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Arsenic contamination in the food chain: A threat to food security and human health

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ABSTRACT

Arsenic is a toxic metalloid naturally found in the earth's crust and released into the environment through natural and anthropogenic activities. Arsenic becomes exceptionally toxic even at low exposure levels because of its high water solubility and bioaccumulation tendency in different environmental matrices. Crops receiving arsenic contaminated irrigation water accumulate it in different degrees depending on the species and variety. Consumption of contaminated crops and drinking water has been identified as important routes for its transfer into the food chain. Besides, consuming seafood and livestock-based food products such as meat and milk from arsenic endemic regions also contributes to the food chain transfer and contamination. The literature clearly indicates that the toxic effect of arsenic in any food product is highly dependent on its chemical speciation. Inorganic arsenic compounds are generally more toxic than organic forms. On consumption of contaminated food products and water, only the bioavailable form of arsenic goes directly into human body and interferes with different metabolic pathways. Thus, prolonged arsenic toxicity leads to carcinogenic and non-carcinogenic health risks such as arsenicosis, cancers, hepatotoxicity, kidney failure, and skin diseases. Therefore, this review highlights the distribution and mobility of arsenic in soil-plant system, its bioavailability in plant and livestock-based food products, arsenic transfer into the food chain, and human health risks. In the current state when arsenic has emerged as a worldwide threat, an integrated strategy is urgently required to combat arsenic contamination, mandating the creation of national and international action strategies for arsenic contamination mitigation.

1. INTRODUCTION

Urbanization and industrialization are the chief routes of human development in multiple ways today. However, contaminants generated by anthropogenic activities and some natural incidences have endlessly polluted the environment. Arsenic is naturally found in the earth's crust and is extensively distributed in various components of the environment. It has a 74.9 g/mol atomic weight, 5.73 g cm^{-3} specific gravity, and a boiling and melting point of 614°C and 817°C, respectively [1]. It is a firm, breakable crystalline solid with a silver-grey color [1]. Its high industrial value makes it inevitable to circumvent living in an arsenic-free environment. It is used in making semiconductors, herbicides, pesticides, fertilizers, paints, cosmetics, glass industry, fireworks, ammunition, etc. [2]. The International Agency for Research on Cancer has classified inorganic arsenic as a Group 1 carcinogen [3], and Agency for Toxic Substances and Disease Registry has considered it as genotoxic, neurotoxic, and embryotoxic with a half-life (plasma) of 3–4 h [4].

Soil health is essential as it is directly linked to food security, affecting plant growth, productivity, and human health. Soil-bound arsenic in the agroecosystems is transferred to the edible parts of crop plants through natural mineral uptake mechanism. However, prolonged consumption of such contaminated crops may pose health risks to the human population [5,6]. Another route for arsenic in the human body through the food chain is the intake of contaminated drinking water [7], consumption of seafood [8], and livestock-based products [9]. Food products such as milk, meat, eggs, fish, and other dairy and poultry products produced by animals feeding on arsenic contaminated crops and water or thriving in the arsenic contaminated environment could be another source of food chain contamination [10,11].

Arsenic toxicity in humans leads to multiple health risks such as skin disorders, cancers, melanosis, hyperkeratosis, lung disease, peripheral vascular diseases, gangrene, diabetes mellitus, hypertension, and ischemic heart disease [12,13]. Moreover, chronic exposure to inorganic arsenic increases the risk of diabetes mellitus, adverse pregnancy outcomes, and even skin cancers, lungs, and urinary bladder [14].

Therefore, it is crucial to focus on averting an increase in arsenic contamination in the food chain and exploring the novel methods to

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reduce it. Hence, the present study highlights the bioaccumulation of arsenic in soil and water and its subsequent transfer into the crop plants, including cereals, vegetables, seafood along with livestock-based food products, namely, milk, meat, and eggs. It emphasizes on food chain contamination and further outlines various health risks and disorders due to chronic arsenic toxicity. The study reflects the directions for future that may be helpful for global scientific communities, stakeholders, and policy makers to mitigate the arsenic contamination.

2. BIOAVAILABILITY AND MOBILITY OF ARSENIC IN SOIL-PLANT SYSTEM

Different soils have varying levels of arsenic depending on the parent material; in most cases, the baseline of arsenic in agricultural soils may range from 5 to 10 mg/kg soil [15]. However, agricultural soil quality is compromised by the escalation of urban and industrial activities globally. Arsenic is chiefly present as As(III) and As(V) in nature. The other main species of arsenic in natural environments include monomethylarsonite (MMA(III)), monomethylarsonate (MMA(V)), dimethyl arsenite (DMA(III)), dimethyl arsinate (DMA(V)), arsenocholine, arsenosugars, arsenobetaine, trimethylarsine oxide, and tetramethylarsonium ions [16]. Furthermore, the As(III)) has been found more toxic, mobile and soluble than organic arsenic because these can efficiently react with sulfhydryl (–SH) groups of different proteins and restrict the cellular functions that ultimately lead to the death of cells [17].

The mobility and transformation of arsenic in soil are determined by multiple factors such as its oxidation states, soil texture, and iron oxides [18], sorption desorption processes [19], soil pH [20], organic matter and metallic elements [21], redox potential and organic acids [22], oxic anoxic conditions [23], and microbial species [24]. Microbial species augment the interconversion of As(III) and As(VI) by solubilizing or immobilizing arsenic in the soil-plant system [25]. Arsenic dynamics in the soil-cabbage system showed that iron oxides increased arsenic mobilization in soil [18]. In contrast, aluminum oxides contributed strongly to the immobilization of arsenic. Moreover, an increased sand content promoted the mobility of arsenic, whereas increased silt and clay contents showed inhibitory effects [18]. These biotic and abiotic factors alter the biogeochemistry of arsenic in soil-plant system, making it bioavailable to the crop plants. The mechanism of arsenic uptake by plants varies with the chemical speciation. It has been reported that As(V) uses inorganic Phosphate (Pi) channels for its entry into the plant cell [26]. On the other hand, plants uptake As(III) via various nodulin-26-like intrinsic proteins and silicon transporters due to analogous chemical structures [27]. Most arsenic typically ends up in plants' vacuolar compartments, whether in the root or shoot tissue. Arsenic is transported and accumulated to the next level consumer; prolonged consumption of such crops poses numerous health hazards.

3. BIOAVAILABILITY AND MOBILITY OF ARSENIC IN WATER

Chronic arsenic poisoning caused by drinking water is considered one of the world's biggest environmental disasters recorded in the last century [28]. Water sources get contaminated either by natural processes or through anthropogenic activities. Natural processes include the leaching of minerals, the interaction of rocks with water, groundwater movement, geothermal activities, and mineralization [29]. The leaching of arsenic from aquifers depends on the geochemical characteristics of groundwater and arsenic speciation. In groundwater, As(V) is predominant in oxic environments, with significant forms of H_3AsO_4, H_2AsO_4, $HAsO_4$2-, and AsO_4^{3-}, whereas, As(III) is more dominant in anoxic environments, with H_3AsO_3, H_2AsO_3, and $HAsO_3^{2-}$ being the common species [30]. Higher organic contents and alkaline conditions in groundwater and aquifers could also enhance the release of arsenic into groundwater [21,31]. Geogenic arsenic-contaminated groundwater has become a matter of concern in the Ganga delta region, especially for the human population living in India and Bangladesh [32]. Chakraborti *et al*. [7] reported health risks to more than 10 million Indians in the Ganga delta region from fluoride and arsenic due to dependency on groundwater resources. However, anthropogenic activities, including domestic and industrial effluent discharge, agricultural runoff, leaching of agrochemicals, coal power plants, smelting and mining activities [33] also contaminate the water resources. Besides drinking water, aquatic life thriving in arsenic-contaminated water resources also tends to accumulate in their organs. Many researchers have reported high arsenic concentrations in fish, crabs, eels, and other aquatic animals used as seafood [34,35].

4. ARSENIC ACCUMULATION IN CROPS

4.1. In Cereal Grains

Arsenic is a highly toxic metalloid and widely distributed contaminant in the food chain. Because of plants' innate ability to uptake minerals from the soils, food crops such as cereals and vegetables have been regarded as important channels for arsenic exposure in humans. Arsenic contamination in cereals due to geogenic and anthropogenic sources has been reported in numerous studies [6,36] [Table 1]. Rice has a high arsenic accumulation efficiency than any other cereal due to anaerobic conditions that promote its mobilization and uptake by the rice plant [37]. Mining and smelting activities in China have contaminated paddy soils, resulting in high arsenic bioaccumulation in rice grains [38]. Besides, extensive and prolonged use of arsenic-based fertilizers and pesticides also contribute as a source of arsenic in agroecosystems [39]. Other factors that influence the arsenic content in rice include rice grain processing [40], rice variety [41], the region where it is grown [42], irrigation method [43], and the cooking method [44]. Arsenic contamination of the soil–wheat system has been documented as a result of excessive arsenic levels in groundwater used for irrigation in China [45]. In another study, high levels of arsenic in wheat grain (27 µg/kg) were reported from geo-genically contaminated areas of the mid-Gangetic plain of Bihar, India [46].

Food chain transfer of arsenic affects crop quality and productivity, threatening food security and further compromising human health. Prolonged consumption of such crops affects the health and wellness of human beings; moreover, such crops are not considered fit for export. Another study from the same region, Bihar, reported total arsenic in wheat grains (43.64 µg/kg) with a lifetime cancer risk (1.23×10^{-4}), much higher than set by USEPA regulatory range (10^{-4}–10^{-6}) [10] for the rural population due to wheat consumption grown in that region. Since Bihar exports wheat across the country, arsenic exposure through wheat-based food consumption may occur in the non-endemic areas of the country with a similar wheat-based diet [10]. The other factors influencing the arsenic accumulation and bioavailability in wheat crop include, the wheat variety [47], industrial and mining activities [48], wastewater irrigation and sludge application [39], coal-fired thermal power plants [49], waste dumping in the vicinity of fields, and extensive use of agrochemicals [50].

4.2. In Vegetables

Vegetables are an essential component of the human diet; thus, they are also an important channel of arsenic exposure to humans. Vegetable

Table 1: Arsenic in cereal grains (µg/kg).

Country	Crop	Sample size (*n*)	Arsenic (mean)	Arsenic (range)	References
China	Rice	5	656.00	603–729	Zheng *et al.*[51]
Pakistan	Maise	4	3730.00	1470–3540	Natasha *et al.*[52]
	Wheat	13	2310.00		
Malaysia	Paddy	9	84.76		Zulkafflee *et al.*[53]
Bangladesh	Rice	35	1370.00		Proshad *et al.*[54]
Brazil	Rice	16	212.00	2–1830	Ng *et al.*[55]
China	Maize	18	90.00	60–260	Cai and Li [38]
	Rice	22	130.00		
China	Wheat	22	417.00	271–991	Zhang *et al.*[56]
Saudi Arabia	Rice	13	0.30	0.1–1	Althobiti *et al.*[57]
Iran	Rice	210	0.16	0.05–0.31	Roya and Ali [58]
Italy	Paddy	168	155.00	49–523	Tenni *et al.*[59]
India	Wheat	35	27.00	7.7–108	Kumar *et al.*[46]
	Green g	6	23.00	7.9–49	
	Maize	31	13.00	4.8–43	
	Paddy	15	51.00	2.51–132	
China	Wheat	25	66.90	22.8–154	Tong *et al.*[45]
China	Wheat	75	33.30	6.5–54.9	Shi *et al.*[48]

cultivation in arsenic endemic regions threatens food security and human health to a greater extent. The arsenic contamination in vegetables depends on multiple factors, including the type of vegetable, soil type, irrigation water quality, vicinity area, anthropogenic pressure, and geogenic contamination [Table 2]. In a study from Samta village, West Bengal, India (arsenic endemic region), arsenic levels in vegetables surpassed the national and international limits. The contamination in vegetables was associated with arsenic-contaminated tube well water (0.24 mg/L) used for irrigation [60]. In another study from the mid-Gangetic plain of Bihar, India, the mean arsenic concentration in the vegetables was reported to be very high (452 µg/kg) and in the range of 37–3947 µg/kg, due to the geogenic source with some diffused anthropogenic activities [46]. The arsenic transfer to the food chain via irrigation water (contaminated ground water resources) has been well documented. Huq *et al*. [61] reported that excessive groundwater withdrawal for irrigating agricultural fields in Bangladesh has contributed to high arsenic levels in surface soils, further leading to contamination of crops. Industrial and mining activities also strongly influence arsenic availability in different components of environs and alter the quality of water, soil, and food crops [62]. Furthermore, wastewater irrigation-mediated arsenic food chain transfer is a significant pathway, particularly in developing countries with limited water resources and inadequate wastewater treatment facilities [52].

The root-to-shoot translocation and accumulation of arsenic species differ between plant species and even between the variety of cultivars [63]. Arsenic translocation to the above-ground parts of the vegetables is generally limited [64] due to various tolerance mechanisms developed by plants [65]. Therefore, grains, seeds, lentils, and fruits end up with relatively lower levels of arsenic as compared to its concentration in roots and other belowground plant organs [66]. Overall, root tuber and leafy vegetables accumulate more arsenic content than fruity or fleshy vegetables of above-ground parts [67]. Due to the tolerance mechanisms, minimum arsenic translocation was found in wheat, and maximum tolerance was reported in Brinjal (38.80 mg/kg), followed by tomato (35.41mg/kg) [68]. In the xylem sap, arsenite predominated in tomato, cucumber, and rice while arsenate predominated in castor bean, wheat, and Indian mustard [69]. Besides, the external root skin on root vegetables has more arsenic concentration than within the root, implying that the washing and peeling process for edible tubers such as potatoes and carrot effectively reduces exposure for human beings [70]. The differential accumulation/tolerance ability of crop plants can provide target crops for cultivation in arsenic endemic regions with a high tolerance for arsenic, thereby reducing the chances of arsenic transfer to the food chain.

5. ARSENIC BIOAVAILABILITY IN MILK, SEAFOOD, AND LIVESTOCK-BASED FOOD PRODUCTS

5.1. In Milk

Arsenic-contaminated water and feed for cattle is a well-established route of arsenic entry into the food chain. Arsenic is transferred to humans via the consumption of milk and meat from such animals. It may pose a carcinogenic and non-carcinogenic risk to the health of children and adults [11]. Arsenic contamination in milk is of particular concern because milk is primarily consumed by infants and children [77]. The arsenic concentration in cattle milk depends on their feeding habits, food, water, and environmental contamination. High arsenic concentration in raw milk (4.24–4.93 µg/L) was reported from the cows grazing on pastures near lava ground with high thermal activity in Turkey [78]. In a study from Pakistan (Tharparkar region), where elevated concentration of arsenic was found in milk samples of different milch animals, namely, cows, buffalos, sheep, goats, and camels (15.1–18.4, 2.6–7.7, 25.7–33.2, 10.5–37.3, and 6.6–13.7 µg/L, respectively) due to the contaminated drinking water (geogenic arsenic) given to cattle. A high carcinogenic risk to children was found in milk consumption from the said area [11].

According to the WHO recommendations, breastfeeding is essential for babies up to 6 months. An additional 2 years of breastfeeding and appropriate complementary foods are also much needed [79]. However, the composition of human milk is not constant and depends on the

Table 2: Arsenic in vegetables (mean, µg/kg) and their contamination sources.

Country	Crop type	Source	Arsenic	References
China	Spinach, broccoli, tomato, tine peas	Anthropogenic	95.7, 112.0, 107.0, 115.0	Zheng *et al.*[51]
Pakistan	Spinach, mustard, carrot, cabbage, fenugreek	Wastewater irrigation	400.0, 390.0, 240.0, 200.0, 190.0	Natasha *et al.*[52]
Bangladesh	Brinjal, potato, bottle gourd, pumpkin, green amaranth	Geogenic and anthropogenic contamination	350.0, 280.0, 430.0, 320.0, 360.0	Haque *et al.*[5]
China	Lettuce, rape, bitter, mustard, garlic, pakchoi	Mine water irrigation	1990.0, 870.0, 3260.0, 3160.0, 1820.0	Qin *et al.*[62]
Bangladesh	Bitter gourd, okra, bean, chilli, bottle gourd, cucumber, sponge gourd	Industrial activities	2030.0, 2550.0, 1640.0, 2910.0, 2850.0, 1640.0, 3890.0	Proshad *et al.*[54]
Zimbabwe	Tomato, okra, onion, pumpkin, leaves, spinach	Contaminated soil	600.0, 1000.0, 1300.0, 5200.0, 4030.0	Meck *et al.*[71]
China	Radish, carrot, cabbage, rice, celery	Industrial activities	50.0, 20.0, 70.0, 130.0, 110.0	Cai *et al.*[72]
Brazil	Beans, cabbage, carrot, garlic, lettuce	Mining activities	50.0, 6.0, 7.0, 13.0, 17.0	Ng *et al.*[55]
Nigeria	White yam, pumpkin, spinach, coriander, tomato	Mining activities	100.0, 400.0, 1990.0, 2050.0, 560.0	Obiora *et al.*[73]
China	Spinach, coriander, celery, pea, amaranthus	Mining activities	110.0, 340.0, 170.0, 290.0, 280.0	Luo *et al.*[74]
Pakistan	Spinach, coriander	Wastewater irrigation	4180.0, 4030.0	Khan *et al.*[75]
Pakistan	Radish, turnip	Wastewater irrigation	3370.0, 3510.0	Ahmad *et al.*[76]
India	Luffa, okra, cucumber, brinjal	Geogenic contamination	800.0, 375.0, 399.0, 492.0	Kumar *et al.*[46]

Table 3: Arsenic in milk (mean, µg/L), meat, and egg samples (mean, µg/kg).

Country	Sample	Source	Arsenic	References
India	Cow milk	Geogenic	6.37	Das *et al.*[86]
	Goat milk		<3	
Brazil	Cow milk	Gold mine	3.00	Ng *et al.* [55]
Bangladesh	Cow milk	Geogenic	440.00	Ahmed *et al.* [9]
United States	Breast milk	Geogenic	0.62	Carignan *et al.* [87]
Taiwan	Breast milk	Industrial waste incineration and coal power plant in the vicinity	1.50	Chao *et al.* [88]
United States	Breast milk	Lifestyle, Contaminated food	0.01	Gaxiola-Robles *et al.* [89]
Bangladesh	Cow milk	Chronic as exposure from drinking water	51.0	Islam *et al.* [90]
Sweden	Breast milk	Food habits	0.55	Björklund *et al.*[91]
Japan	Breast milk		1.40	Sakamoto *et al.*[92]
Portugal	Breast milk		5.80	Almeida *et al.*[93]
China	Pork meat	Anthropogenic	482.00	Zheng *et al.*[51]
	Beef		280.00	
	Chicken meat		318.00	
India	Chicken meat	Geogenic	94.50	Das *et al.*[86]
	Goat meat		107.00	
	Eggs		1.00	
Brazil	Chicken meat	Gold mine	21.00	Ng *et al.*[55]
	Beef		21.00	
Bangladesh	Duck egg	Geogenic	76.00	
	Chicken meat		33.00	
Bangladesh	Beef	Geogenic	570.00	Ahmed *et al.*[9]
	Mutton		140.00	
	Chicken meat		430.00	
	Duck meat		160.00	

mother's nutritional status, diet, lactation stage, socio-demographic status, lifestyle, and environmental contamination [80]. The presence of geogenic arsenic (50 mg/L) in drinking water contributed to the high arsenic (149 mg/L) in the breast milk of lactating women in West Bengal, India. Moreover, in the lack of mother's milk, children were further exposed to arsenic from an early age due to their dependency on local cattle milk [81]. Newborns absorb metals to a greater extent than adults. They have a lower capacity to excrete arsenic compounds in the bile, decreasing the body clearance further leading to severe consequences of arsenic toxicity [82].

5.2. In Meat and Poultry Products

Meat and poultry products are nutritional diets necessary for human growth and development as they contain fat, protein, and other essential minerals [83] The use of organo-arsenic drugs as animal feed and antiparasitic agents promotes arsenic transfer in cattle and poultry products [84]. Roxarsone is an arsenic-containing component of chicken feed that supports growth, helps gain weight, improves feed utilization efficiency, and increases chicken meat pigmentation [84]. However, the elevated level of arsenic observed in different chicken tissues was strongly correlated with the use of roxarsone in chicken feed in Guangzhou, China [84]. Another study investigated the total arsenic in cooked chicken meat samples (3.0 µg/kg) due to roxarsone application; arsenic was detected in 50% of samples [85].

Contaminated groundwater has been reported to augment arsenic levels in cattle and poultry [Table 3]. High arsenic was reported in broiler meat (breast-0.633 mg/kg and liver-0.943 mg/kg) and Cock meat (breast meat-0.457 mg/kg and liver-0.379 mg/kg) in poultry farms of Bangladesh [95] due to drinking contaminated groundwater. In poultry farms, arsenic-rich drinking water and feed additives may accumulate a substantial concentration in their flesh and eggs, transfer to human beings upon prolonged consumption, and pose a health risk to the local population. Moreover, high arsenic levels have been found in poultry excreta in Bangladesh. Applying such excreta as fertilizer may cause an augmentation of arsenic contamination in soil, leading to recontamination of the food chain [96].

5.3. In Seafood

Among the food products, seafood supplies the majority of the total arsenic to humans; the US Food and Drug Administration indicated that seafood, including finfish, shellfish, seaweed, and other seafood, accounts for 90% of the total human arsenic exposure globally [8,97]. Seafood is the chief source of organic arsenic, such as arsenosugars, arsenobetaine, and arsenolipids [98]. Although more toxic form, that is, inorganic arsenic levels in seafood, are generally relatively low. But some aquatic organisms, such as mussels and algae like Sargassum (a higher alga), can have a high concentration of inorganic arsenic [34], which may transfer it to the human body upon consumption. Arsenic bioaccumulation and transfer in aquatic organisms depend on various biological and environmental factors such as arsenic species, organism type and species, body size, trophic level, and age [99,100]. For instance, arsenobetaine and arsenosugars are the most abundant arsenic compounds in finfish and seaweed [8]. The accumulation efficiency also varies from organism to organism; Crabs can efficiently accumulate the inorganic arsenic compared to finfish due to the presence of chitosan in shells containing charged amino acids which easily attach with the As(V) [100].

Many researchers have reported high arsenic contamination in seafood due to geogenic and anthropogenic sources [Table 4]. For example, Perry *et al*. [35] reported very high arsenic levels (7.3 mg/kg) in the crab's muscles in the Gulf of Mexico. However, according to the national standard limit, inorganic arsenic should not exceed 0.5 mg/kg for aquatic crustaceans [105]. The population of coastal regions where the diet is mainly seafood based are more susceptible to arsenic toxicity. High seafood consumption is linked with more elevated arsenic in blood and urine [106], infant cord blood and breast milk [107], and arsenobetaine and dimethylarsinic acid in blood and urine [98].

Table 4: Arsenic in seafood (µg/kg).

Country	Sample	Source	Arsenic (µg/kg)	References
Santa Catarina, Brazil	Oreochromis niloticus	Anthropogenic	27500.00–49200.00	Steckert *et al*.[108]
Paracatu, Brazil	Squalus acanthias	Anthropogenic	233.00	Ng *et al*.[55]
Bangladesh	Labeo rohita	Geogenic	110.00	Islam *et al*.[94]
	Pangasius pangasius		230.00	
	Oreochromis niloticus		940.00	
	Channa panctatus		230.00	
Augusta, Southern Italy	Pagellus erythrinus	Anthropogenic	3620.00	Di Bella *et al*. [109]
	Pagellus acarne		4720.00	
	Mullus barbatus		9940.00	
	Sepia offcinalis		2268.00	
Shandong Province, China	Ctenopharyngodon idella	Anthropogenic	41.00	Yang *et al*. [110]
	Carassius carassius		89.00	
	Hypophthalmichthys nobilis		118.00	
	Scomberomorus niphonius		995.00	
	Trichiurus lepturus		1130.00	
	Larimichthys polyactis		1400.00	
	Lateolabrax japonicus		852.00	
	Sardina pilchardus		2260.00	

Physicochemical parameters, namely, pH, salinity, the presence of other elements, and dissolved organic matter along with food ingestion rate, gut passage time, gut environment, living prey/food composition, species, and density, also affect the assimilation of arsenic from food [101]. Physiological functions such as excretion, molting, and reproduction also affect aquatic organisms' bioaccumulation rate by physically removing arsenic from their body [101,102]. The seafood cooking method also affects arsenic bioavailability; even the same cooking method can affect arsenic bioavailability in different seafood's [103]. In conformity with this, Perelló *et al*. [104] reported that deep frying and baking increased the inorganic arsenic levels in bivalve shells and squids. However, more in-depth studies are needed to focus on various *in vivo* models to monitor the transformation of arsenic species during assimilation of seafood inside the gastrointestinal tract till its accumulation at the cellular level and excretion from the human body.

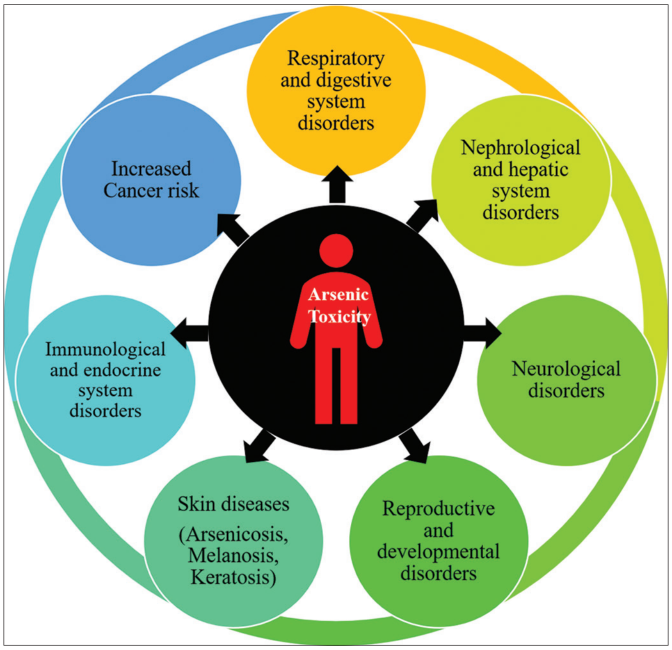

Figure 1: Health disorders and diseases caused by arsenic toxicity.

6. ARSENIC IN FOOD CHAIN AND HUMAN HEALTH RISK

Millions of people are chronically exposed to arsenic via food, air, water, and soil, leading to adverse long-term health consequences [32] [Figure 1]. In humans, arsenic exposure and toxicity arise due to environmental, occupational, or dietary exposure. It is a challenging task yet critical to monitor the food chain as human beings are the top consumers of the food chain. Thus contaminated food chain brings more degree of carcinogenic health risks on prolonged arsenic exposure through various dietary routes [Figure 2]. According to epidemiological studies, chronic arsenic exposure is associated with an increased risk of liver, kidney, prostate, skin, bladder, and lung cancers due to its ability to cause oxidative stress, DNA damage, cellular mutations, and enzyme inhibition [111]. Neuropathies of the central nervous system are attributed to its penetrability to the blood-brain barrier by altering the mitochondrial membrane instability, neurotransmitter impairment, and enzyme disruption [112]. Due to its capacity to cross placental

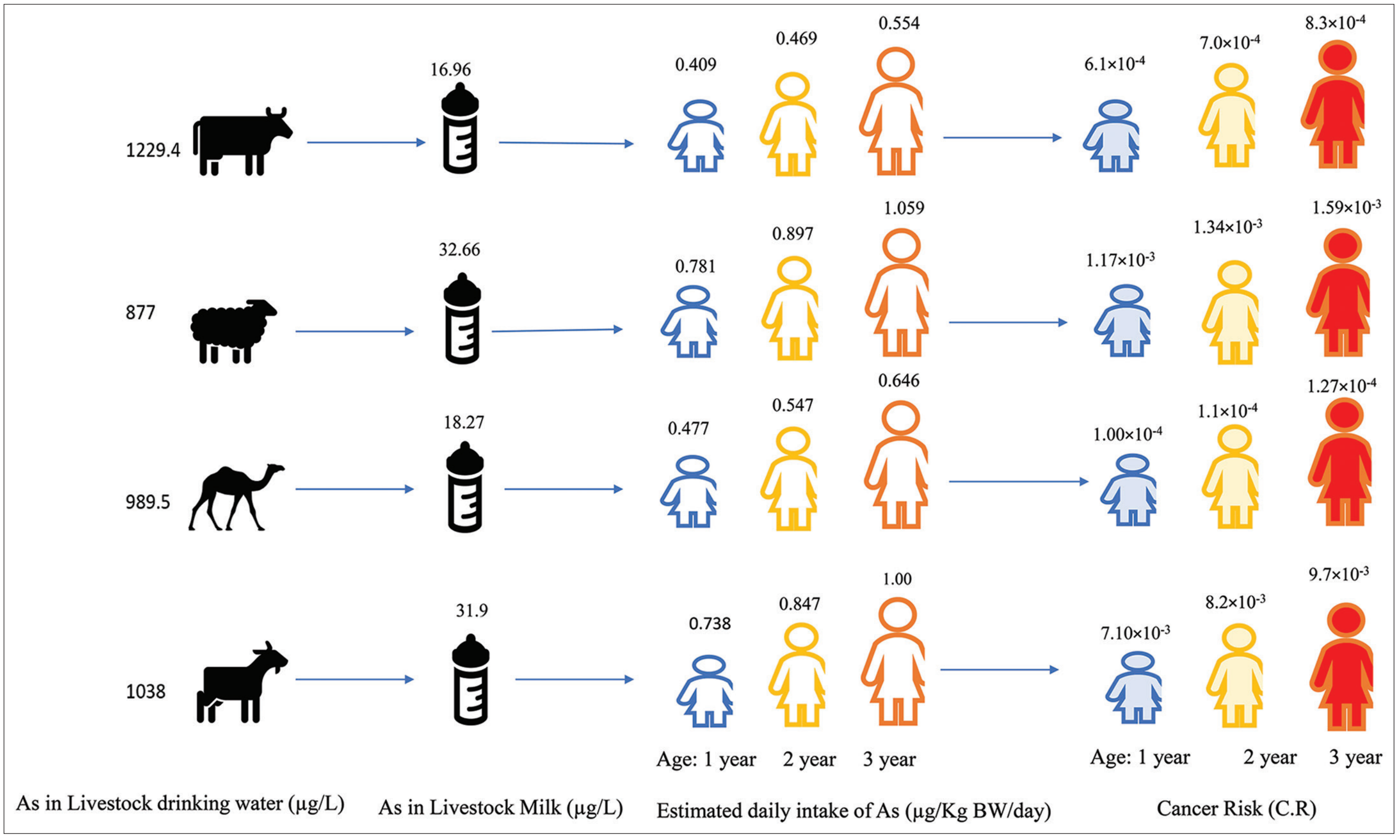

Figure 2: Transfer of Arsenic in the food chain [(Arsenic in drinking water of livestock, milk produced by livestock, estimated daily intake of Arsenic and Cancer risks in children of three age groups); (Source: created from data reported by Kazi *et al*. [11])].

barriers, it can reach fetuses from mothers, potentially causing adverse pregnancy outcomes [113]. It poses deleterious effects on reproductive health by increasing infant mortality and preterm birth and negatively influencing neonatal development [114]. Other reported outcomes of arsenic toxicity include skin disorders [53], hyperpigmentation, keratosis, bronchitis, chronic obstructive pulmonary disease, bronchiectasis, as noncirrhotic portal fibrosis, and others such as polyneuropathy, hypertension, peripheral vascular disorders, ischemic heart disease, diabetes, and edema of hands and feet [13,111,112]. In addition to these dermatological, lung, and heart illnesses, chronic arsenic toxicity also causes variable clinical consequences, the treatments of which are sometimes only indicative and are worse [13].

Several studies have been conducted to evaluate arsenic toxicity and human health risk in various arsenic-contaminated regions [10,52]. Arsenic risk assessment studies have received massive attention in the recent past due to the fatal effects of its toxicity; these studies evaluate whether occupants of a specific area are exposed to arsenic from different media of the biosphere (soil/air/water/food). If so, whether those exposure levels pose an unacceptable health risk to the population or not. Risk assessment entails contaminant exposure, toxicity, and risk characterization. Many countries have used various models and indices to calculate the magnitude and likelihood of human health risk, namely, Iran [113], China [6,48], India [46,32], Pakistan [114], and Bangladesh [54] Consumption of highland barley irrigated with geothermally arsenic contaminated water in Tibet posed a cancer risk of 5.4 in 10,000 [6]. Kazi *et al*. [11] assessed the cancer risk in children from milk consumption of the local livestock. High arsenic in the milk samples of cows, sheep, goats, and camels was observed (range of 15.1–18.4, 25.7–33.2, 10.5–37.3, and 6.6–13.7 μg/L, respectively) due to drinking water. Arsenic in livestock drinking water of each farm/flock was found in the range of 238–2000 μg/L. The total hazard quotient for children consuming the milk of sheep, goats, cows, and camels was found >1 of the reference dose for arsenic, posing the adverse effects on the health of the local children [Figure 2].

Thus, it is evident that arsenic transfer from different environmental matrices may enter the food chain through dietary route, leading to severe risks to food security, and human health. Henceforth, focus on controlling the possible elevation of arsenic contamination in the food chain and its possible abatement is much needed. Novel methods such as transgenic approach and bioremediation along with conventional practices may help in mitigating the arsenic from various environmental metrics and food chain, further lowering the risks to human health [115].

7. CONCLUSION

Arsenic, being the first-class member of carcinogen, imparts high risks to the human population due to its characteristics such as toxicity, high persistence, and bioaccumulation capacity in different matrices of the environment. Arsenic contamination of soil, water resources, and food crops due to anthropogenic and geological sources is of profound environmental health concern. In this study, we found extensive evidence of elevated arsenic in the food chain, mainly in rice and vegetables. The uptake of arsenic by rice crops showed a significant exposure pathway to the population thriving in the arsenic endemic regions and where a rice-based diet is dominant. Arsenic in livestock-based food products such as milk, seafood, poultry, and meat products is a significant contributor to food chain contamination, especially in arsenic endemic regions. Chronic exposure can cause skin diseases, developmental, reproductive, respiratory, nephrological and endocrinological diseases, and various cancer types in human beings. Hence, in current scenario where arsenic has become a global menace, there is a dire need of an integrated approach to combat the arsenic contamination thus necessitating formulation of national and global action plan for arsenic contamination mitigation.

8. AUTHOR CONTRIBUTION

Siril Singh: Conceptualization of the idea, methodology, data curation, writing original draft, editing, and revisions Rajni Yadav and Sheenu Sharma: Data curation and editing Anand Narain Singh: Advising, supervision, and modifications.

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10. CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

11. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

12. DATA AVAILABILITY

All the data reported are included within this review article.

13. ACKNOWLEDGMENTS

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