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Bioaccumulation and Bioremediation of Arsenic in Fish: A Review

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ABSTRACT:
Arsenic contamination in aquatic ecosystems poses significant risks to fish health, aquatic biodiversity and human consumers through bioaccumulation and biomagnification. This review comprehensively examines the mechanisms by which arsenic accumulates in various fish tissues, the toxicological impacts on fish physiology and behaviour and the current analytical methods employed for arsenic detection and speciation. Moreover, the paper highlights emerging bioremediation strategies utilizing microbes, plants and innovative technologies to mitigate arsenic toxicity and reduce its bioaccumulation in fish. The review emphasizes the ecological and human health implications of arsenic contamination, discusses regulatory standards and identifies critical research gaps. The objective is to provide a consolidated understanding of arsenic bioaccumulation dynamics and effective bioremediation approaches to inform sustainable management of contaminated aquatic environments. The findings underscore the urgent need for integrated remediation techniques and stricter monitoring to protect aquatic life and public health.

Keywords:
Arsenic Bioaccumulation, Fish Toxicity, Arsenic Speciation, Bioremediation, Aquatic Pollution, Microbial Remediation, Phytoremediation, Environmental Toxicology, Aquaculture Safety.

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INTRODUCTION

Background on arsenic contamination in aquatic environments

Arsenic (As), a naturally occurring metalloid, is ubiquitously present in the Earth's crust and is released into aquatic environments through both natural processes such as volcanic activity and weathering of arsenic-rich rocks and anthropogenic activities including mining, industrial discharge, pesticide use and improper waste disposal (Nriagu, 2021). The atomic number of arsenic is 33, atomic weight is 74.92, symbol is As and it has been placed in group V of the periodic table. International Agency for Research on Cancer (IARC) has placed it among the Group I carcinogen of humans (Straif *et al.*, 2009). In recent decades, arsenic contamination in freshwater and marine systems has emerged as a critical environmental issue, particularly in South Asia and other arsenic- prone regions due to groundwater irrigation and effluent discharges (Kumar *et al.*, 2023). Arsenic is highly toxic even at trace concentrations and exists in both organic and inorganic forms, with inorganic and organic arsenic species (Wang *et* *al*., 2022). Arsenic on combination with chlorine, sulphur and oxygen forms inorganic arsenic forms which include oxidized As^{5+} (pentavalent arsenate) and reduced As^{3+} (trivalent arsenite) while on combination with hydrogen and carbon lead to the formation of organic forms (Hirano *et al*., 2003). Prolonged exposure to arsenic can lead to severe health effects in both aquatic organisms and humans, including genotoxicity, carcinogenicity, endocrine disruption and neurotoxicity (Ahmed *et al*., 2024). The persistence and bioavailability of arsenic make it a priority pollutant as classified by several environmental agencies, including the World Health Organization (WHO, 2022). Fish are widely used as bioindicators for aquatic pollution due to their ability to accumulate contaminants through water, food and sediment interaction (Zhou *et al*., 2023). The bioaccumulation of arsenic in fish tissues, particularly in edible parts such as muscle and liver, raises serious concerns for ecological health and food safety. Understanding the pathways and factors influencing arsenic uptake and retention in fish is essential for risk assessment and policymaking (Chen *et al*., 2023). Moreover, biomagnification of arsenic through the food chain further amplifies its ecological and human health risks. Bioremediation offers a promising, eco-friendly approach to mitigate arsenic contamination by employing living organisms such as bacteria, fungi, algae and aquatic plants to detoxify or immobilize arsenic in aquatic systems (Mitra and Bhattacharya, 2022). Recent advancements in molecular biology and environmental biotechnology have enabled the identification of arsenic- resistant microbial strains and genetically engineered species capable of transforming toxic arsenic into less harmful forms (Ghosh *et al*., 2023). In addition, phytoremediation using macrophytes like *Eichhornia crassipes* and *Lemna minor* has shown considerable potential in reducing arsenic levels in water bodies (Zhang *et al*., 2022).

Aim and objectives of the review

This review aims to synthesize recent findings on the bioaccumulation mechanisms of arsenic in fish and to evaluate current and emerging bioremediation strategies for arsenic detoxification in aquatic environments. The specific objectives are:

- To elucidate the sources, speciation and environmental behaviour of arsenic in aquatic systems.
- To describe the uptake, distribution and toxicological effects of arsenic in fish species.
- To review the analytical techniques used for arsenic detection and speciation in aquatic organisms.
- To analyse recent developments in microbial, phytoremediation and nanotechnology-based bioremediation techniques.
- To identify knowledge gaps and propose future research directions for sustainable arsenic mitigation in aquaculture and aquatic ecosystems.

SOURCES AND FORMS OF ARSENIC IN AQUATIC SYSTEMS

Natural and anthropogenic sources of arsenic

Arsenic is introduced into aquatic ecosystems through both natural geological processes and anthropogenic activities. Naturally, arsenic is released into water bodies through the weathering of arsenic- bearing minerals, volcanic emissions and geothermal activities (Shakoor *et al*., 2023). In regions such as the Ganges- Brahmaputra delta, high arsenic concentrations in groundwater have been linked to natural geochemical processes like reductive dissolution of iron oxides (Dutta *et al*., 2022). Anthropogenic sources have intensified arsenic contamination globally. These include mining and smelting operations, industrial effluents, use of arsenic- based pesticides and herbicides, coal combustion and improper disposal of arsenic-laden waste (Ali *et al*., 2023). Irrigation with arsenic-contaminated groundwater in agriculture further exacerbates the arsenic load in adjacent freshwater ecosystems (Dey *et al*., 2024).

Worldwide arsenic concentration in some aquatic system

Aquatic system with location	Arsenic concentration	References
Moira lake, Canada	62 μg/l in summer and 22 μg/l in winter	Jose *et al.*, 1995
Handle lake, Canada	170	Palmer *et al.*, 2019
Long lake, Canada	35	Palmer *et al.*, 2019
Thompson lake, New Zealand	5	Moore, 1981
Bowron lake,	0.2	Azcue *et al.*, 1995
Great lakes, USA	0.55	Rossmann and Barres, 1988
Pyramid lake, USA	99.64	Hamilton-Galat and Galat, 1983
Manchar lake, Pakistan	97.5	McCleskey *et al.*, 2002
Mono lake, USA	10,000 – 20,000	Maest *et al.*, 1992
Lkae Biwa, Japan	2.2	Hasegawa *et al.*, 2010
Walker lake, USA	117.63	Hamilton-Galat and Galat, 1983
Rewalsar lake, India	10-110	Kashyap *et al.*, 2015
Saline lake, Central Tibet Plateau	1.80-10,775.40	Xiong *et al.*, 2020
River Ganga, India	4730	Chakraborti *et al.*, 2018
Tinto river, Spain	600 (As^{III}); 200 (As^{V})	Daniel *et al.*, 2005
Odiel river, Spain	100 (As^{V})	Daniel *et al.*, 2005
Mekong river, Cambodia and Vietnam	39- 217	Berg *et al.*, 2007
Red river, Vietnam	159	Berg *et al.*, 2007
Peral river, China	300	Luo, 2021
Fox river, USA	1-3100	Knoblech *et al.*, 2006
Po river, Italy	1.3	Pettine *et al.*, 1997
Oghji river, Armenia	0.938	Gabrielyan *et al.*, 2018
Jinzhou bay, China	2.19	Wang *et al.*, 2012
Patuxtent river, USA	0.2(January)-1(July)	Riedel, 1993
River water, Peru	0.1-93.1	George and Gqaza, 2015
Nile Delta, Egypt	1.2-18.2	Abdel-Moati , 1990
Lao river, Chile	21,000	Cáceres *et al.*, 1992
Willow river, Canada	0.6	Azcue *et al.*, 1995

Different chemical forms of arsenic

Understanding the chemical form of arsenic is critical, as its toxicity, mobility, bioavailability and remediation efficiency depend significantly on its speciation (Wang and Tang, 2024). Arsenic exists in the environment in several oxidation states and forms, mainly categorized into inorganic and organic species. It exists mainly in four oxidation states- arsenic (As^{0}), arsenite (As^{III}), Arsenate (As^{V}) and arsine (As^{-III}). Inorganic arsenic, which includes arsenite (As^{III}) and arsenate (As^{V}) is the most toxic and predominant form in contaminated water bodies. Arsenite (As^{III}) is more mobile, soluble and toxic compared to arsenate (As^{V}) (Kumar *et al.*, 2023). Arsenite (As^{III}) typically dominates under reducing conditions, whereas arsenate (As^{V}) prevails in oxidizing environments. Organic arsenicals, such as monomethylarsonic acid (MMA) and dimethylarsenic acid (DMA), are often byproducts of microbial methylation processes. These forms are generally considered less toxic and occur primarily in biota and sediments (Zhou *et al.*, 2023). The speciation of arsenic in aquatic systems is influenced by pH, redox potential (Eh), dissolved oxygen, microbial activity, temperature and the presence of competing ions such as phosphate and sulphate (Chen *et al.*, 2023). In oxygen-rich waters, arsenate (As^{V}) is more stable, while arsenite (As^{III}) is prevalent in anoxic sediments and groundwater. Arsenic can undergo adsorption- desorption, precipitation-dissolution and redox transformations, often mediated by microbial communities and mineral surfaces (Rao *et al*., 2023). Microbial oxidation and reduction play a vital role in controlling arsenic mobility, converting arsenite to arsenate or vice versa, depending on environmental conditions. Microbes also affect arsenic mobility and speciation through oxidation and reduction reactions as part of resistance and respiratory processes (Stolz *et al*., 2006). Arsenic may also complex with dissolved organic matter, iron, manganese oxides or clay particles, impacting its transport and availability to aquatic organisms (Liu *et al*., 2024). Such dynamic behaviour makes arsenic remediation complex, requiring site-specific strategies based on local chemical speciation and hydrological characteristics.

MECHANISMS OF ARSENIC BIOACCUMULATION IN FISH

Uptake routes: Gills, gastrointestinal tract and skin

Fish can absorb arsenic through multiple physiological pathways, primarily via gill membranes, the gastrointestinal (GI) tract and to a lesser extent, the skin. The gills serve as the primary site for direct uptake from water due to their large surface area and rich vascularization, facilitating rapid diffusion of soluble arsenic species, especially arsenite (As^{III}) (Ranjan *et al*., 2023). The gastrointestinal tract becomes the main route of exposure when fish ingest contaminated food or sediment. Organic arsenic compounds are often absorbed through this route and subsequently transformed within the liver (Gupta *et al*., 2023). The skin also acts as a secondary uptake route, particularly in benthic fish species that dwell in arsenic-rich sediments (Han *et al*., 2022). Arsenic bioaccumulation is influenced by several biotic and abiotic factors. Species- specific differences in physiology and feeding habits significantly affect arsenic uptake. Age and size also play a role, with juvenile fish often showing higher accumulation due to higher metabolic rates and surface-to-volume ratios (Zhou *et al*., 2023). Water chemistry, including pH, salinity, hardness and the presence of competing ions (e.g., phosphate), can affect arsenic solubility and bioavailability (Kumar *et al*., 2024).

Arsenic metabolism and biotransformation in fish

Arsenic after uptake undergoes biotransformation in fish, predominantly in the liver. The inorganic forms (As^{III} and As^{V}) may be converted into organic forms, such as monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA), through methylation pathways facilitated by arsenic methyltransferase enzymes (Chen *et al*., 2023). This process helps reduce toxicity, although in some cases intermediate metabolites can be more toxic than the parent compounds. Fish exhibit interspecies variation in their methylation efficiency, which influences overall arsenic retention and excretion (Liu *et al*., 2023). Detoxification can also involve sequestration in lysosomes or binding with metallothionein and glutathione complexes.

Tissue distribution of arsenic in fish

Arsenic distributes unevenly across fish tissues. Liver and kidney generally show the highest concentrations due to their role in detoxification and excretion. Gills accumulate arsenic directly from water and serve as early indicators of exposure, while muscle tissues, though less concentrated, are critical from a human health risk perspective due to their consumption (Rahman *et al*., 2023). A recent study on *Oreochromis niloticus* found the tissue accumulation pattern as liver > kidney > gills > muscle, consistent with previous findings (Ahmed *et al*., 2023).

List of arsenic speciation

Name of arsenic species	Formula	Abbreviation	References
Arsenite	$As(OH)_3$	As^{III}	Sadee *et al.*, 2015
Arsenate	$AsO(OH)_3$	As^{V}	Sadee *et al.*, 2015
Mononmethylarsonic acid	$CH_3AsO(OH)_2$	MMA^{V}	Sadee *et al.*, 2015
Dimetylarsinic acid	$(CH_3)_2AsO(OH)$	DMA^{V}	Sadee *et al.*, 2015
Trimethylarsine oxide	$(CH_3)_3AsO$	$TMAO[As^{V}]$	Sadee *et al.*, 2015
Monomethylmonothioarsonic acid	$AsS(OH)_2CH_3$	$MMMTA^{V}$	Sun *et al.*, 2016
Dimethylmonothioarsinic acid	$AsSOH(CH_3)_2$	$DMMTA^{V}$	Sun *et al.*, 2016
Arsenocholine	$(CH_3)_3As^+CH_2CH_2O$	-	Norin *et al.*, 1983
Sulfate arsenosugar	$C_{10}H_{19}AsO_9SO^-$	-	Luvonga *et al.*, 2020
Phosphate arsenosugar	$C_{13}H_{26}AsO_{11}P$	-	Luvonga *et al.*, 2020
Glycerol arsenosugar	$C_{10}H_{21}AsO_7$	-	Luvonga *et al.*, 2020
Arsenosugar phospholipids	$C45H_{88}AsO_{14}P$	-	Glabonjat *et al.*, 2021

Bioaccumulation vs biomagnification

Bioaccumulation refers to the buildup of arsenic within an organism over time from water and diet, whereas biomagnification is the increase in concentration of arsenic as it moves up the trophic levels of the food chain (Ghosh *et al.*, 2022). While inorganic arsenic typically does not bio magnify significantly, some methylated and lipid-soluble organic arsenic compounds can increase in concentration in higher trophic fish, especially in closed ecosystems (Singh and Mehta, 2024). Understanding the distinction between these two processes is crucial for assessing ecological and human health risks.

TOXICOLOGICAL EFFECTS OF ARSENIC ON FISH

Acute and chronic toxicity symptoms

Arsenic exposure results in both acute and chronic toxic effects in fish, depending on concentration, exposure time and species sensitivity. In zebrafish, acute exposure to high concentrations of arsenic can lead to respiratory distress, loss of equilibrium, erratic swimming and increased mucus secretion, often resulting in mortality (Islam *et al.*, 2023). Chronic exposure even at sub-lethal levels in Indian carp, causes cumulative physiological and biochemical damage, such as anorexia, lethargy, fin erosion and immunosuppression (Kumar *et al.*, 2024). Long-term exposure also impacts organ function, leading to systemic toxicity.

Effects on fish growth, reproduction, behaviour and physiology

Arsenic disrupts multiple physiological functions in fish. Growth inhibition occurs due to reduced feeding efficiency and altered metabolic enzyme activity. Reproductive impairment is linked to decreased gonadosomatic index (GSI), reduced sperm motility and altered hormone levels such as oestradiol and testosterone (Sarkar and Das, 2023). Behavioural abnormalities like reduced aggression, impaired predator avoidance and abnormal schooling behaviour have also been reported (Rahman *et al.*, 2023). Physiologically, arsenic affects osmoregulation, haematology (e.g., reduced haemoglobin and RBC count) and respiration by damaging gill function in common carp (Wang *et al.*, 2024).

Biochemical and molecular responses

Arsenic induces several biochemical and molecular alterations in fish. Oxidative stress is one of the primary mechanisms of arsenic toxicity. It generates reactive oxygen species (ROS), leading to lipid peroxidation, protein oxidation and disruption of mitochondrial function (Ali *et al.*, 2023). Antioxidant enzyme inhibition is commonly observed, with decreased activity of superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), disrupting cellular redox balance (Kundu *et al.*, 2023). DNA damage and genotoxicity are marked by increased micronuclei formation, chromosomal aberrations and DNA strand breaks in liver and gill tissues (Mandal *et al*., 2023). These effects raise concerns about transgenerational toxicity and population-level impacts.

Histopathological changes

Histopathological analysis reveals structural damage in various organs. Liver shows alterations in hepatocyte size, peripheral displaced nuclei and multinucleate hepatocytes due to its role in detoxification (Patel *et al*., 2024). Heart shows atrophied cardiac muscles, impaired epicardium, hypertrophied nuclei, clumped nuclei and uneven distribution of nuclei. Gills exhibit lamellar fusion, epithelial lifting, hyperplasia and aneurysm, compromising respiration and osmoregulation (Rahim *et al*., 2023). Kidneys show thickened blood capillary walls, hypertrophy in proximal tissue, loss of normal rounded shape in kidney structure and thickened arterioles (Nabi *et al*., 2023). Gonads may show reduced follicle development and spermatogenesis inhibition under chronic exposure (Sahoo and Mohanty, 2024). Arsenic administered hepatocytes showed vast propagation, cholangiocytes and granulomas in *Oncorhynchus mykiss* (rainbow trout; Kotsani and Iliopoulou-Georgudaki, 1999). Exposure of fish to different concentrations of arsenic trioxide for 10 to 30 days resulted in various histopathological changes like pycnotic nuclei, vacuolization of tubular cells, glomerular contraction, tubular lumen enlargement, renal tubule degeneration, hematopoietic tissue disintegration and necrosis in kidney tubules of *Clarias batrachus* (Datta *et al*., 2009). These histological changes provide critical biomarkers for arsenic exposure and are essential for ecotoxicological risk assessment.

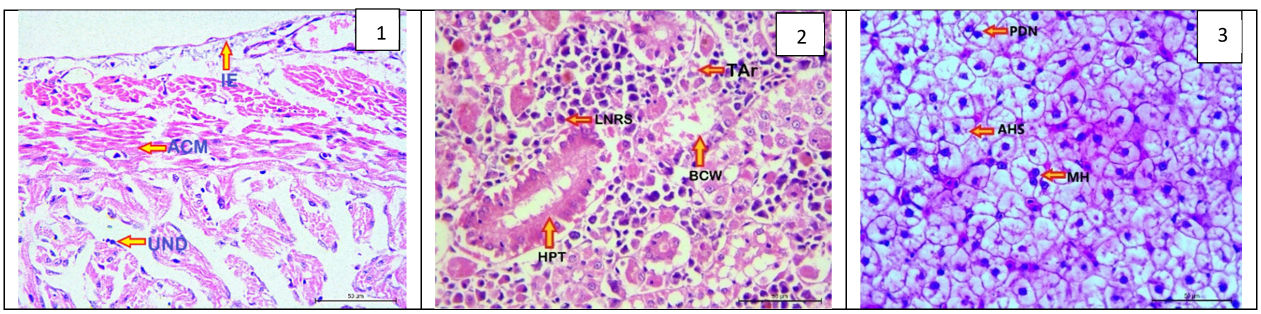

Figure 1: Heart of *Cyprinus carpio* exposed to 0.9 mg of arsenic trioxide/kg of body weight exhibit atrophied cardiac muscles (ACM), impaired epicardium (IE), hypertrophied nuclei, clumped nuclei (CN) and uneven distribution of nuclei (UND).

Figure 2: Kidney of *Cyprinus carpio* exposed to 0.9 mg/kg arsenic trioxide showing thickened blood capillary walls (BCW), hypertrophy in proximal tissue (HPT), loss of normal rounded shape (LNRS) in kidney structure and thickened arterioles (TAr) after 30 days.

Figure 3: Liver of *Cyprinus carpio* exposed to 1.8 mg of arsenic trioxide/kg body weight demonstrated alterations in hepatocyte size (AHS), peripheral displaced nuclei (PDN) and multinucleate hepatocytes (MH).

ANALYTICAL METHODS FOR ARSENIC DETECTION IN FISH

Accurate detection of arsenic in fish tissues is critical for evaluating exposure risks, understanding bioaccumulation patterns and informing regulatory decisions. The reliability of arsenic measurement depends significantly on proper sampling and preparation techniques. Fish samples are typically collected from contaminated aquatic systems and dissected to isolate relevant tissues such as muscle, liver, kidney and gills. These tissues are then subjected to drying, homogenization and acid digestion- commonly using nitric acid or a mixture of nitric and perchloric acids- to convert the arsenic into a measurable form (Liu *et al*., 2023). Microwave- assisted digestion has gained popularity for its ability to enhance sample throughput and minimize contamination (Rao *et al.*, 2024).

Among instrumental techniques, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) remains the gold standard for total arsenic quantification due to its high sensitivity, low detection limits (ng/L levels) and multi-element detection capability (Chen *et al.*, 2023). Atomic Absorption Spectroscopy (AAS), particularly Hydride Generation AAS (HG-AAS), is also widely used because of its specificity for arsenic and relatively lower cost; however, it lacks the ability to distinguish between arsenic species. For more detailed characterization, High-Performance Liquid Chromatography coupled with ICP-MS (HPLC-ICP-MS) is employed, offering excellent resolution and accuracy for arsenic speciation, which is essential in differentiating toxic inorganic forms from less harmful organic species such as MMA and DMA (Singh and Zhang, 2023).

Speciation analysis is crucial, as the toxicity and mobility of arsenic in biological systems are highly dependent on its chemical form. HPLC-ICP-MS enables separation of arsenic species based on their ionic properties before quantification, making it indispensable in toxicological and food safety assessments. Emerging techniques like capillary electrophoresis and synchrotron-based X-ray absorption spectroscopy (XAS) are also being explored for advanced speciation studies, offering insights into arsenic binding mechanisms within fish tissues (Zhao *et al.*, 2024).

Despite technological advancements, several challenges remain in arsenic detection. Matrix interference from biological compounds, loss of volatile arsenic species during digestion and the complexity of extracting arsenic from lipid- rich tissues can compromise accuracy (Khan *et al.*, 2023). Moreover, standardizing methods across laboratories and developing certified reference materials for arsenic in diverse fish tissues continue to be pressing issues. However, advancements such as nano- enhanced sensors, portable field detection kits and machine learning- assisted signal processing are paving the way for more sensitive, rapid and cost-effective detection methods (Wang and Patel, 2024). In summary, the integration of robust sample preparation protocols with advanced analytical instrumentation such as ICP-MS and HPLC-ICP-MS ensures accurate detection and speciation of arsenic in fish. Continued innovation in this area is vital for environmental monitoring and public health protection.

Bioremediation approaches for arsenic in aquatic environments

Bioremediation is an eco-friendly, sustainable approach that employs biological systems- such as microorganisms, plants and microbial consortia- to detoxify or remove pollutants like arsenic from contaminated environments. Unlike conventional physico- chemical methods, bioremediation is cost-effective, generates less secondary pollution and can be tailored to site-specific conditions (Kumar and Jaiswal, 2023). The efficacy of bioremediation in aquatic ecosystems depends on the ability of biological agents to transform toxic arsenic species into less harmful or immobile forms through reduction, oxidation, methylation and sequestration.

Microbial bioremediation involves the use of naturally occurring or engineered bacteria, fungi and algae that have evolved mechanisms to survive in arsenic-rich environments. Certain bacterial genera such as *Pseudomonas*, *Bacillus* and *Shewanella* possess arsenic- resistance (ars) operons that enable arsenate (As^{V}) reduction to arsenite (As^{III}), which is then extruded from the cell to minimize toxicity (Singh *et al.*, 2023). Other strains can oxidize arsenite back to arsenate, facilitating adsorption onto iron and manganese oxides. Fungi, like *Aspergillus* and *Penicillium*, have been shown to bioaccumulate arsenic through cell wall binding and intracellular sequestration, aided by thiol-containing peptides such as glutathione (Zhou *et al.*, 2023). Additionally, microalgae like *Chlorella* and *Scenedesmus* can uptake arsenic via phosphate transporters and modulate their redox state, offering a promising route for arsenic removal in aquatic habitats (Rana *et al.*, 2024).

Phytoremediation, particularly using aquatic macrophytes, is another promising strategy. Species such as *Eichhornia crassipes* (water hyacinth), *Lemna minor* (duckweed) and *Typha latifolia* (cattail) have demonstrated strong arsenic uptake and translocation capabilities (Nath *et al*., 2023). These plants absorb arsenic through their root systems and often sequester it in vacuoles or convert it into organic complexes, thus reducing its bioavailability. Phytoremediation is advantageous for shallow water bodies and constructed wetlands, especially in tropical and subtropical climates. The role of biofilms and microbial mats in arsenic removal is gaining increasing attention. Biofilms- complex aggregates of microbial communities embedded in extracellular polymeric substances (EPS)- enhance the surface area for metal adsorption and create microenvironments conducive to arsenic redox transformations (Sharma *et al*., 2024). Cyanobacterial mats in particular have shown dual capacity for arsenic oxidation and immobilization, offering potential applications in passive water treatment systems.

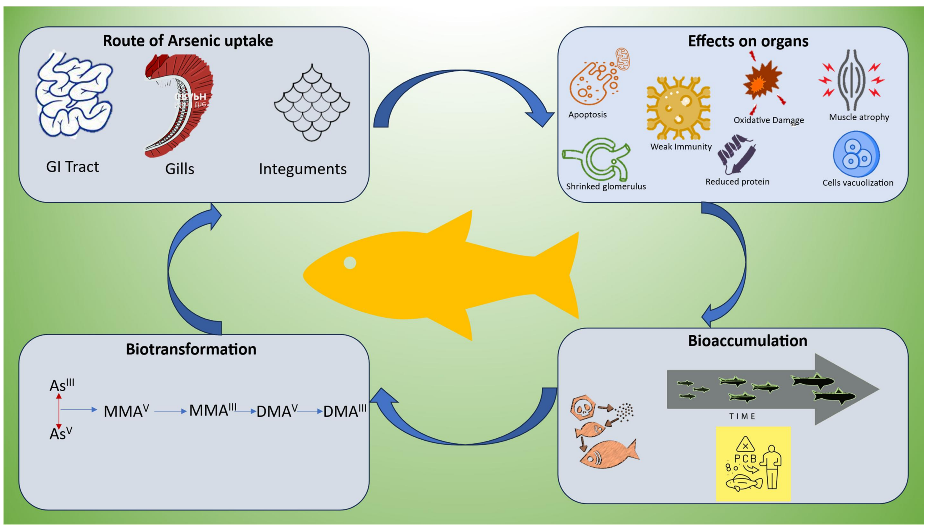

Figure 4: Routes of Arsenic uptake, effects on organs, biotransformation and bioaccumulation in fish

At the molecular level, the genetic and metabolic pathways involved in arsenic detoxification are well characterized in several microbial species. The arsenic resistance (ars) operon, commonly found on plasmids and chromosomes, includes genes such as arsC (arsenate reductase), arsB (arsenite efflux pump) and arsR (regulatory protein) (Patra and Mahapatra, 2023). Some microbes also harbour arsenite oxidase and arsenate respiratory reductase gene clusters that facilitate redox cycling of arsenic as a part of energy metabolism under aerobic or anaerobic conditions. Advances in metagenomics and transcriptomics have revealed additional stress-response genes, transporters and metal-binding proteins that enhance arsenic tolerance and transformation efficiency (Bhatt and Tiwari, 2024). Genetic engineering approaches are also being explored to enhance arsenic bioremediation capacity in model organisms.

In conclusion, bioremediation through the synergistic use of microbes, plants and biofilms offers a sustainable and effective method for arsenic detoxification in aquatic systems. Further integration of molecular biology tools with ecological engineering can significantly improve the efficiency and applicability of these strategies in real-world scenarios.

Bioremediation strategies targeting arsenic in fish

Direct bioremediation strategies targeting arsenic in fish focus on mitigating arsenic uptake, enhancing detoxification and minimizing tissue accumulation to ensure fish health and food safety in aquaculture systems. One promising approach involves the use of probiotics and beneficial microbes. Specific probiotic strains such as *Lactobacillus plantarum* and *Bacillus subtilis* have been shown to enhance antioxidant enzyme activity and reduce oxidative stress caused by arsenic exposure in fish (Ahmed *et al*., 2023). These microbes modulate the gut microbiota and bind arsenic ions in the gastrointestinal tract, preventing systemic absorption and promoting excretion. Recent studies have also reported the colonization of arsenic-resistant probiotic strains in the gut, contributing to microbial arsenic methylation and detoxification (Chen *et al*., 2024).

Another important strategy is the incorporation of dietary supplements and feed additives that facilitate arsenic detoxification in fish. Supplements such as selenium, vitamin C, curcumin and spirulina have demonstrated significant protective effects by enhancing the expression of detoxifying enzymes, scavenging free radicals, and restoring tissue integrity (Jain *et al*., 2023). For instance, selenium plays a crucial role in arsenic antagonism by forming stable, non-toxic seleno-arsenide complexes that are excreted through bile or urine. In addition, feed-based delivery of adsorbents like activated carbon, zeolites or clay minerals can physically bind arsenic in the gut, reducing its bioavailability (Wang *et al*., 2024).

The role of nanotechnology and bioengineered materials in aquaculture- based arsenic mitigation is an emerging frontier. Nanoparticles such as nano- iron oxides, nano-zeolites and graphene-based composites exhibit high surface area and reactivity, making them effective arsenic adsorbents in aquaculture water and feed systems. These nanomaterials can be engineered for slow release or encapsulation with nutrients and probiotics, creating multifunctional delivery systems. Furthermore, genetically modified microbial strains expressing enhanced arsenic detoxification pathways (e.g., overexpression of *arsC* and *arsB*) are being explored for inclusion in fish tanks or biofilters to reduce ambient arsenic concentrations (Li *et al*., 2024).

Several case studies and experimental trials validate these strategies in controlled and semi-field conditions. For example, an integrated study on *Oreochromis mossambicus* showed that feeding with a diet supplemented with *Lactobacillus rhamnosus* and selenium significantly reduced arsenic accumulation in liver and muscle tissues over 45 days (Sharma and Bhattacharya, 2023). In another trial, the use of iron oxide nanoparticles in aquaculture ponds led to a 62% reduction in waterborne arsenic, with improved fish survival and growth rates (Das *et al*., 2023). Such findings highlight the feasibility of combining dietary and environmental interventions to manage arsenic exposure in aquaculture. In conclusion, integrating microbial, nutritional and nanotechnological interventions offers a multi-pronged approach for reducing arsenic bioaccumulation in fish. These strategies not only safeguard aquatic animal health but also ensure the safety of fish as a food source, contributing to the sustainability of aquaculture systems.

Environmental and Ecological Implications

The accumulation of arsenic in fish has significant implications for aquatic ecosystems, affecting not only individual species but also the structure and functioning of entire food webs. Arsenic toxicity impairs fish survival, growth, reproduction and immune competence, leading to population declines, especially in sensitive or endemic species (Zhou *et al*., 2023). Reduced biodiversity, altered predator-prey interactions and disrupted energy flow in aquatic food chains have been observed in arsenic-polluted freshwater systems. For instance, invertebrate and plankton communities, which serve as food sources for fish, may also bioaccumulate arsenic, propagating toxicity through trophic levels (Singh and Devi, 2024). Such disruptions can have cascading effects, destabilizing ecosystem resilience and productivity.

From a public health perspective, arsenic-contaminated fish represent a direct pathway for human exposure, particularly in communities that rely heavily on fish as a dietary staple. Chronic ingestion of arsenic- laden fish can lead to numerous health conditions including skin lesions, cardiovascular disorders, diabetes, developmental issues and various forms of cancer (Khan *et al*., 2024). Inorganic arsenic, particularly arsenite, is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC). The health risk is exacerbated in regions like Bangladesh, India and parts of Southeast Asia, where fish from arsenic-contaminated water bodies are frequently consumed without prior testing or regulation (Rahman *et al.*, 2023). Therefore, fish safety monitoring becomes critical in both aquaculture and capture fisheries.

To mitigate these risks, regulatory standards and guidelines have been established by international and national agencies. The World Health Organization (WHO) recommends a maximum permissible limit of 10 µg/L of arsenic in drinking water, which indirectly guides environmental safety benchmarks (WHO, 2022). For food products, the Codex Alimentarius sets limits for arsenic in fish and shellfish, generally at 0.5-1.0 mg/kg depending on the region and species. The U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) also maintain similar thresholds for total and inorganic arsenic in seafood (EFSA, 2023). However, inconsistencies in regional standards, lack of species-specific regulations and limited monitoring capacity often undermine the effectiveness of these guidelines in developing nations. Hence, arsenic contamination poses a dual threat ecologically through the disruption of aquatic biodiversity and food web dynamics and socially through its impact on food safety and public health. Effective implementation of environmental regulations, routine monitoring of arsenic levels in fish and adoption of remediation strategies are essential to protect both ecosystems and human populations from the long-term consequences of arsenic pollution.

DISCUSSIONS

Despite significant advancements in understanding arsenic dynamics in aquatic systems, several gaps in current knowledge hinder the development of effective mitigation strategies. Most research focuses on total arsenic concentrations, while less attention is given to arsenic speciation, tissue-specific accumulation patterns, and long-term ecological impacts in diverse aquatic environments (Chakraborty and Dutta, 2023). To address these limitations, emerging technologies for arsenic detection and removal are being explored. Advanced techniques such as lab-on-chip sensors, portable electrochemical arsenic detectors and biosensor-based systems provide real-time, on-site monitoring of arsenic in water and fish tissues with high sensitivity (Sharma *et al.*, 2023). On the removal front, innovations in nanomaterial-based adsorbents, including graphene oxide, nano-iron oxides and magnetic biochar, have demonstrated superior arsenic removal capacities due to their high surface area and customizable functional groups (Gupta *et al.*, 2024). However, their environmental safety, scalability and cost effectiveness need to be critically assessed before field deployment. Integrating bioremediation with other remediation techniques offers a promising way to enhance the efficiency of arsenic management. Hybrid systems that combine microbial treatment with filtration, constructed wetlands with phytoremediation or nanotechnology assisted biofilters can simultaneously address arsenic and co-contaminants, improving system resilience (Wang and Zhang, 2024). Such integrated approaches also help overcome the limitations of single-method strategies, especially in complex, high- load environments. Promoting sustainable aquaculture practices is vital for long-term arsenic risk mitigation. This includes selecting arsenic-resistant fish species, using clean feed additives with detoxifying properties, and routinely monitoring water and sediment quality. Adoption of recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA) can reduce arsenic exposure through controlled environments and nutrient cycling (Fernandes *et al.*, 2023). Moreover, stakeholder education, policy support and affordable testing technologies are essential to promote safe aquaculture practices, particularly in arsenic-affected regions of Asia and Africa.

CONCLUSION

Arsenic contamination in aquatic environments remains a pressing global concern due to its toxic effects on fish health, ecological stability and human food safety. This review highlighted the multifaceted processes of arsenic bioaccumulation in fish, including uptake pathways, tissue distribution and species-specific physiological responses. It also emphasized the toxicological effects ranging from oxidative stress and DNA damage to histopathological changes that impair fish growth, reproduction and survival. Analytical methods such as ICP-MS and HPLC-ICP-MS have enabled accurate quantification and speciation of arsenic, which are essential for risk assessment and environmental monitoring. Bioremediation has emerged as a sustainable and cost-effective strategy for managing arsenic pollution. Microbial communities, aquatic plants, biofilms and probiotics offer promising avenues for arsenic detoxification in aquatic ecosystems and within fish themselves. Dietary interventions, nanotechnology-based materials and integrated remediation approaches have further expanded the scope of feasible solutions. Continued research is crucial to fill existing knowledge gaps, especially regarding arsenic speciation, chronic low dose exposure and the long-term ecological impacts of arsenic in aquaculture systems. Future studies should also explore genetic engineering, real-time monitoring tools and ecosystem level bioremediation strategies to ensure both environmental safety and economic viability.

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