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Arsenic contamination in food chain - a menace to food safety, human nutrition and health

S. Das Sarkar[1], P.R. Swain[1], S.K. Manna[1], S. Samanta[1]*, P. Majhi[1], A.K. Bera[1], B.K. Das[1] and B.P. Mohanty[1,2]

[1]ICAR-Central Inland Fisheries Research Institute, Barrackpore-700 120, India

[2]ICAR-Fisheries Science Division, Krishi Anusandhan Bhawan II, New Delhi-110 012, India

***Corresponding Author Email :** samantacifri@gmail.com

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Abstract

The metalloid arsenic is one of the persistent toxic elements that has affected a vast population of human being across the globe. Its lethal and unsafe levels in drinking water have been witnessed by more than 100 million people in the South and South-east Asia alone. Literatures suggest that contaminated groundwater is the potential source for arsenicosis. Widespread arsenic contamination in surface water, soil and sediments-either of geogenic or anthropogenic origin-has resulted in presence of this carcinogenic pollutant in plant and animal produce such as rice, vegetables, milk, meat, fish, etc. Further, the arsenic mediated stress to all living organisms is of great concern. Thus, the entire biome is under massive threat of arsenic.

The extent and severity of arsenic contamination in human diet has challenged the safety aspect of human nutrition and health. The chronic arsenicism in human is of greater concern and demands immediate implementation of mitigative measures. The risk of arsenic toxicity through water as well as food and possible way-out have been discussed in this review.

Key words: Arsenic, Food chain, Health, Human diet, Nutrition

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Introduction

Assured and nutritious food is a prerequisite for healthy civilization. It is a big challenge to feed the enormous 7.6 billion world populace with nutritionally secured diet. The challenge faced is even much higher in the tropical countries like India, encountering naturally depleting resources, rapid biodiversity loss, pollution, poverty, illiteracy, unemployment, natural disasters and extreme weather events, poor health care facilities, pandemics which earnestly hinders the health sustenance (Kasthuri, 2018). A recent report by World Food Program states that the country India holds 94^{th} rank in 2020 Global Hunger Index (GHI) with a serious level of hunger scoring 27.2 (https://www.globalhungerindex.org/india.html). The report emphasized malnourishment, stunted growth in child, child wasting, and infant mortality as major health security indicators. In this context, it's an enormous responsibility for the researchers, and especially the nutritionists to ascertain for wholesome as well as safe food for a better nation. A wholesome diet comprises of macronutrients (carbohydrate, protein and fat), micronutrients (vitamins and minerals) and water as per dietary requirement (Cena and Calder, 2020). Simultaneously, we are greatly dependent on nature for plant- and animal-based food items. At the same time, nature itself is on robust grasp of various anthropocene or natural threat factors.

Among these, one of the most loquacious components is pollution. Both aquatic systems and its terrestrial counterpart are more prone to several types of pollutants, of which the metalloid arsenic is the most potent one affecting the biotic community. In human and animals, its health impacts are collectively known as "arsenicosis". Arsenic enters the ecosystem through a number of processes *viz.,* geogenic phenomenon (thermal regime, volcanic activities, weathering and leaching), anthropogenic activities (urbanization, industrial establishments, groundwater extraction for irrigation, exhaustive use of pesticides and fertilizers) and biogenic (plant, animal, microorganism and aquatic biota induced) (Pathak, 2012; Samanta, 2013). Whatever may be the mode of admittance, immediately after entry the contaminant has potential to impose its detrimental effects by deteriorating the environmental quality and the functional aspects for the wide range of biotic community through trophic transfer mechanism.

Arsenic is categorised as class-I carcinogen ubiquitous to atmosphere, soils, natural waters, and organisms (Mateo *et al.,* 2019). It occurs in different inorganic and organic forms with the trivalent arsenite (As^{III}) and pentavalent arsenate (As^{V}) as the predominant inorganic forms - found mostly in the underground constituents. Among arsenite and arsenate, the former is 60 times more toxic than the other to human being (WHO, 1981; Akter *et al.,* 2005). In general, the organoarsenical such as arsenobetaine are nontoxic or least toxic to mammals and are mostly found in marine life and in organisms of deep-sea hydrothermal vent ecosystems which is attributed for their cytoprotective functions against osmotic and temperature stress (Hoffmann *et al.,* 2018). Being the greatest bio-accumulator of As, the marine organisms are reported to produce arsenobetaine, arsenocholine, algal arsenosugars which are safe for the system (Saha *et al.,* 1999). The monomethylarsonate (MMA), dimethylarsinate (DMA) and arsenosugars are mainly found in freshwater organisms (Caumette *et al.,* 2012). Different researchers have reported that the anadromous salmonids contain higher concentration of arsenobetaine than the non-migratory species in which arsenosugars and DMA forms were predominant (Slejkovec *et al.,* 2004). Arsenic contamination levels spread over the lower trophic biota of freshwater origin with sulphur complexed arsenate (As^{V}-S) in phytoplankton and arsenite (As^{III}-S) in zooplankton (Caumette *et al.,* 2011, 2014).

Arsenic speciation studies in the aquatic ecosystems have also revealed that inorganic arsenic (iAs) are absorbed into the phytoplankton which are further converted into methylarsenicals (AsMe) or arsenosugars (AsS) (Francesconi and Edmonds, 1996). In the mineralization processes, bacteria can convert the organic form of arsenic to iAs and methylarsenicals (Hanaoka *et al.,* 1995). As mentioned above, forms or species of arsenic is important in toxicity rather than the total arsenic content. However, a majority of arsenic quantification data focused on total arsenic, rather than its forms due to paucity of speciation facility. This might lead to considerable over-estimation of health risks from dietary arsenic exposure. Moreover, a collective information on dietary uptake of arsenic is lacking. The present review focuses on arsenic contamination levels in different plant, animal and fish-based food items along with their health risks. In addition, the article also emphasizes on possible mitigation measures against arsenic poisoning in human.

Arsenic ingestion in human: Arsenic enters the human body through several pathways - drinking and cooking water, crop and vegetable cultivated in As contaminated area, and through animal products (meat, milk, and egg) resulting into serious health deterioration on chronic exposure across food pyramid. Human diet consists of cereals, pulses, vegetables, fruits and animal proteins that might contribute to total arsenic intake by an individual. Despite wide presence of As in different food items, only few studies have quantified total As intake. EFSA Panel on Contaminants in the Food Chain (CONTAM Panel) quantified the inorganic arsenic exposure from food and water across 19 European countries to range from 0.13 to 0.56 μg kg^{-1} b.wt. per day for average consumers.

The dietary exposure levels per kg body weight were 2-3 times higher for children under 3 years of age than adults (EFSA, 2009). Signes-Pastor *et al.* (2008) had examined flow of arsenic through different food items in arsenic endemic zone of West Bengal and reported a higher level of iAs (170 μg day^{-1}) in daily diet. In As-endemic lower Bengal delta, an adult human is found to consume about 43-568 μg arsenic daily, mainly through rice and water (Ohno *et al.,* 2007; Mondal *et al.,* 2010) which is much above the provisional tolerable weekly intake (PTWI) of 15 μg kg^{-1} b.wt. established by the Joint FAO/WHO Expert Committee on Food Additives. The presence of total arsenic in human food items is mentioned in Table 1. The medical and veterinary uses of As are well known for several decades. The oral administration of Fowler's solution in tonic stimulants are widely used to treat asthma, leukaemia and other deadly cancerous diseases (Leslie and Smith, 1978; Zachariac *et al.,* 1974).

Arsenic contamination through drinking and cooking water: Groundwater resources contribute a pre-eminent share of global drinking water, especially in the rural areas. In Indian subcontinent and Southeast Asian countries, harvesting groundwater for drinking through bore wells/tube wells has been a great boon in reducing cholera, dysentery, and other enteric diseases prevalent in the area. However, this safe tube well water has brought / dug out another serious problem, the arsenic from below the surface. The presence of arsenic in groundwater has exposed millions of people in South and Southeast Asian countries *viz.* India, Bangladesh, Vietnam, Cambodia, Laos, Thailand to unsafe level of arsenic which were above WHO permissible limit of 10 $\mu g\ l^{-1}$ (Kim *et al.,* 2011). This has caused "the worst mass poisoning in history". Besides high level of exposure, arsenic in groundwater often remains in highly toxic inorganic As^{3+} form which has added to the toxicity in worst affected Bengal delta. Water is the greatest source of toxic inorganic arsenic As^{III}, while relatively less toxic As^{V} forms the major part of arsenic in foods. More lucidly, arsenic induced patho-physiological abnormalities in human metabolism emanated from drinking water are collectively gathered as HACRE (hidroarsenicismocrónico regional endémico) or chronic regional endemic hydroarsenicism (Litter *et al.,* 2019).

In general, the ground water contains more amount of arsenic with reported level of 27-3700 $\mu g\ l^{-1}$ (Chakraborti *et al.,* 2009) than that in the surface waters with recorded arsenic concentration of 2-174 $\mu g\ l^{-1}$ in the arsenic contaminated Nadia and North 24 Parganas districts of West Bengal, India (Chowdhury *et al.,* 2015). Authors also reported arsenic contamination in the range of 1.3-37.3 mg kg^{-1} in aquatic sediment of same area. The arsenic levels in surface water and aquatic sediments were much higher than those in a reference site from Hooghly district in West Bengal with recorded levels of 1-8 $\mu g\ l^{-1}$ in water and 1.4-5.2 mg kg^{-1} in sediment. Besides drinking, a large amount of water is used for cooking rice. Concentration of arsenic in rice may vary based upon different cooking process besides the original level present in raw rice. Rice cooked using contaminated ground water contains more iAs than uncooked rice due to chelation of As by rice grain and evaporation of water while cooking that concentrates the metalloid in remaining water (Rahman *et al.,* 2011). Besides this, different processing methods (parboiled/non-parboiled) are also found responsible for As accumulation (Sengupta *et al.,* 2006; Signes *et al.,* 2008).

Study suggested that additional cooking processes including use of high volume arsenic free water (30:1:: water: rice) are prerequisite to remove iAs (86% reduction) from rice grain (Pathak, 2012); however, such precautionary measures are rarely taken. Other than arsenicosis, uptake of As contaminated water, vegetables and grains have also increased the risk of type 2 diabetes in human in Asian population (Hassan *et al.,* 2017). Additionally, daily use of contaminated water for cleaning, bathing and other core household activities increases the absorption of As through skin (Kim *et al.,* 2011).

Arsenic contamination through groundwater, soil and crop: Rice is the most common food item found to be heavily contaminated with As. Being the second most rice consuming country among the South and Southeast Asian countries (Source: Faostat, Helgi Analytics Calculation), India is highly vulnerable to arsenic exposure through rice (Baldwin *et al.,* 2012). In the eastern part of India, specifically in rural West Bengal rice constitutes 51% of daily diet, which can step up to 70% during shortage of non-vegetarian food items (Signes-Pastor *et al.,* 2008). Rice grown in arsenic contaminated areas, near industrial areas, cotton fields, etc., accumulates more amount of iAs from soil than other crop (Seyfferth *et al.,* 2014; Williams *et al.,* 2007). In general, the phosphate transporter mechanism is responsible for As uptake in plants, but the multiple transport mechanisms are also active in rice which results in excessive accumulation of iAs in this crop (Ma *et al.,* 2008).

Indian subcontinent is known for erratic and irregular rainfall which compels the farmers to go for irrigation using groundwater and results in higher iAs accumulation in topsoil as well as in growing plants and their produce (Rahman and Hasegawa, 2011; Brammer and Ravenscroft, 2009). Moreover, researchers also anticipated that excessive lifting of ground water have resulted in faster arsenopyrite oxidation process which increases the availability of As in water (Roy and Saha, 2002). Meanwhile, there are studies which emphasize that the brown rice retains more amount of As (70-80% higher) than the polished white rice due to presence of high amount of arsenic in germ layer in the former (Sun *et al.,* 2008). Williams *et al.* (2005) reported iAs concentration in different varieties of rice such as basmati (0.02-0.04 $\mu g\ g^{-1}$), brown basmati (0.04 $\mu g\ g^{-1}$), long red rice (0.05 $\mu g\ g^{-1}$), but higher concentrations in Thai (0.11-0.51 $\mu g.g^{-1}$) and Jasmine (0.11 $\mu g\ g^{-1}$) rice. Further, unlike many other foods, inorganic arsenic constitutes about 27-93% of total arsenic in rice that increases its food safety risk (EFSA, 2009).

Studies of Jackson *et al.* (2012) highlighted that rice and rice products, baby foods and sports drinks contained higher level of iAs than the drinking water permissible limit of 10 $\mu g\ l^{-1}$. Hassan *et al.* (2017) emphasized that the consumption of rice with 0.08 $\mu g\ g^{-1}$ of arsenic on regular basis have similar impact like intake of drinking water with 10 $\mu g\ l^{-1}$ of iAs. Arsenic contamination has been detected in large majority of food items, but at different concentrations (Jones, 2007). Among common human food items, roots and tubers generally possess the highest As concentrations (Peryea, 2001). Among the vegetables, leafy, bulbous and rooted tubers contain higher amount of As. Significantly higher contents of total arsenic have also been reported in majority of food commodities from the contaminated areas of Nadia district of West Bengal. Fruits and fruit drinks also contain iAs (3.57±4.42 $\mu g\ l^{-1}$), DMA (0.30±0.55

Table 1: Reported arsenic concentrations in different food items and associated permissible limits

	Food items	Total arsenic concentration	References	Permissible limit (PL)
Grains	Paddy	550±13 μg kg^{-1}	Signes *et al.*, 2008	-
	Un-boiled rice	339 ±14 μg kg^{-1}		200 μg kg^{-1}* (Codex Standards, 2019)
	Boiled rice	507±52 μg kg^{-1}		-
	Puffed rice	120±3 μg kg^{-1}	Signes-Pastor *et al.*, 2008	-
	Rice	100–590 μg kg^{-1}	ICAR, 2011	350 μg kg^{-1}* (Codex Standards, 2019)
	Wheat	450–1080 μg kg^{-1}		-
	Barley	180 μg kg^{-1}	Xue *et al.*, 2020	-
Leafy vegetables	Amaranth	572 μg kg^{-1}	Farid et al., 2003	3500 μg kg^{-1} (Eisler, 1988)
	Red amaranth	321 μg kg^{-1}		
	Stem amaranth	284 μg kg^{-1}		
	Indian spinach	189 μg kg^{-1}		
Vegetables	Chilli	112 μg kg^{-1}		
	Potato	103 μg kg^{-1}		
	Carrot	112±10 μg kg^{-1}	Signes-Pastor *et al.*, 2008	
	Kidney beans	42±3 μg kg^{-1}		
	Radish	154±11 μg kg^{-1}		
	Tomato	54±5 μg kg^{-1}		
	Onion	56±6 μg kg^{-1}		
	Cauliflower	60±9 μg kg^{-1}		
	Brinjal	48±2 μg kg^{-1}		
	Brinjal	1500 – 2550 μg kg^{-1}	ICAR, 2011	
	Pointed gourd	1200 – 3650 μg kg^{-1}		
	Cabbage	2500 – 5600 μg kg^{-1}		
Spices	Coriander seed	76±10 μg kg^{-1}	Signes-Pastor *et al.*, 2008	-
	Turmeric	71±5 μg kg^{-1}		-
	Cumin seed	76±8 μg kg^{-1}		-
	Mustard	48±5 μg kg^{-1}		-
	Ginger	208±5 μg kg^{-1}		-
	Fenugreek seed	28±2 μg kg^{-1}		-
	Mustard	1370 – 1600 μg kg^{-1}	ICAR, 2011	-
Fruits	Betel nut	26±5 μg kg^{-1}	Signes-Pastor *et al.*, 2008	3500 μg kg^{-1} (Eisler,1988)
	Apple	4.8±3.1 ng g^{-1}	Schoof *et al.*, 1999	
	Banana	2.3±0.74 ng g^{-1}		
	Grapes	10.2±3.1 ng g^{-1}		
	Orange	1.6±1 ng g^{-1}		
	Peach	3.4±1.2 ng g^{-1}		
	Watermelon	40.2± 2.8 ng g^{-1}		
	Papaya	1800 – 5600 μg kg^{-1}	ICAR, 2011	
	Banana	1200 – 4800 μg kg^{-1}		
	Grape juice	58.3±3.0 ng g^{-1}	Schoof *et al.*, 1999	200 μg kg^{-1}* (total arsenic) (GAIN Report, 2006)
	Apple juice	7.6±2.3 ng g^{-1}		
	Orange juice	4.8±1.3 ng.g^{-1}		
Animal products	Dairy	180 μg kg^{-1}	Xue *et al.*, 2020	140 μg l^{-1} (FAO, 2013)
	Meat	210 μg kg^{-1}		<500 μg kg^{-1} (Eisler,1988)
	Egg	0.227 μg g^{-1}	Rana *et al.*, 2014	
Fish and processed products	*Oreochromis mossambicus*	1.01±0.18 mg kg^{-1}	Kumar *et al.*, 2021	-
	Labeo catla	0.79±0.10 mg kg^{-1}		-
	Labeo rohita	0.53±0.34 mg kg^{-1}		-
	Freshwater fish	0.297 mg kg^{-1}	Mania *et al.*, 2015	0.1 mg kg^{-1}*

Table continued

Table 1: Reported arsenic concentrations in different food items and associated permissible limits

	Food items	Total arsenic concentration	References	Permissible limit (PL)
				(inorganic arsenic) (GAIN Report, 2006)
	Marine fish	0.516 mg kg^{-1}		6 mg kg^{-1} (Eisler,1988)
	Fish products	1.48 mg kg^{-1}		-
	Seafood	0.87 mg kg^{-1}		6 - 10 mg kg^{-1} (Eisler, 1988)
	Demersal fish flounder	9.36 mg kg^{-1}	Ruttens *et al.,* 2012	-
	Oreochromis niloticus	0.203 ± 0.039 µg g^{-1}	Ruangwises et al., 2012	-
	Puntius gonionotus	0.217 ± 0.040 µg g^{-1}		-
	Pangasius hypophthalmus	0.201 ± 0.029 µg g^{-1}		-
	Channa striata	0.354±0.087 µg g^{-1}		-
	Puntius ticto	0.32±0.01 mg kg^{-1}	Ahmed *et al.,* 2016	-
	Puntius sophore	0.19±0.01 mg kg^{-1}		-
	Puntius chola	0.17 mg kg^{-1}		-
	Labeo rohita	0.73±0.03 mg kg^{-1}		-
	Glossogobius giuris	0.20±0.01 mg kg^{-1}		-
	Channa punctata	0.02-0.04 mg kg^{-1}	Das *et al.,* 2004	-
	Tenualosa ilisha	2.55±1.3 mg kg^{-1}	Al-Rmalli *et al.,* 2016	-
	Carica soborna	1.4±0.2 mg kg^{-1}		-
	Gudusia chapra	0.39±0.2 mg kg^{-1}		-
	Channa punctata	0.09±0.007 mg kg^{-1}		-
	Nandus nandus	0.15±0.04 mg kg^{-1}		-
	Sperata aor	0.014±0.01 mg kg^{-1}		-
	Micropterus cataractae	0.012 mg kg^{-1}		
	Cirrhinus cirrhosus	0.005 mg kg^{-1}		
Shellfish	*Machrobrachium rosenbergii*	0.20±0.02 mg kg^{-1}	Kumar *et al.,* 2021	10 mg kg^{-1} (Eisler,1988)
Snail	*Bellamya bengalensis*	2.18±0.04 mg kg^{-1}		
Foods (not specified)				1.1 mg kg^{-1}(FSSAI, 2020)

*Value are presented as Maximum level (ML)

µg l^{-1}) and MMA (0.30±0.71 µg l^{-1}) (Wang *et al.,* 2015). It has been shown that vegetables grown in Bangladesh has a mean level of 0.0545 µg g^{-1} (range: 0.005 to 0.54 µg g^{-1}) which is 2-3 fold higher in As content than UK-grown vegetables. However, the levels were below the regulatory limit of 1 µg g^{-1} (Al-Rmalli *et al.,* 2005).

Arsenic contamination through animal meat/flesh: Residue of arsenic has also been reported in animal tissues, namely, meat, milk, poultry meat, egg, fish, shrimps and bivalves worldwide. Roxarsone (ROX) and nitarsone are arsenic based feed additives widely incorporated in poultry feed. A China based study has reported 0.19-9.7 mg kg^{-1} of inorganic arsenic in ROX incorporated feed for poultry industries (Hu *et al.,* 2017). Research conducted at the Bloomberg School of Public Health, Johns Hopkins Centre suggested that although cooking reduces the level of roxarsone, it also increases the iAs concentration in cooked meat (JHBSPH, 2013). Hence, it is advised to use arsenic free feeds, *i.e.,* feeds devoid of roxarsone (ROX) and nitarsone for poultry to combat the As related health hazards among consumers (Nachman *et al.,* 2013). Though As gets accumulated in non-edible feather parts also, these by-products are used as fertilizer or as diet for other livestock (Nachman *et al.,* 2013). Further, arsenic accumulated in poultry litter enters directly into the agricultural field by its use as fertilizer. Arsenic contaminations have been reported for different organs in broiler birds from arsenic endemic zone of Bangladesh with recorded concentration of 219±12 µg kg^{-1} in skin,102±8 µg kg^{-1} in liver, 96 ± 6 µg kg^{-1} in lung, 88±7 µg kg^{-1} in kidney and 68 ± 5 µg kg^{-1} in thigh muscle (Ghosh *et al.,* 2012). Besides meat, egg albumen, yolk and other poultry products are also sources of arsenic for human being (Datta *et al.,* 2012).

Seafish and other seafood contain high level of arsenic (2-60 mg kg^{-1} d.wt.) and are the major source in non-Asian countries. Among all food items, fish contains the highest concentrations of total arsenic. However, major part of the As remains in least toxic organic forms (mostly as arsenobetaine) and inorganic arsenic levels generally remains below 0.2 mg kg^{-1} dry mass (EFSA, 2009). Arsenic has also been quantified in freshwater fish with highest level in *Labeo catla* (147±13 µg kg^{-1}), followed by *L. rohita* (110 ± 13 μg kg^{-1}), *Cirrhinus mrigala* (72±7 μg kg^{-1}) and *L. bata* (69±18 μg kg^{-1}) (Sarkar, 2012). However, data on As speciation in freshwater fish is not available obscuring safety issues of freshwater fish. Arsenobetaine is however, reported to be synthesized mostly as a protective response to salinity and freshwater fish might not synthesize it in large amounts. Arsenic concentration in fish is dependent on its level in water and sediment, however, the relationship is not linear. Bioconcentration and bioaccumulation values of arsenic ranges widely from 0.1 to 3091 in freshwater fish (EFSA, 2009). However, the accumulation is much higher in benthic organisms including bivalves and molluscs. Among fishes, the highest accumulation occurs in liver and avoiding liver might be a safe food habit, especially in arsenic affected areas (Kumar *et al.,* 2021).

Egg as a source of arsenic: Egg is considered as a daily diet of human since pre-historic days; the delicacy, nutrient value and easy availability makes it one of the top consumer preferred food item globally. Reports have shown that poultry (chicken and ducks) reared in As-contaminated areas and use of As rich poultry feed causes accumulation of As in poultry meat as well as in egg (Hothem and Welsh 1994). Rana *et al.* (2014) reported considerable presence of As in whole egg (0.227 μg g^{-1}) and its different compartments: 0.065 μg g^{-1} in albumin and 0.107 μg g^{-1} in yolk of chicken egg whereas, 0.155 μg g^{-1} arsenic in whole duck egg and 0.095 μg g^{-1} in albumin and 0.046 μg g^{-1} in yolk. Thus, As concentration of yolk is more than in albumin of chicken, while reverse was noticed in duck egg.

Meat and meat products as source of arsenic: Pork and pork products like processed cold pork meat, sausage are delicacy in many countries such as East and Southeast Asia and Central Europe including North and South America. While studying the health implications of pesticides and heavy metals in food samples of South Western Spain, Bordajandi *et al.* (2004) reported a higher residue level of As in pork meat (62.4 ng g^{-1}) as compared to processed sausage (16.1 ng g^{-1}). Similarly, meats (chevon, mutton and beef) from the animals reared in the contaminated areas contains As which might have accumulated through their feed and drinking water sources. A study conducted on Black Bengal goat, a predominant goat variety in the As endemic zone of Gangetic delta was estimated with arsenic level of 0.186 mg kg^{-1} in meat; 0.473 mg l^{-1} in blood, 0.291 mg l^{-1} in urine, 1.283 mg kg^{-1} in faeces and 0.771 mg kg^{-1} in hair (Rana *et al.,* 2012). Cattle reared in the endemic area are reported to accumulate more arsenic than in non-endemic area due to the presence of more As in their diet and drinking water. Studies have shown that the metalloid As has a tendency to accumulate higher in skin/hair followed by in faeces, urine and milk (Datta *et al.,* 2012).

Fish as a source of arsenic: Fish is one of the most nutritious food with desired essential amino acids, micronutrients, PUFA, etc. (Mohanty *et al.,* 2017). Fish, as integral component of aquatic food chain, has potency to transfer the element from aquatic environments to top level consumer including human (Hicks, 1993). South and South-east Asian races are the major fish-eating population in the world. Their daily dishes consist of fish with boiled rice coupled with processed vegetables (Lipoeto *et al.,* 2012). In addition, they also prefer edible snails and bivalves as delicacy which are recently considered as one of the rich sources of total arsenic. Lai *et al.* (2012) reported 83 mg arsenic per kg (TETRA and arsenosugars) of freshwater snails in Thailand.

Study also suggest that among the major aquatic groups (shrimps, bivalves, fish, gastropod), gastropods were found with meagre quantity of harmless arsenobetaine but with a higher level of inorganic As^{III} probably because these benthic organisms are continually exposed to high levels of sediment As (Hahn, 2016). A study in Russia showed higher levels of As in benthic organisms in shallow lakes as compared to those in deeper lakes in summer emphasizing the role of summer processes in As release and bioavailability (Hull *et al.,* 2021). Among all the animal produce, seafoods have high concentration of total arsenic, however, the arsenic often remains as arsenobetaine and arsenocholine which are less toxic and thus, these foods are considered safe for human consumption. However, as a precautionary measure it is better to exclude gastropods and bivalves from arsenic contaminated areas in diet (Chowdhury and Samanta, 2012).

Impact of arsenic on human health: Gangetic plains are endemic to groundwater arsenic contamination which has exposed over 100 million people to unsafe levels of arsenic (Argos *et al.,* 2012). The arsenic intake through water and food has led to the clinical conditions called arsenicosis. It is the chronic form of toxicity where clinical signs develop between 6 to 24 months of As exposure (Saha *et al.,* 1999). The exposed people develop different levels of skin lesions such as hyper- or hypo-pigmentation, rain drop pigmentation and keratosis (Guha Majumder, 2012). In addition, prolonged exposure to As also results in multi-organ pathophysiological changes which include respiratory insufficiency, dyspepsia, liver and cardiovascular disintegration, paraesthesia, anaemia, reproductive failure and infant mortality in human (Von *et al.,* 2006). Moreover, cancer development in skin, urinary bladder and lungs are common consequences of prolonged exposure to arsenic (Saha, 2003). Intake of contaminated food and water has comparatively more critical health risk than dermal exposure (Zhang *et al.,* 2019).

Authors also surmised that the carcinogenic risk is higher in adults than children while non carcinogenic risks are apparently higher in children than adults. Besides cancers, arsenic ingestion is also related with other diseases like atherosclerosis, hypertension, diabetes mellitus, etc. (WHO, 2001). In human population from arsenic contaminated region, chronic lung disease, neuropathy and chronic liver disease over and above skin manifestations are the major cause of morbidity while chronic lung disease and cancer are major cause of mortality among the arsenic exposed population (Guha Mazumder, 2016). Recently, Bhowmick *et al.* (2018) have given an exhaustive review on the critical consequences of arsenicism in human, with emphasis on infants and community-based mitigation measures. Arsenic contamination also has a greater impact on the socio-cultural amenities of people by affecting their living and livelihood standards (Rahman *et al.,* 2018).

Mitigation measures: South and Southeast Asian nations are more vulnerable to arsenic induced health hazards though food chain. India and Bangladesh, the worst As-affected countries, have gradually witnessed a greater loss of physical, social and economic resources. Although studies and awareness campaigns have educated people, total avoidance of arsenic contaminations is almost impractical due to the natural and geogenic abundance of arsenic. One of the vital measures against arsenicism would be provision of safe As-free drinking water to human and animal populations through commissioning of arsenic-treatment plants in affected villages under community-based initiatives, or supply of filtered and chlorinated surface water as safe source of drinking and domestic use. These precautionary options have been substantially effective in reducing arsenic intake through drinking water and associated human sufferings in arsenic contaminated areas.

Extensive survey on quantification of arsenic in different food matrices and total dietary intake by a susceptible population is the need of the hour. A comprehensive database on speciation of As across all food types is imperative (Taylor *et al.,* 2017). This will not only fill the data gaps but also will help to identify the low-arsenic food items and thereby create public awareness on cultivation and consumption of such items. Recently, Kumar *et al.* (2021) had identified low As accumulating food fishes *viz. Cirrhinus mrigala*, *Ctenopharyngodon idella* and *Macrobrachium rosenbergii* from aquaculture pond of arsenic affected area at Basirhat-I, North 24 Parganas district of West Bengal. The authors also recommended these candidate species for fish farming, that would aid to minimize the risk of human exposure through consumption. Similarly, development and cultivation of low arsenic accumulating crop varieties and animal husbandry practices should be practiced. Harvesting of rainwater and its utilization is an excellent option which is reported to reduce the concentration of As through dilution.

According to Sanyal (2019), recharge of ground water with harvested rainwater can eventually reduce As contamination and is thereby recommended for farming. It not only reduces the risk of arsenic contamination in farmyard crops but will also help in preventing shrinking of groundwater level. Use of As-contaminated ground water for refilling of aquaculture ponds in summer is a major source of As in fish. Thus, rainfall and evaporation are two major environmental phenomena which have great influence on As content in fish ponds (Sarkar, 2012). Good rainfall reduces As levels both in surface waters through dilution and in agricultural fields through As-percolation to groundwater. Thus, rainwater harvesting is an essential requirement in As-prone areas. Ground water from deep aquifers, which is relatively free off As contamination, is the last option for pond refilling during summer. Additionally, there should be distinct demarcation on consumer products like labelling of rice, rice products and similar arsenic-prone items for arsenic contents. A complete ban of arsenic-containing agrochemicals and animal growth promoters should be implemented. Development of efficient waste treatment and disposal systems to prevent arsenic contamination of soil and water from industrial activities have become more prioritized avenues (Ellis *et al.,* 2002). The comprehensive report on arsenic treatment technologies for solid, waste and water by U.S. Environmental Protection Agency (USEPA) surmised various arsenic treatment technologies along with evaluating their efficiencies applicable for industrial arsenic. Generally, soil and waste are being treated by immobilization process through solidification/stabilization (S/S) which reduces arsenic level to below 5 ppm. Similarly, pyrometallurgical processes are equally suitable for soil and waste from metal mining and smelting industries. At the same time, precipitation/co-precipitation processes are routinely used for arsenic-contaminated water. However, adsorption and ion exchange techniques are found more promising for smaller systems and recognised as polishing technology for larger treatment systems.

Several researchers have examined feasibility of bioremediation of As. Rhizoremediation is a process in which arsenic resistant bacteria associated to rhizosphere play vital roles in plant growth and might be used for phytoextraction of arsenic from contaminated soils (Mesa *et al.,* 2017; Lampis *et al.,* 2015). Thus, it promotes plant-bacteria interaction in the rhizosphere augmenting phytoremediation purposes (Mosa *et al.,* 2016; Rajkumar *et al.,* 2010). Therefore, phytoremediation has become the most feasible option to eradicate arsenic from contaminated areas (Mateo *et al.,* 2019). Potential role of microbes like *Citrobacter koseri* and *Pseudomonas putida* in accumulation of As from the environment has also been highlighted (Das and Das, 2021). Application of organic amendments-farmyard manure, vermicompost, etc., are found to reduce As contamination effectively in soil-plant biosystem (Sarkar, 2012). Vermicompost is effective in reducing available As through metal-organic matter bonding which envisage greater stability between As and fulvic acid, a natural compound of humus. In the process, phosphate and nitrate are found to be the most relevant nutrient responsible to unlock and move As from organometal complexes. Taking a lead on the research of inorganic amendments, author also disclosed that phosphate-based fortifications can reduce inorganic forms of As in rice grain. Further, vermicompost is also reported to reduce As^{V}, while the As^{III} can be removed by applying FYM.

Taken together, modified organic manuring along with appropriate inorganic amendments with iron/zinc/silicate would be a better option to mitigate arsenic in soil-plant-water-biological systems (Sanyal, 2019; Sarkar, 2012). Indigenous drug like curcumin, a natural dietary polyphenolic compound of turmeric plant *Curcuma longa*, provides an excellent source of antioxidants useful to reduce/cure chronic illness like arsenicosis with skin lesion by reducing free radicals (Sarkar, 2012). The compound is reported to cure neurological disorders and hence possess a greater demand in medical science with reference to stem/progenitor cells (Jahan-Abad *et al.,* 2017). The regulatory role highlighting the biomolecular mechanism of curcumin on arsenic-induced toxicity is also well versed across globe (Rahaman *et al.,* 2020). The phytochemical curcumin has been successfully utilized in preventing DNA damage therapies in human lymphocytes by arresting reactive oxygen species and lipid peroxidation and elevating the antioxidant activity thereby (Biswas *et al.,* 2010). Lastly, clinico-epidemiological surveys surmising fish consumption pattern, socio-economic status, and drinking water source of arsenic endemic area will envisage a better option to understand the chronic impacts of arsenic on human and thereby creating awareness and educating people against this deadly disease. Involvement of local participants will appraise a better initiative contemplating the need for knowledge gain and precautionary measures about slow arsenic poisoning, *i.e.,* arsenicism and chronic arsenical poisoning *i.e.,* arsenicalism (Kapaj *et al.,* 2006). A typical example by Santhana *et al.* (2020) details about the arsenic related cancer risk emanated from water and fish-borne arsenicosis. Hence, the authors have urged for suitable mitigation measures to tackle such deadly disease.

Arsenic is sourced from natural deposits as well as from anthropocene comprising atmospheric fall out, effluent dumping, and terrestrial runoff. The geogenic arsenic is affecting each trophic compartment of soil-water-plant-animal-biological ecosystem of both terrestrial and aquatic domains. The trophic transfer mechanism has been the sole pathway for bioconcentration, bioaccumulation, biomagnification and biodilution of metalloid from biota of lower to higher trophic guilds. Thus, the potential toxic effects, persistence and bioaccumulation of toxicant is of global concern. Episodes of chronic arsenic poisoning has been detrimental to humans due to its carcinogenic role and subsequent multisystem disorders. In purview of minimizing arsenical intoxication in vast population of South and Southeast Asia it is imperative to implement mitigation measures at community level.

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Add-on Information

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