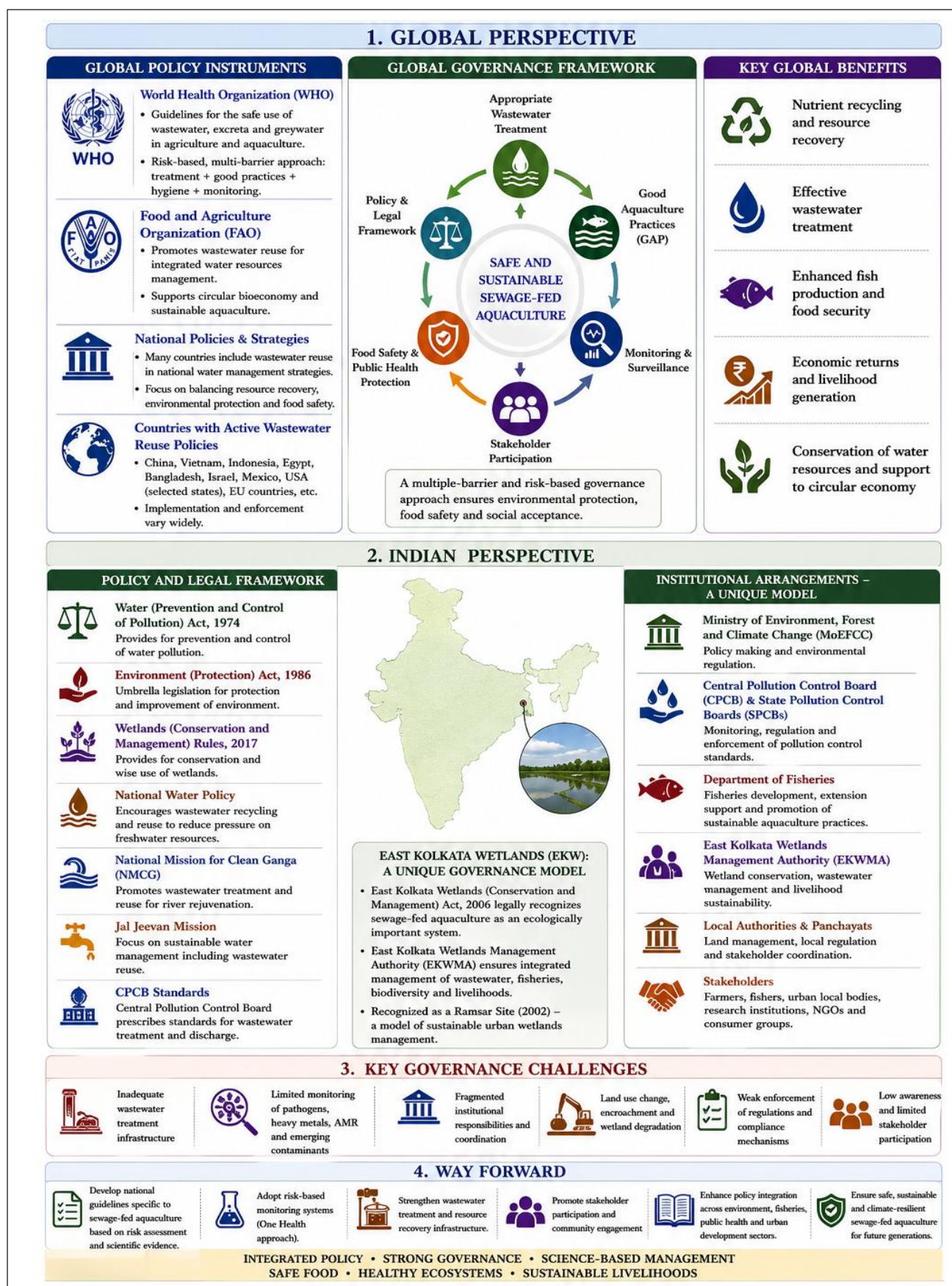


Figure 5: Policy and governance for sewage-fed aquaculture: Global and Indian perspectives

to enforce compliance with water standards. This, therefore, demands that the policymaker provide a supporting framework to promote study and innovation, ease access to finance for small-scale farmers and promote partnerships between governments, NGOs and the private sector to boost growth in sustainable sewage-fed aquaculture systems. Better policy regimes could then overcome most challenges and unlock the full potential of sewage-fed aquaculture in the manufacture of food, alleviation of and management of wastewater.

In India, policies and laws on sewage-fed aquaculture are not integrated but are dispersed in different environmental, agricultural and water management laws (Schellenberg *et al.*, 2020). Wastewater management, including treatment and discharge into aquatic systems, is regulated by bodies such as the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs). These agencies set guidelines for the treatment of wastewater and, in the case of specific pollutants, for example, limits on biological oxygen demand (BOD) and chemical oxygen demand (COD). No specific legislation for sewage-fed aquaculture has been established, but regulation does fall under a broader set of environmental laws under the Water (Prevention and Control of Pollution) Act, 1974 and the Environment Protection Act, 1986, in India. Both acts deal more with the control of water pollution and require industries, including aquaculture, to treat water before discharging it into a natural watercourse. Furthermore, although the National Aquaculture Development Policy includes provisions for sustainable aquaculture, it makes no reference to sewage-fed aquaculture. The food safety guidelines published by the FSSAI address food safety, thereby indirectly affecting the production of safe fish through wastewater-fed systems by maintaining monitoring of contaminants in food products. Although there are regulatory controls, no clear, enforceable standards for wastewater reuse are defined for aquaculture; thus, their implementation is largely uneven (Breitenmoser *et al.*, 2022).

Opportunities and Future Prospects

Sewage-fed aquaculture offers great opportunities and prospects for scaling, environmental impact and worldwide integration. Their scalability and commercial opportunities stem from their ability to adapt to a wide range of scenarios, from small-scale community-driven projects to large, commercially feasible operations. With advances in wastewater treatment technologies and increased interest in sustainable aquaculture, these systems will offer high-value products, such as fish and aquatic plants, while addressing urban wastewater management challenges. In addition, modern practices such as aquaponics and biofloc technology enhance productivity, making them more attractive for investment and large-scale application (Edwards, 2005).

Climate change mitigation is another crucial opportunity. By recovering nutrients and organic matter from wastewater, thereby avoiding synthetic fertilisers and the greenhouse gases associated with them during waste management, sewage-fed aquaculture contributes to the circular economy

(Kurniawan *et al.*, 2025). Furthermore, wetland-based systems advocate for aid in carbon sequestration and the minimisation of methane generation from unattended wastewater and such practices serve global climate change initiatives. This means that the adoption of sewage-fed aquaculture in urban and peri-urban areas will also reduce the ecological footprint of food production.

International co-operation and knowledge sharing can also accelerate the development process of sewage-fed aquaculture. Collaboration among various governments, research centers and NGO's can help in sharing expertise, technologies and policies which can be used for implementing such a project (Naylor *et al.*, 2023). For example, joint research can help develop standards for waste treatment and more efficient monitoring methods and the global network of such projects can provide training and capacity building for farmers involved in the process. Countries like India, China and Australia, which have adopted sewage-fed aquaculture should be learnt from to achieve maximum benefit. More research and technology will make aquaculture on a sewage diet an important part of the world's sustainable food chain.

Conclusion

Aquaculture based on sewage is a revolutionary method to produce environment friendly and resource efficient food in line with the objectives of environmental conservation and food security. The use of treated or untreated wastewater in the system for culturing fish shows the application of circular economy concepts that give innovative ideas on how to manage wastes in urban area. Sewage-fed aquaculture offers opportunities such as waste recycling, socioeconomic development and environmental revitalization whereas challenges include public health implications, environmental pollution and social considerations. The optimal exploitation of sewage-fed aquaculture technology requires a heavy investment in waste water purification, efficient monitoring processes and sound governance approaches that are able to ensure the production of healthy foods and environmental sustainability. Some of the measures required to overcome barriers within this sector involve research and innovation, international cooperation and knowledge sharing. Social involvement and public education initiatives represent some of the key areas that would ensure success of the project in the long run. To conclude, sewage-fed aquaculture presents a unique chance of achieving sustainable economic development and ecological sustainability at the same time. Targeted intervention programs aimed at managing risks associated with this technology and exploitation of its potential can ensure its success.

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Ethical Statement

The authors declare that no generative artificial intelligence tools were used in drafting or preparing this manuscript. The manuscript was written, interpreted and revised solely by the authors, who take full responsibility for its content.

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