VOLUME 9 ISSUE 2 2023

ISSN 2454 – 3055

INTERNATIONAL JOURNAL OF ZOOLOGICAL INVESTIGATIONS

Forum for Biological and Environmental Sciences

Published by Saran Publications, India

International Journal of Zoological Investigations Vol. 9, No. 2, 65-74 (2023)

International Journal of Zoological Investigations
Contents available at Journals Home Page: www.ijzi.net
Editor-in-Chief: Prof. Ajai Kumar Srivastav
Published by: Saran Publications, Gorakhpur, India

ISSN: 2454-3055

Impact of Arsenic Contamination on Aquatic Life of North-East India

Alika Borphukan Borah[1*], Dhiramani Bhuyan[2], Nur Jahan Amin[1] and Habiba Khatun[1]

[1]Department of Zoology, University of Science and Technology Meghalaya, Ri-Bhoi, Meghalaya, India
[2]Department of Zoology, Jagannath Barooah College (Autonomous), Jorhat, Assam, India

**Corresponding Author*

Received: 7th May, 2023; **Accepted:** 22nd June, 2023; **Published online:** 11th July, 2023

https://doi.org/10.33745/ijzi.2023.v09i02.006

Abstract: Environmental pollution is a threat to all living organisms, including aquatic organisms. Heavy metal pollution from substances such as lead, arsenic, cadmium, chromium, and mercury are harmful to both freshwater and marine ecosystems. Exposure to heavy metals can have detrimental effects on aquatic organisms over both short and long periods of time. Fish are often used as a model to determine the degree of aquatic pollution. This review focuses on the impact of arsenic contamination on aquatic life of North-East India. It also helps in understanding the environmental and biological fate of arsenic and different parameters responsible for posing it as an environmental pollutant. Natural sources are estimated to emit about 1.5 times more arsenic into the atmosphere than human activities. However, due to continuous emissions and accumulation, both organic and inorganic forms of arsenic have been found in higher concentrations in aquatic environments compared to terrestrial environments.

Keywords: Arsenic, Environmental pollution, Aquatic organism, Aquatic ecosystem, Heavy metals

Citation: Alika Borphukan Borah, Dhiramani Bhuyan, Nur Jahan Amin and Habiba Khatun: Impact of arsenic contamination on aquatic life of North-East India. Intern. J. Zool. Invest. 9(2): 65-74, 2023.

https://doi.org/10.33745/ijzi.2023.v09i02.006

Introduction

Industrialisation, urbanisation and population explosion have deleterious impacts on the entire ecosystem. Globally pollution, especially in the aquatic ecosystem due to heavy metal contamination, has become a significant cause of concern for the environmentalist. The bio-life of aquatic ecosystems is adversely affected due to the constant release of heavy metals due to their characteristic of long persisting nature or longer half-life, bioaccumulation mechanism, bio-magnification process and non-biodegradability (Bakshi and Panigrahi, 2018).

Even in small concentrations, heavy metals in the food chain cause cumulative harmful effects on aquatic organisms (Velma *et al.*, 2009; Velma and Tchounwou, 2009). Heavy metals are thus considered to have an ecological, evolutionary, nutritional and environmental impact on the ecosystem (Jaishankar *et al.*, 2014). Recently, freshwater ecosystems have been polluted mainly by waste water released from different industries and municipalities. The most frequently available heavy metals in the waste water are Lead, Arsenic, Cadmium, Chromium and Mercury (Bakshi, 2016; Mehana *et al.*, 2020). There is a significant impact on fish development and physiological processes such as breeding, spawning, and overall organ development, and a decline in quantity and quality of offspring production due to the contamination by heavy metals in the aquatic environment. Furthermore, due to the intake of such waterborne contamination, there seem to be abnormalities and disruption of function and structure of many tissues and organs of the aquatic life (Jezierska *et al.*, 2001, 2008).

Arsenic is considered one of the most potent and prominent toxicants in the aquatic environment among all the known heavy metals. Arsenic has also been reported to cause severe water pollution, affecting the growth of aquatic flora and fauna (Ratnaike, 2003; Oremland *et al.*, 2003). Furthermore, the uncontrolled influx of industrial wastes and pesticides in the aquatic environment has made this toxic metalloid widely available in rivers, canals, ponds, lakes, groundwater and seawater, thereby causing a global threat (Kumari *et al.*, 2016).

Regarding public health arsenic has been reported to be the most dangerous chemical as per the WHO reports (Babich *et al.*, 2019). In most countries, arsenic levels have been reported to be up to 800 and 2500 ppm (Naujokas *et al.*, 2013). There have been several studies reporting the adverse effect of the high level of arsenic exposure resulting in diseases such as lung and skin cancer and liver and cardiovascular disorders in case of humans (Liu *et al.*, 2008; Kundu *et al.*, 2011; Gong *et al.*, 2012; Bräuner *et al.*, 2014). Previous research has demonstrated the adverse effects of Arsenic on the overall growth and development of the fishes, histopathological and genetic alteration and mortality (Hayat *et al.*, 2007; Ahmed *et al.*, 2013; Banerjee *et al.*, 2015; Foley *et al.*, 2016; Minatel *et al.*, 2017; Han *et al.*, 2019). Exposure to the higher concentration of Arsenic in fish have been reported to cause changes in body physiology, including effects on the overall growth, mortality, ion exchange system, immune system, reproduction, enzyme activity, histology and gene regulation (Farag *et al.*, 1995; Pedlar *et al.*, 2002; Datta *et al.*, 2009)

Arsenic and its characteristics:

Arsenic is one of the harmful heavy metals (metalloids) in aquatic biolife. It has a metalloid property and is predominantly available in oxides (arsenate and arsenite) or sulfides or as a salt of sodium, iron, copper, calcium, etc. (Singh *et al.*, 2007). The emissions of arsenic into the atmosphere from natural sources are estimated to be about 1.5 times higher than those from human activities (Chilvers *et al.*,1987). However, due to continuous emissions and accumulation, both organic and inorganic forms of arsenic have been found in higher concentrations in aquatic environments compared to terrestrial environments (IPCS, 2001). Although arsenic contamination in aquatic biological communities originates from geogenic sources, it occurs through accumulation from lower to higher trophic levels, particularly in members of the Class Pisces (Jankong *et al.*, 2007; Grotti *et al.*, 2008; Srivastava and Sharma, 2013; Taleshi *et al.*, 2014; Williams *et al.*, 2014; Oliveira *et al.*, 2017; Han *et al.*, 2019). The degree of accumulation and biomagnification of arsenic in aquatic flora and fauna varies based on geographical settings, such as freshwater, estuarine, transitional, and marine ecosystems, as well as across species and their trophic status within the food web, which strongly controls exposure and uptake routes (Chen and Folt, 2000; McGeer *et al.*, 2003; Schafer *et al.*, 2015; Oliveira *et al.*, 2017).

Aquatic organisms, like their terrestrial counterparts, can absorb varying amounts of arsenic from their environment. They are exposed to different forms of inorganic and organic arsenic, commonly through food, water, and other environmental sources. The metabolism of arsenic is complex due to the variety of physiochemical properties and bioavailability of each form, and is further complicated by the influence of other metals and metalloids on arsenic metabolism within and between species (Mandal and Suzuki, 2002). Organic forms of arsenic, such as arsenobetaine, have been widely observed in marine aquatic flora and fauna, but are virtually absent in most freshwater invertebrates and vertebrates (Schaefer *et al.*, 2006).

Organic forms of arsenic are produced by algae and passed along the food chain (Wrench *et al.*, 1979). Both microalgae and macroalgae, which form the base of lower trophic levels, may accumulate more arsenic than organisms at higher trophic levels (Garcı´a-Salgado *et al.*, 2012). In addition to algae, drifting organisms such as phytoplankton and zooplankton can also accumulate arsenic. Studies have shown that phytoplankton can accumulate large amounts of inorganic arsenic and/or convert it into other organic forms, such as arsenobetaine. Higher trophic level organisms, such as fish, crabs, prawns, and shrimps, also play an important role in the speciation of arsenic within aquatic environments (Šlejkovec *et al.*, 2014).

The global occurrence of water-soluble arsenic concentration above the permissible limit is primarily due to excessive use of arsenical pesticides, industrial activities, mining operations and chemical laboratory exhaustion. Water soluble inorganic arsenic (iAS) is converted to methylated arsenical forms, i.e., monomethyl arsonic acid (MMA) and dimethylarsinic acid (DMA), through enzymatic activities in the organism's body. These arsenical forms are long-term arsenic exposure's primary end metabolites and biomarkers (Jaishankar *et al.*, 2014; Kumari *et al.*, 2016). The adversative impact on the hydrobiological quality of water bodies such as lakes, ponds and rivers all over the world has been due to extensive industrialization, exploitation and rapid urbanization (Praveena *et al.*, 2013), hence it has been observed that the exposure of the aquatic biolife to arsenic may be waterborne and diet-borne. The main routes of entry for it into the aquatic organism is through gills and GI tract. After taking entry through gill, waterborne arsenic significantly accumulates in the gill, liver and intestine and manipulates the growth of the fish (Tsai and Liao, 2006; Han *et al.*, 2019).

Inorganic Arsenic (iAs) may be present in two forms, i.e., iAs (III) and iAs (V). According to Kumari *et al.* (2016), after the entry of iAs (V), it converts into iAs (III). Then iAs (III) changes into MMA(V) coupled with SAM –SAH conversion (SAM: S-adenosylmethionine; SAH: S-adenosyl-homocysteine). After that MMA(V) transforms into the most toxic and accumulating form MMA (III), through reduction reaction by the action of MMA(V) reductase or GSTO 1 (glutathione S-transferase omega 1). MMA (III) can also be converted into DMA coupled with a SAM –SAH conversion (SAM: S-adenosyl-methionine; SAH: S-adenosylhomocysteine). Most biotransformation reactions occur in the liver (Han *et al.*, 2019).

When arsenic compounds come with food, they accumulate in the digestive tract. From the digestive tract, it goes to the liver, where most of the biotransformation takes place. It then accumulates in other organs or body tissues, i.e., brain, gonads, muscles either directly or through circulation and accumulate (Tsai *et al.*, 2012). Arsenic compounds dissolved in water can also pass through the gills and be deposited directly into the brain, kidneys, gonads, and other tissues. Absorption through food shows accumulation in the gastrointestinal tract until the end of exposure, but the concentration gradually decreases during elimination. Although there are many different studies, the liver is reported as the most metal accumulating organ in most cases (Kumari *et al.*, 2016; Han *et al.*, 2019).

Arsenic detection in the North-East region:

Arsenic is one of the most available metals that can be found in soil, rocks, natural waters and organisms. It occurs through different natural processes such as weathering, microbial metabolism and volcanic eruptions which leads to

Table 1: Distribution of total arsenic content in a carbonaceous matter of North-east India

States	Types of Carbonaceous materials	Carbon (wt %)	Arsenic (µg/kg)	
			Range	Average
Assam	Sub-bituminous	70.381–71.143	44.0–78.0	61.0
Nagaland	Lignitic	53.825–56.124	56.0–68.0	62.0
Meghalaya	Sub-bituminous	58.202–58.791	106.0–238.0	172.0
Arunachal Pradesh	Graphitic	66.012–71.981	39.0–50.0	44.5

arsenic contamination. Anthropogenic activities like mining, combustion of fossil fuels, use of arsenical pesticides, herbicides and crop desiccants and agricultural additives for livestock are also responsible for exaggerating the arsenic in soil and groundwater (Buragohain *et al.*, 2012). Though researchers have made advancements in understanding the distribution, occurrence and mobilisation of arsenic in groundwater on a global scale, on a regional extent, it still needs to be improved and needs proper knowledge and information. Most North East India people primarily depend on dug-well, ponds, and naturally occurring spring water. It has been estimated that 60% of these water sources are contaminated with arsenic concentrations. The concentration being much higher than the WHO and BIS guidelines of 10 µg/l and 50 µg/l, respectively (WHO, 1993; Shukla *et al.*, 2010; BIS, 2013). A study conducted by the North-eastern Regional Institute of Water and Land Management (NERIWALM) found that 20 out of 24 districts of Assam have a content exceeding 50 µg/l (Bordoloi, 2012). Another study has reported that Karimganj and Dhemaji districts are the worst affected areas of Assam, where 19.1% of groundwater has arsenic concentration above 50 µg/l, and 2.1% contains more than 300 µg/l (Saikia *et al.*, 2012). Continuous water consumption can pose serious health hazards to the local population. Though several restorative and precautionary measures have been taken to supply arsenic free water to the affected population and develop devices for arsenic removal, the effort is insignificant when looking at the larger arena of the stated problem.

The detection of Arsenic in groundwater from large areas of the North-eastern region of India few years back has rung the bell of concern for millions (Das *et al.*, 2015). Arsenic distribution in natural water mainly depends on the geochemical characteristics of the aquifer materials. It has been observed that most of the arsenic affected floodplains in Asia are by the side of the rivers that originate in the Himalayas foothills. Hence, the Himalayas and surrounding mountains are considered to be the possible sources of Arsenic bearing minerals. For example, the sediments of Bengal Delta Plain (the 13th Largest Delta in the World) has been reported to contain high percentage of clay and organic matter deposits. This reacts with Fe and Mn - Oxyhydroxide minerals accordingly that reaches high Reduction Potential (Eh) value and strongly absorb arsenical elements for auxiliary release of the toxic in the groundwater (Selima *et al.*, 2010; Santra *et al.*, 2013). It has also been reported that the average arsenic content of carbonaceous matter from the North-eastern Region is 95.1 mg/kg (Mudhoo *et al.*, 2011). The weathering sulphide content in the carbonaceous matter produces Arsenic-rich iron oxyhydroxide. This in an oxygen-deficient environment which has been reported to release arsenic to the existing sedimentary layers of Arunachal Pradesh, Assam, Nagaland and Meghalaya (Table 1).

Different sources of Arsenic in North-East India:

The most abundant element in the earth's crust is Arsenic, and its traces can be found in more than 245 types of minerals. These are typically ores containing sulphide, copper, nickel, lead, cobalt etc. The earthly profusion of arsenic is approximately 1.5-3 mg/kg. Most of the reported cases of arsenic in the Himalayan region cause sedimentary mobilisation under natural hydrogeological conditions, and few cause human extravagance. The sources of Arsenic in the environment can be subcategorised into natural and anthropogenic sources (Devi *et al.*, 2009; Mudhoo *et al.*, 2011).

Natural sources: Although the definite source of groundwater arsenic contamination in the Ganga-Brahmaputra basin is yet to be identified, several arsenic bearing sediments have already been reported in the Bengal delta plain, Gondwana coal seams, Bihar mica belt, pyrite bearing shale, Son valley gold belt etc. (Chakraborti *et al.*, 2004; Barringer *et al.*, 2013; IARC, 2014). The Ganges-Brahmaputra River system which covers the North-eastern states, had over the time several sediment deposits that functions as a reservoir of Arsenic, and the concentration of the element in these deposits can reach to as high as 490 mg/kg.

Anthropogenic activities: The extensive use of pesticides, application of fertilisers, agricultural additives for livestock, crop desiccants burning of coal and leaching of metals from coal-ash tailings are the major causes of human caused contamination. The average Arsenic content in Indian coal ranges up to 3.72 mg/kg. Whereas a maximum value of 40 mg/kg has also been reported in North-eastern regions. Thus coal combustion is considered to be one of the most important sources of anthropogenic arsenic emission in the environment in North eastern India. In addition, several metallurgical plants, cement factories, incinerators and chemical plants also pose a threat to the pollution to the environment in this region (Chakraborti *et al.*, 2013; Barringer *et al.*, 2013; IARC, 2014).

Adverse effect of Arsenic on Aquatic life:

Among the aquatic organisms, fish can serve as a model to study arsenic toxicity, as they are continuously exposed to arsenic through gills and get accumulated in various tissues. The accumulation of arsenic compounds basically takes place in the digestive tract once it enters through food. It takes it course through and goes to the liver, where the major biotransformation takes place. Inorganic arsenic, potent carcinogen is methylated in the body by altering the reduction of pentavalent arsenic (Arsenate, As^{V}) to trivalent (Arsenite As^{III}) with an addition of methyl group from S-adenosylmethionine. Although it has been reported that the site of arsenic methylation is the liver, however, there are also reports that most organs also show arsenic methylation activity. Methylarsonic (MMA) and dimethylarsinic acid (DMA) may be less reactive organic arsenic and readily excreted in the urine, they may form reactive immediate such as MMA III and DMA III which might be absorbed in the body and results in toxicity (Vahter *et al.*, 2002).

After arsenic enters aquatic systems, it exerts detrimental effects on aquatic organisms directly through inhalation and drinking or indirectly by uptake through the food chain (Rahman *et al.*, 2012). It is then accumulated in the body tissues and organs such as muscles, brain, gonads etc. (Tsai *et al.*, 2012). Kumari *et al.* (2016) has also reported in one of the purification experiments that a small amount of metal traces has also been observed in faeces. Different biological and environmental factors (Zhang *et al.*, 2022) also play an important role in arsenic bioaccumulation in aquatic organisms. Absorption of Arsenic is also influenced by various parameters such as type of species, body size, age, pH, salinity, dissolved organic matter levels, moulting, food density, prey types, pre-exposure, presence of phosphate etc. From lower-level microorganisms to marine fish, many enzymes take significant roles in the biotransformation of inorganic arsenic to less toxic organic arsenic species. Although there are several reports on influence of various factors on arsenic bioaccumulation in aquatic organism, however, no comprehensive and systematic information related to entire bioaccumulation process have been reported.

Once ingested the Arsenic compounds are reported to be deposited in different organs and tissues of the aquatic organisms. This leads to various physiological and biochemical disorders such as poisoning, enzyme activity, immune function, liver lesions, cell and tissue damage, decreased fertility and cell death too (Ribeiro *et al.*, 2005; Bears *et al.*, 2006). Bioaccumulation of arsenic may also trigger a change in water temperature which can cause metabolic disorder in some aquatic organisms. The rise in the temperature accelerates the process of oxygen consumption which can induce stress and immunity degradation too (Lushchak and Bagnyukova, 2006; Bagnyukova *et al.*, 2007). As a result of toxicity, it has also been reported tthat he feed intake rate and metabolic rate decreases which in turn results in the overall growth rate of the fishes (Farkas *et al.*, 2002; Hayat *et al.*, 2007).

The haematological characteristics as a result of arsenic toxicity have also been extensively studied in case of fishes. There are several reports on decrease of haematological parameters such as RBC counts, haematocrit (Ht), and haemoglobin (Hb). The striking decrease in RBC count was observed at the highest arsenic concentration regardless of temperature. Arsenic toxicity have also been demonstrated to be associated with bone marrow damage and arsenic-induced anaemia due to haemolysis of intravascular erythrocytes (Cockell *et al.*, 1991; Carvalho and Fernandes, 2006; Ferrario *et al.*, 2008).

Protein synthesis disorder due to decreased plasma proteins is associated to be the result of Arsenic accumulation in the liver (Lavanya *et al.*, 2011). Kavitha *et al*. (2010) have elaborated the effect of arsenic on glucose metabolism due to changes in the cellular metabolism and metal complexes formation that ultimately affects the carbohydrate metabolism such as glucose, glycogen and lactate.

Fishes when exposed to arsenic for a longer period has been reported to develop lesions in the liver, gall bladder and kidney which further results in the damage of the hepatic and renal functions (Pedlar *et al.*, 2002, Roy and Bhattacharya, 2006). In an experiment conducted by Pedlar *et al*. (2002), the feeding of lake whitefish (*Coregonus clupeaformis*) with arsenic resulted in histopathological alterations, inflammation and necrosis of the liver, gallbladder etc. Abdel-Hameid (2009) reported substantial increases in GOT and GPT of catfish (*Clarias gariepinus)*, exposed to arsenic, and elevated levels of these parameters may reflect liver damage due to arsenic toxicity.

Conclusion

Arsenic in the environment can significantly affect aquatic organisms. It can accumulate in these organisms through processes such as solute absorption and dietary assimilation. Both biological and environmental factors affect arsenic absorption and assimilation. Inside the body, arsenic can change to another species. Many enzymes play an important role in the conversion of inorganic arsenic to less toxic organic forms in organisms from microorganisms to marine fish. However, many processes such as AsB synthesis and degradation pathways are still not fully understood. Elimination is another important factor in determining arsenic bioaccumulation. Through this review, we tried to understand the mechanisms of arsenic intake, its biotransformation, adverse effects on aquatic organisms and the whole environment. Arsenic contamination has become an environmental hazard and strategies must be implemented to control it. Effective legislation, guidelines and regular monitoring must be prioritized to combat this environmental menace. If the pollution is not controlled, it can lead to serious complications in the future due to the harmful effects of such heavy metals. Monitoring exposure and release of heavy metals and implementing measures to reduce further exposure to the environment are critical to addressing this problem. Cooperation at the national and international levels is essential to develop effective strategies to prevent the negative effects of heavy metal toxicity.

References

Abdel-Hameid NAH. (2009) A protective effect of calcium carbonate against arsenic toxicity of the Nile catfish, *Clarias gariepinus*. Turkish J Fish Aquat Sci. 9: 191-200.

Ahmed MK, Habibullah-Al-Mamun M, Parvin E, Akter MS and Khan MS. (2013) Arsenic induced toxicity and histopathological changes in gill and liver tissue of freshwater fish, tilapia (*Oreochromis mossambicus*). Exp Toxicol Pathol. 65(6): 903-909.

Babich R and Van Beneden RJ. (2019) Effect of arsenic exposure on early eye development in zebrafish (*Danio rerio*). J Appl Toxicol. 39 (6): 824-831.

Bagnyukova TV, Lushchak OV, Storey KB and Lushchak VI. (2007) Oxidative stress and antioxidant defense responses by goldfish tissues to acute change of temperature from 3 to 23 C. J Thermal Biol. 32(4): 227-234.

Bakshi A. (2016) Analysis of anthropogenic disturbances and impact of pollution on fish fauna of River Churni with special reference to Chromium pollution. Doctoral Dissertation, Kalyani University, Kalyani, India.

Bakshi A and Panigrahi AK. (2018) A Comprehensive review on chromium induced alterations in fresh water fishes. Toxicol Rep. 5: 440-447.

Banerjee S, Mitra T, Purohit GK, Mohanty S and Mohanty BP. (2015) Immunomodulatory effect of arsenic on cytokine and HSP gene expression in *Labeo rohita* fingerlings. Fish Shellfish Immunol. 44(1): 43-49.

Barringer JL and Reilly PA. (2013) Arsenic in groundwater: A summary of sources and the biogeochemical and hydrogeologic factors affecting arsenic occurrence and mobility. In: Current perspectives in contaminant hydrology and water resources sustainability, (ed.) by Paul M. Bradley, ISBN 978-953-51- 1046-0.

Bears H, Richards JG and Schulte PM. (2006) Arsenic exposure alters hepatic arsenic species composition and stress-mediated gene expression in the common killifish (*Fundulus heteroclitus*). Aquat Toxicol. 77(3): 257-266.

Beyers DW, Rice JA, Clements WH and Henry CJ. (1999) Estimating physiological cost of chemical exposure: Integrating energetics and stress to quantify toxic effects in fish. Can J Fish Aquat Sci. 56 (5): 814-822.

Bordoloi R. (2012) Existence of arsenic in ground water and its effect on health. Int J Computer Application Engineer Sci. 2(3): 270-272.

Bräuner EV, Nordsborg RB, Andersen ZJ, Tjønneland A, Loft S and Raaschou-Nielsen O. (2014) Long-term exposure to low-level arsenic in drinking water and diabetes incidence: A prospective study of the diet, cancer and health cohort. Environ Hlth Perspec. 122: 1059-1065.

Buragohain M and Sarma HP. (2012) A study on spatial distribution of arsenic in ground water samples of Dhemaji district of Assam, India by using Arc View GIS software. Sci Rev. Chem Commun. 2(1): 7-11.

Bureau of Indian Standards (BIS) (1991) 10500:1991, Second Revision ICS No. 13.060.20., http://www.bis.org.in/sf/fad/FAD25(2047)C.pdf., 20-02-13, (2013).

Carvalho CS and Fernandes MN. (2006) Effect of temperature on copper toxicity and hematological responses in the neotropical fish *Prochilodus scrofa* at low and high pH. Aquacult. 251: 109-117.

Chakraborti D, Rahman MM, Murrill M, Das R, Siddayya Patil SG, Sarkar A, Dadapeer HJ, Yendigeri S, Ahmed R and Das KK. (2013) Environmental arsenic contamination and its health effects in a historic gold mining area of the Mangalur greenstone belt of North-eastern Karnataka, India. J Hazardous Materials 262: 1048-1055.

Chakraborti D, Sengupta MK, Rahman MM, Ahamed S, Chowdhury UK, Hossain MA, Mukherjee SC, Pati S, Saha KC, Dutta RN and Quamruzzaman Q. (2004) Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra plain. J Environ Monitor. 6(6): 74N-83N.

Chen CY and Folt CL. (2000) Bioaccumulation and diminution of arsenic and lead in a freshwater food web. Environ Sci Technol. 34(18): 3878-3884.

Chilvers DC and Peterson PJ. (1987) Global cycling of arsenic. In: Lead, mercury, cadmium and arsenic in the environment, (ed.) Meema K.M., Hutchinson TC. Wiley, Chichester, pp. 279-303.

Cockell KA, Hilton JW and Bettger WJ. (1991) Chronic toxicity of dietary disodium arsenate heptahydrate to juvenile rainbow trout (*Oncorhynchus mykiss*). Arch Environ Contam Toxicol. 21(4): 518-527.

Das S, Sudipta BS, Jyoti LP, Madhumita B, Yadav RNS and Mridul C. (2015) Groundwater arsenic contamination in North Eastern States of India. J Environ Res Develop. 9(3): 621-632.

Datta S, Ghosh D, Saha DR, Bhattacharaya S and Mazumder S. (2009) Chronic exposure to low concentration of arsenic is immunotoxic to fish: role of head kidney macrophages as biomarkers of arsenic toxicity to *Clarias batrachus*. Aquat Toxicol. 92(2): 86-94.

Devi NL, Yadav CI and Qi S. (2009) Recent status of arsenic contamination in groundwater of North-eastern India: A review. Rep Opinion 1(3): 22-32.

Farag AM, Stansbury MA, Bergman HL, Hogstrand C and MacConnell E. (1995) The physiological impairment of free-ranging brown trout exposed to metals in the Clark Fork River, Montana. Can J Fish Aquat Sci. 52 (9): 2038-2050.

Farkas A, Salánki J and Specziár A. (2002) Relation between growth and the heavy metal concentration in organs of bream *Abramis brama* L. populating Lake Balaton. Arch Environ Contam Toxicol. 43(2): 236-243.

Ferrario D, Croera C, Brustio R, Collotta A, Bowe G, Vahter M and Gribaldo L. (2008) Toxicity of inorganic arsenic and its metabolites on haematopoietic progenitors "in vitro": Comparison between species and sexes. Toxicology 249: 102-108.

Foley CJ, Bradley DL and Höök TO. (2016) A review and assessment of the potential use of RNA:DNA ratios to assess the condition of entrained fish larvae. Ecol Indicators 60: 346-357.

García-Salgado S, Quijano MA and Bonilla MM. (2012) Arsenic speciation in edible alga samples by microwave-assisted extraction and high-performance liquid chromatography coupled to atomic fluorescence spectrometry. Analytica Chim Acta 714: 38-46.

Gong G and O'Bryant SE. (2012) Low-level arsenic exposure, AS3MT gene polymorphism and cardiovascular diseases in rural Texas counties. Environ Res. 113: 52-57.

Grotti M, Soggia F, Lagomarsino C, Goessler W and Francesconi KA. (2008) Arsenobetaine is a signifcant arsenical constituent of the red Antarctic alga Phyllophora antarctica. Environ Chem. 5(3): 171-175.

Han JM, Park HJ, Kim JH, Jeong DS and Kang JC. (2019) Toxic effects of arsenic on growth, hematological parameters, and plasma components of starry flounder, *Platichthys stellatus*, at two water temperature conditions. Fish Aquat Sci. 22: 3.

Hayat S, Javed M and Razzaq S. (2007) Growth performance of metal stressed major carps viz. *Catla catla*, *Labeo rohita* and *Cirrhina mrigala* reared under semi-intensive culture system. Pakistan Vet J. 27: 8-12.

IARC. (2014) Arsenic and arsenic compound. IARC Monograph. http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-6.pdf., 20-02-13,

Jaishankar M, Mathew BB, Shah MS and Gowda KRS. (2014) Biosorption of few heavy metal ions using agricultural wastes. J Environ Poll Human Hlth. 2(1): 1-6.

Jankong P, Chalhoub C, Kienzl N, Goessler W, Francesconi KA and Visoottiviseth P. (2007) Arsenic accumulation and speciation in freshwater fish living in arsenic-contaminated waters. Environ Chem. 4(1): 11-17.

Jezierska B and Witeska M. (2001) Metal toxicity to fish. Wydawnictwo Akademii Podlaskiej: Siedlce, Poland, pp. 318.

Jezierska B, Ługowska K and Witeska M. (2009) The effects of heavy metals on embryonic development of fish (a review). Fish Physiol Biochem. 35(4): 625-640.

Kumari B, Kumar V, Sinha AK, Ahsan J, Ghosh A, Wang H and De Boeck G. (2016) Toxicology of arsenic in fish and aquatic systems. Environ Chem Letts. 15: 43-64.

Kundu M, Ghosh P, Mitra S, Das JK, Sau TJ, Banerjee S, States JC and Giri AK. (2011) Precancerous and non-cancer disease endpoints of chronic arsenic exposure: the level of chromosomal damage and XRCC3 T241M polymorphism. Mut Res. 706(1-2): 7-12.

Lavanya S, Ramesh M, Kavitha C and Malarvizhi A. (2011) Hematological, biochemical and ionoregulatory responses of Indian major carp *Catla catla* during chronic sublethal exposure to inorganic arsenic. Chemosphere 82(7): 977-985.

Liu J and Waalkes MP. (2008) Liver is a target of arsenic carcinogenesis. Toxicol Sci. 105(1): 24-32.

Lushchak VI and Bagnyukova TV. (2006) Temperature increase results in oxidative stress in goldfish tissues. 2. Antioxidant and associated enzymes. Comp Biochem Physiol Toxicol Pharmacol 143(1): 36-41.

Mandal BK and Suzuki KT. (2002) Arsenic round the world: a review. Talanta 58(1): 201-235.

Mazumder DN, Ghosh A, Majumdar KK, Ghosh N, Saha C and Mazumder RN. (2010) Arsenic contamination of ground water and its health impact on population of district of Nadia, West Bengal, India. Indian J Community Med. 35(2): 331-338.

McGeer JC, Brix KV, Skeaff JM, DeForest DK, Brigham SI, Adams WJ and Green A. (2003) Inverse relationship between bioconcentration factor and exposure concentration for metals: implications for hazard assessment of metals in the aquatic environment. Environ Toxicol Chem. 22(5): 1017-1037.

Mehana EE, Khafaga AF, Elblehi SS, Abd El-Hack ME, Naiel MAE, Bin-Jumah M, Othman SI and Allam AA. (2020. Biomonitoring of heavy metal pollution using acanthocephalans parasite in ecosystem: An updated overview. Animals 10(5): 811.

Minatel BC, Sage AP, Anderson C, Hubaux R, Marshall EA, Lam WL and Martinez VD. (2018) Environmental arsenic exposure: From genetic susceptibility to pathogenesis. Environ Int. 112: 183-197.

Mudhoo A, Sharma AK, Garg VK and Tseng CH. (2011) Arsenic: An overview of applications, health, and environmental concerns and removal processes, Critical Rev Environ Sci Technol. 41(2): 435-519.

Naujokas MF, Anderson B, Ahsan H, Aposhian HV, Graziano, JH, Thompson C and Suk WA. (2013) The broad scope of health effects from chronic arsenic exposure: Update on a worldwide public health problem. Environ Hlth Perspective 121: 295-302.

Oliveira LHB, Ferreira NS, Oliveira A, Nogueira ARA and Gonzalez MH. (2017) Evaluation of distribution and bioaccumulation of arsenic by ICP-MS in Tilapia (*Oreochromis niloticus*) cultivated in different environments. J Brazilian Chem Soc. 28: 2455-2463.

Oremland RS and Stolz JF. (2003) The Ecology of rsenic. Science 300(5621): 939-944.

Panigrahi AK, Bakshi A and Pattanayak S. (2021) A comprehensive review on the uptake by and accumulation of some heavy metals in fresh water fishes. Biosc Biotech Res Comm. 14(1).

Pedlar RM, Ptashynski MD, Evans R, Klaverkamp JF. (2002) Toxicological effects of dietary arsenic exposure in lake whitefish (*Coregonus clupeaformis*). Aquat Toxicol. 57(3): 167-189.

Praveena M, Sandeep V, Kavitha N and Jayantha Rao K. (2013) Impact of tannery effluent, chromium on Hematological parameters in a fresh water fish, *Labeo rohita* (Hamilton). Res J Anim Vet Fish Sci. 1(6): 1-5.

Rahman MA, Hasegawa H and Lim RP. (2012) Bioaccumulation, biotransformation and trophic transfer of arsenic in the aquatic food chain. Environ Res. 116: 118-135.

Ratnaike RN. (2003) Acute and chronic arsenic toxicity. Postgraduate Med J. 79(933): 391-396.

Ribeiro CA, Vollaire Y, Sanchez-Chardi A and Roche H. (2005) Bioaccumulation and the effects of organochlorine pesticides, PAH and heavy metals in the eel (*Anguilla anguilla*) at the Camargue Nature Reserve, France. Aquat Toxicol. 74(1): 53-69.

Roy S and Bhattacharya S. (2006) Arsenic-induced histopathology and synthesis of stress proteins in liver and kidney of *Channa punctatus*. Ecotoxicol Environ Saf. *65*(2): 218-229.

Saikia KC and Gupta S. (2012) Assessment of surface water quality in an arsenic contaminated village. Am J Environ Sci. 8(5): 523-527.

Santra SC and Samal AC. (2013) Arsenic scenario in Gangetic delta of West-Bengal: risk and management. The Ecoscan 3(1): 41-55.

Schaeffer R, Francesconi A, Kienzl N, Soeroes C, Fodor P, Váradi L, Raml R, Goessler W and Kuehnelt D. (2006) Arsenic speciation in freshwater organisms from the river Danube in Hungary. Talanta 69(4): 856-865.

Schäfer S, Buchmeier G, Claus E, Duester L, Heininger P, Körner A, Mayer P, Paschke A, Rauert C, Reifferscheid G, Rüdel H, Schlechtriem C, Schröter-Kermani C, Schudoma D, Smedes F, Steffen D and Vietoris F. (2015) Bioaccumulation in aquatic systems: methodological approaches, monitoring and assessment. Environ Sci Europe 27(1): 5.

Selim Rezaa AHM, Jeana JS, Leeb MK, Yanga HJ and Liua CC. (2010) Arsenic enrichment and mobilization in the Holocene alluvial aquifers of the Chapai Nawabganj District, Bangladesh: A geochemical and statistical study. Appl Geochem. 25(8): 1280-1289.

Šlejkovec Z, Stajnko A, Falnoga I, Lipej L, Mazej D, Horvat M and Faganeli J. (2014) Bioaccumulation of arsenic species in Rays from Northern Adriatic Sea. Int J Molec Sci. 15(12): 22073-22091.

Shuklaa DP, Dubeya CS, Singha NP, Tajbakhshb M and Chaudhrya M. (2010) Sources and controls of Arsenic contamination in groundwater of Rajnandgaon and Kanker District, Chhattisgarh Central India. J Hydrology 395(1-2): 49-66.

Singh N, Kumar D and Sahu AP. (2007) Arsenic in the environment: effects on human health and possible prevention. J Environb Biol. 28(2 Suppl): 359-365.

Srivastava S and Sharma YK. (2013) Arsenic occurrence and accumulation in soil and water of eastern districts of Uttar Pradesh, India. Environ Monitoring Assessment 185(6): 4995-5002.

Taleshi MS, Seidler-Egdal RK, Jensen KB, Schwerdtle T and Francesconi KA. (2014) Synthesis and characterization of arsenolipids: Naturally occurring arsenic compounds in fish and algae. Organometallics 33(6): 1397-1403.

Tsai JW and Liao CM. (2006) Mode of action and growth toxicity of arsenic to tilapia *Oreochromis mossambicus* can be determined bioenergetically. Arch Environl Contam Toxicol. 50(1): 144-152.

Tsai JW, Huang YH, Chen WY and Liao CM. (2012) Detoxification and bioregulation are critical for long-term waterborne arsenic exposure risk assessment for tilapia. Environ Monitoring Assessment 184(1): 561-572.

Vahter M. (2002) Mechanisms of arsenic biotrans-formation. Toxicology 27:181-182.

Velma V and Tchounwou PB. (2011) Hexavalent chromium-induced multiple biomarker responses in liver and kidney of gold fish, *Carassius auratus*. Environ Toxicol. 26(6): 649-656.

Velma V, Vutukuru SS and Tchounwou PB. (2009) Ecotoxicology of hexavalent chromium in fresh water fish: A critical review. Rev Environ Hlth. 24(2): 129-145.

Weerasiri T, Wirojanagud W and Srisatit T. (2012) Arsenic contamination in soils, water and plants surrounding gold mine at Wangsaphung, Loei province, Thailand. J Environ Res Develop 6(3): 381.

Williams L, Schoof RA, Yager JW and Goodrich-Mahoney JW. (2014) Arsenic bioaccumulation in freshwater fishes. Human Ecol Risk Assessment 12(5): 904-923.

World Health Organization (1993) Guidelines for drinking water quality. Geneva: World Health Organization. http://www.lenntech.com/WHO's-drinking- water-standards. html., 20-02-13.

Wrench J, Fowler SW and Ünlü MY. (1979) Arsenic metabolism in a marine food chain. Mar Poll Bull. 10(1): 18-20.

Zhang W, Miao AJ, Wang NX, Li C, Sha J, Jia J, Alessi DS, Yan B and Yong SO. (2022) Arsenic bioaccumulation and biotransformation in aquatic organisms. Environ Int. 163: 107221.