Arsenic Contamination in Bihar, India: Exploring the Impact, Mitigation, and Bioremediation Strategies

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Abstract

Arsenic is a metalloid that is naturally present in the environment. Exposure to arsenic can cause health issues like cancer, cardiovascular, neurological, and respiratory complications. With more than a million people affected due to arsenic contamination in groundwater, Bihar is one of the worst arsenic-affected states in India. Groundwater is one of the primary sources for cooking, farming, and other household chores. People are exposed to arsenic through food as well as contaminated drinking water. As a result, arsenic has made its way into the food chain. Several cases of cancer, arsenical dermatosis, and keratosis have been reported in Bihar. The source of arsenic contamination in Bihar has yet to be identified, although the Himalayan sediments have been suspected as one of the prime reasons. The government has taken steps to prevent and control arsenic contamination in the state; however, reports in recent years indicate the number of blocks affected by arsenic contamination has been rapidly increasing. This necessitates a more comprehensive arsenic mitigation tool. Various technologies can be employed to mitigate levels of arsenic in groundwater, of which bioremediation is one of the more cost-effective and sustainable methods. The current article is an attempt to give an overview of the sources and areas of Bihar with arsenic contamination, and the concentration in different regions. It also provides a piece of detailed information on arsenic contamination on health, and the current state of arsenic bioremediation.

Introduction

Arsenic is a metalloid element that is present in abundance in the earth's crust. It is ubiquitous in all environments, including soil, groundwater, air, and minerals. Arsenic is largely prevalent in groundwater (pH 6–9) in two oxidation states: arsenite (As III) and arsenate (As V), with the former being more poisonous than the latter. Arsenic contamination is an alarming problem because arsenic does not degrade; rather, it circulates in different forms in the environment (Ghosh et al. 2007a). It is estimated that globally, around 200 million people are exposed to arsenic-contaminated drinking water at levels well above the permissible limits set by the (WHO 2003). Approximately 70 countries, including Bangladesh, China, Nepal, Brazil, Mexico, etc., have been identified as being affected by arsenic contamination. The permissible limit of arsenic in drinking water, according to the WHO, is 0.01 µg/L. However, in India, the Bureau of Indian Standards has set the limit of arsenic in drinking water at 0.05 µg/L in the absence of an alternative drinking source.

In India, the first case of arsenic contamination in groundwater was reported from Chandigarh in 1976(Datta and Kaul 1976). Since then, several states in India have reported cases of groundwater contamination. West Bengal reported four districts affected by groundwater arsenic contamination(Garai et al. 1984). In 2003, Ara, Bhojpur, Bihar(Chakraborti et al. 2003), and 23 villages in Ballia, Uttar Pradesh, reported arsenic contamination. Similarly, Assam (2004) and Manipur (2007) also reported cases of arsenic contamination in groundwater (Ghosh et al. 2009). There has been an exponential increase in the number of cases being reported in India for groundwater contamination. The states of Jharkhand, Punjab, Haryana, Himachal Pradesh, and Rajasthan have all reported arsenic contamination. In 2018, the

Ministry of Drinking Water and Sanitation (MDWS) reported that West Bengal has the most arsenic-affected habitation, followed by Assam, Bihar, Uttar Pradesh, and Punjab (Table 1). Recently, in 2019, the Ministry of Water Resources, River Development, and Ganga Rejuvenation *(Mower, RD, and GR)* identified hotspots across India for arsenic contamination (Fig. 1). 26 districts and UTs were identified to have arsenic contamination above 50 µg/L. It was reported that West Bengal has the highest number of districts affected by arsenic contamination ranging higher than 50 µg/L (Fig. 1). Whereas Bihar has the highest number of arsenic-affected districts, ranging from 10–50 µg/L.

The Government of India, Ministry of Jal Shakti, Department of Water Resources, River Development, and Ganga Rejuvenation (2022), reports different states across India for arsenic-contaminated water. Out of the 17 blocks in Nadia and Malda districts in West Bengal, all the blocks were found to be arsenic-contaminated(Das et al. 2020; Mazumder et al. 2020b). In Punjab, the Bari Doab region of the Indus basin reported arsenic contamination of 0-255.6 µg/L(Kumar et al. 2019a). In Uttar Pradesh, arsenic contamination was reported above the permissible range across approximately 61 km in the Gomti River near Lucknow (Khan et al. 2020). North Tripura, Dharmanagar, reported the co-occurrence of Fluoride and Arsenic in 59% of assessed groundwater ((Bhattacharya et al. 2020a).

Table 1
State-wise number of arsenic affected habitations as reported by the Ministry of Drinking Water and Sanitation in 2018. **Source**: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd & Gr)(2019)

States	**No.of affected habitation**
West Bengal	9,250
Assam	4,327
Bihar	815
Uttar Pradesh	745
Punjab	652
Jharkhand	19
Karnataka	3

The land in Bihar is extremely fertile, and agriculture is the main occupation and source of livelihood for people. Groundwater is the main source of water for cooking, drinking, agriculture, and other household purposes. The majority of the population affected by arsenic contamination lives in poverty in rural areas of Bihar and is often unaware of the contamination and its effects on health. Continuous and unabated use of arsenic-contaminated water and a lack of awareness cause serious health effects. People may be exposed to arsenic through direct ingestion of contaminated water or indirectly through contaminated food. Arsenic poisoning can lead to serious health consequences such as cancer of the liver, lungs, bladder, skin, etc. It can also cause serious cardiovascular, respiratory, neurological, and gastrointestinal complications.

The objective of this review is to draw attention to the present scenario of arsenic contamination in Bihar. It targets the readers to know the sources, extent, and rapid increase in the spread of arsenic in the state, thereby risking the habitation. It also intends to draw attention to the extent of the spread of arsenic in the food chain and the health effects experienced by the population in Bihar. In this article, an attempt is also made to update the various schemes and policies implemented by the government to mitigate arsenic contamination and the loopholes in the implementation of these policies. The review article also highlights bioremediation as the most effective, economically feasible, and environmentally feasible method for mitigating arsenic contamination.

Arsenic contamination in Bihar: Past and current status

Arsenic in the groundwater of Bihar was first identified in Semaria-Palti Ojha village of Ara block in Bhojpur district in 2002 (Chakraborti et al. 2003). Subsequently, arsenic contamination in other districts of Bihar was also identified. The review presents here a brief report of district-wise levels of arsenic in the state of Bihar.

1. **Bhojpur**: (Singh et al. 2014a) reported a total of 27 villages in Shahpur to be severely contaminated with arsenic **(**Table 2**).** The arsenic concentration in the groundwater of the village of Karnamepur was as high as 598 µg/L. Out of the 27 villages, 12 showed levels of arsenic above 50 µg/L. The government has recognized Shahpur, Ara, Bihia, Koilwar, and Barharaas as arsenic-contaminated. In 2016, 4704 tube-well water samples from all 88 villages of Shahpur were analyzed for levels of arsenic. It was found that 40.3 and 21.1% of the tube-wells had arsenic above 10 and 50 µg/L, respectively, with maximum concentration of 1805 µg/L (Chakraborti et al. 2016). Studies by Thakur et al. (2019) reported 60% of the 173 villages in Sahapur Block to be contaminated with arsenic.
2. **Buxar**: The highest arsenic contamination was reported by MOWR (2013) in Ekdar village (1220µg/L) and Chakni village. Arsenic levels higher than 50µg/L was seen at Brahampur, Simri, Chakki, and Buxar blocks. In 2015, two villages in Buxar, Simri and Tilak Rai Ka Hatta, were also reported to have arsenic levels as high as 1929 µg/L and 1908 µg/L respectively (Kumar 2015a). In 2019, Simiri village in Buxar reported arsenic levels of 857 µg/L (Kumar and Upadhyay 2019a).
3. **Patna**: 17 arsenic-contaminated hotspots from 4 different blocks of Patna were reported byGhosh et al. (2009) in the range of 148 to 724 µg/L **(**Table 1**).** The highest levels were seen in Naya Tola village of Maner (724 µg/L). In 2011, two more villages, Maner, Rampur Diara, and Haldichapra, were reported to have arsenic levels ranging from 880 to 498 µg/L, which is approximately 50 times higher than the recommended level of the WHO (Singh and Ghosh 2011a). Subsequently, in 2013, all 23 blocks of Patna recorded arsenic contamination, with 15 blocks having arsenic levels of more than 50 µg/L **(**Table 1**).** Danapur and Naubatapur showed arsenic contamination of more than 100µg/L

(Nath et al. 2012a).Dubey et al. (2018) revealed arsenic contamination in 4 out of 7 villages in Maner (Table 2), of which Nayatola village showed the highest levels of 90µg/L.

4. **Bhagalpur**: Two villages in Bhagalpur, Masharu and Mamalkha, were reported to have arsenic contamination ranging from 3 µg/L to 143 µg/L (Singh et al. 2014a). In 2016, seven blocks of Bhagalpur were reported to be arsenic-contaminated (Table 2). Topra village in Pirpainti block had the highest arsenic levels recorded at 417.1 µg/L (Mishra et al. 2016). In 2017, eight villages in Nathnagar block were reported to be arsenic-contaminated (Table 2), with the village of Gosaidaspur showing arsenic levels as high as 1900 µg/L (Mishra et al. 2016). In 2020, the Gangetic plains of Bhagalpur were reported to have arsenic contamination above 0.05 µg/L (Kumar et al. 2020a).
5. **Vaishali**: Singh et al. (2014) reported that two villages, Chaukia and Terahrasiya, in Vaishali district were contaminated with arsenic. In 2017, four villages from two blocks of Vaishali also reported arsenic contamination (Table 2). The village of Tehrasiya had the highest contamination level recorded at 1352 µg/L (Kumar and Singh 2020).

Previous data reported that arsenic contamination was limited to a 10 km area along the Ganga River in Bihar. However, recent studies have indicated that arsenic contamination is being observed at significant distances from the river. In 2014, Khap Tola village in West Champaran, located approximately 139 km from the Ganga River, reported arsenic contamination ranging from 10 to 50 µg/L (Bhatia et al. 2014a). Similarly, in the same year, Samastipur reported arsenic contamination in four blocks (Table 2), with the highest level recorded in Mohanpur at 60.4 µg/L (Baboo et al. 2022). In 2015, Kishanganj, approximately 125 km away from the Ganga River, reported arsenic levels within the range of µg/L (Kumar 2015a). Supaul also reported arsenic contamination in six blocks (Table 1). Similar cases were reported in Purnea, Katihar, Arariya, and Darbhanga, situated approximately 80 km away from the Ganga River (Table 2) (Nath et al. 2012b; Mishra et al. 2016). The highest recorded arsenic levels were 911 µg/L in Paghari village, Baheri (Kumar and Singh 2020b). Purnea (approximately 65 km away from the Ganga River) exhibited arsenic contamination in three blocks (Table 2), with the highest level reported at 55.70 µg/L (Mishra et al. 2016). Katihar reported contamination in five blocks, with the highest level observed in Kursela at 80.24 µg/L, while Arariya reported contamination in three blocks (Table 2), with the highest level reaching 177 µg/L (Mishra et al. 2016). Siwan, approximately 100 km away from the Ganga River, reported the highest arsenic level recorded at 150 µg/L (Singh and Ghosh 2014).

Though these districts may be located away from the Ganga River, it is important to consider the presence of other rivers in close proximity to these affected areas. For example, in Siwan, the Ghaghara River, which is a tributary of the Ganges, flows approximately 19 km away from the contaminated site. This river originates on the Tibetan plateau, crosses Nepal, and meets the Sardar River in Brahma Ghat before entering Bihar and Uttar Pradesh through Siwan. Similarly, the Gandak River flows approximately 6 km away from the contaminated areas in West Champaran. Originating in Tibet, it enters Indian territory through Nepal and forms the boundary between Uttar Pradesh and Bihar. The river flows through West Champaran and ultimately joins the Ganges at Hazipur in Bihar. In Supaul, the Koshi River originates from the Himalayas, crosses Nepal, and enters India at Madhubani and Darbhanga. It then passes through Supaul and Madhepura before joining the Ganga near Kursela. These rivers, despite being distinct from the Ganga, play a significant role in the region's hydrological system and may contribute to the transport and spread of arsenic contamination in these areas.

Indeed, it is plausible that rivers originating in the Himalayas and crossing Nepal to reach Indian territory could contribute to the increased levels of arsenic in the affected areas. The Himalayan sediments have been identified as a potential source of arsenic contamination, and it is known that Nepal, like India, also faces challenges related to arsenic contamination. However, it is important to note that drawing definitive conclusions regarding the role of these rivers in arsenic contamination requires detailed and meticulous studies. Comprehensive research is necessary to understand the specific sources of contamination and the factors contributing to the presence of arsenic in the affected regions.

Table 2
List of contaminated Blocks and villages in Bihar

District	Block	Village	Concentration	References
Bhojpur	Shahpur	Parsonda	> 50 µg/L	(Singh et al. 2014b)
Bhojpur	Shahpur	Ramdatahi	> 50 µg/L	
Bhojpur	Shahpur	Sonbarsa	> 50 µg/L	
Bhojpur	Shahpur	Sarna	> 50 µg/L	
Bhojpur	Shahpur	Isharpura	> 50 µg/L	
Bhojpur	Shahpur	Milki Gopalpur	> 50 µg/L	
Bhojpur	Shahpur	Karnamenpur	> 50 µg/L	
Bhojpur	Shahpur	Chakki Nauranga Ojhwalia Diara	> 50 µg/L	
Bhojpur	Shahpur	Ram Karhi (Ditto)	> 50 µg/L	
Bhojpur	Shahpur	Mirchaiya Ka Dera (Ditto)	> 50 µg/L	
Bhojpur	Shahpur	Bansipur	> 50 µg/L	
Bhojpur	Shahpur	Misrauliya	50 µg/L	
Bhojpur	Shahpur	Gashainpur	50 µg/L	
Bhojpur	Shahpur	Bishunpur	50 µg/L	
Bhojpur	Shahpur	Dudh Ghat	50 µg/L	
Bhojpur	Shahpur	Nargada	50 µg/L	
Bhojpur	Shahpur	Barsaun	50 µg/L	
Bhojpur	Shahpur	Semariya Palti Ojha	50 µg/L	
Bhojpur	Shahpur	Bahoranpur Dakhinwar	50 µg/L	
Bhojpur	Shahpur	Karja	50 µg/L	
Bhojpur	Shahpur	Paharpur	50 µg/L	
Bhojpur	Shahpur	Jhaua	50 µg/L	
Bhojpur	Shahpur	Dhauri	50 µg/L	
Bhojpur	Shahpur	Pakri	50 µg/L	
Bhojpur	Shahpur	Dumariya	50 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
Bhojpur	Shahpur	Abatana	50 µg/L	
Bhojpur	Shahpur	Dewaich Kundi	50 µg/L	
Bhojpur	Shahpur	Karnamipur	> 50 µg/L	MOWR 2013
Bhojpur	Shahpur	Bariswan	> 50 µg/L	
Bhojpur	Shahpur	Semaria-Palti Ojha	> 50 µg/L	
Bhojpur	Barhara	Sinha	> 50 µg/L	
Bhojpur	Ara	Paharpur	> 50 µg/L	
Bhojpur	Bihiya	Nawada	> 50 µg/L	
Bhojpur	Koliwar	Na		
Buxar	Na	Ekdar Village	1220 µg/L	
Buxar	Na	Chakni Village	1100 µg/L	
Buxar	Brahampur	Na	> 50 µg/L	
Buxar	Simri	Na	> 50 µg/L	
Buxar	Chakki	Na	> 50 µg/L	
Buxar	Buxar Block	Na	> 50 µg/L	
Buxar	Buxar Block	Simri	1929 µg/L	(Kumar 2015b)
Buxar	Buxar Block	Tilak Rai Ka Hatta	1908 µg/L	
Buxar	Buxar Block	Simri Village	857 µg/L	(Kumar et al. 2020b)
Patna	Maner	Zirakhantola	378 µg/L	(Ghosh and Singh 2009a)
Patna	Maner	Ratantola	148 µg/L	
Patna	Maner	Ramnagar	288 µg/L	
Patna	Maner	Ramnagar Po, River Bank	250 µg/L	
Patna	Maner	Badantola Temple	203 µg/L	
Patna	Maner	Pundev Singh,Naya Tola	724 µg/L	
Patna	Maner	Purana Tola	328 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
Patna	Maner	Dhwaja Tola	179 µg/L	
Patna	Maner	Primary School, Satana	340 µg/L	
Patna	Maner	Krishna Mandir, Saat Aana	278 µg/L	
Patna	Maner	Dudhaila	214 µg/L	
District	**Block**	**Village**	**Concentration**	**References**
Patna	Maner	Hathitola	378 µg/L	(Ghosh and Singh 2009b)
Patna	Maner	Rampur Diara	52 µg/L	(Singh and Ghosh 2014)
Patna	Maner	Haldichapra	231 µg/L	(Singh and Ghosh 2011a)
Patna	Maner	Baba Chowk	90.21 µg/L	(Dubey et al. 2018b)
Patna	Maner	Nayatola	72 µg/L	
Patna	Maner	Chihtthar (Asharfi Rai)	56.2 µg/L	
Patna	Maner	Ratantola	69.95 µg/L	
Patna	Danapur	Panapur	370 µg/L	(Ghosh and Singh 2009b)
Patna	Danapur	Kasimchak	452 µg/L	
Patna	Danapur	Harshamchak	409 µg/L	
Patna	Barkh	Malahibanda	484 µg/L	
Patna	Bakhtiyar Pur	Gyaspur Mahaji	553 µg/L	
Patna	Danapur	NA	> 100 µg/L	(Nath et al. 2012a)
Patna	Naubatapur	NA	> 100 µg/L	
Patna	Bakhtiyarpur	NA	> 50 µg/L	
Patna	Barh	NA	> 50 µg/L	
Patna	Belchhi	NA	> 50 µg/L	
Patna	Bikram,	NA	> 50 µg/L	
Patna	Bihta	NA	> 50 µg/L	
Patna	Daniyawan	NA	> 50 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
Patna	Dulhin Bazaar	NA	> 50 µg/L	
Patna	Fatuha	NA	> 50 µg/L	
Patna	Ghoswari	NA	> 50 µg/L	
Patna	Khusrupur	NA	> 50 µg/L	
Patna	Maner	NA	> 50 µg/L	
Patna	Mokama	NA	> 50 µg/L	
Patna	Paliganj	NA	> 50 µg/L	
Patna	Maner	NA	> 50 µg/L	
Patna	Punpun	NA	> 50 µg/L	
Patna	Masaurh	NA	> 50 µg/L	
Patna	Phulwarisharif	NA	> 50 µg/L	
Patna	Sampatchak	NA	> 50 µg/L	
Patna	Patna Sadar	NA	> 50 µg/L	
Patna	Athmalgola	NA	> 50 µg/L	
Patna	Pandarak	NA	> 50 µg/L	
Patna	Mokama	NA	> 50 µg/L	
Patna	Ghoswari	NA	> 50 µg/L	
Patna	Dhanaura	NA	< 50 µg/L	
Bhaghalpur	Masharu	NA	3 µg/L -143 µg/L	(Singh et al. 2014b)
Bhaghalpur	Mamalkha	NA	3 µg/L -143 µg/L	
Bhaghalpur	Sultanganj	NA	60.67 µg/L	(Mishra et al. 2016)
Bhaghalpur	Nathnagar	NA	69.49–409.7 µg/L	
Bhaghalpur	Sabour	NA	38.97–89.62 µg/L	
Bhaghalpur	Kahalgaon	NA	30.38–409.7 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
Bhaghalpur	Pirpainti	NA	0-417 µg/L	
Bhaghalpur	Naugachia	NA	55.31–74.16 µg/L	
Bhaghalpur	Rangra	NA	55.31–60.79 µg/L	
Bhaghalpur	Nathnagar	Gosaidaspur	High	(Mishra et al. 2016)
Bhaghalpur	Nathnagar	Serampur	High	
Bhaghalpur	Nathnagar	Dildarpur Bindtola	High	
Bhaghalpur	Nathnagar	Darapur	High	
Bhaghalpur	Nathnagar	Shankarpur Basa	High	
Bhaghalpur	Nathnagar	Rashadpur Bhit	High	
Bhaghalpur	Nathnagar	Mathurapur	High	
Bhaghalpur	Nathnagar	Rannuchak	High	
Vaishali	NA	Chaukia	20 µg/L	(Singh et al. 2014b)
Vaishali	NA	Terehrasiya	20 µg/L	
Vaishali	Raghopur	Chaukia	190 µg/L	(Abhinav et al. 2016)
Vaishali	Raghopur	Terehrasiya	1352 µg/L	
Vaishali	Bidupur	Goplapur	83 µg/L	
Vaishali	Bidupur	Kalyanpur	211 µg/L	
Katihar	Kursela	NA	80.2-80.24 µg/L	(Mishra et al. 2016)
Katihar	Sameli	NA	30.3–66.2 µg/L	
Katihar	Korha	NA	60.8-62.79 µg/L	
Katihar	Katihar	NA	26.5-30.04 µg/L	
Katihar	Manhari	NA	39.1-104.5 µg/L	
Purnea	Kasba	NA	23.0–23.0 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
Purnea	Purnea	NA	35.6-74.77 µg/L	
Purnea	Garh Banaili	NA	0–0 µg/L	
Purnea	Jalalgarh	NA	26.0-26.03 µg/L	
Arariya	Arariya	NA	26.08–65.04 µg/L	
Arariya	Sikti	NA	35.05–80.24 µg/L	
Arariya	Sahibganj	NA	0-177.5 µg/L	
Darbhanga	Baheri	Paghari	911 µg/L	
Darbhanga	Baheri	Habidih	201 µg/L	
Darbhanga	Bidupur	Parri	843 µg/L	
Darbhanga	Bidupur	Bairumpur	862 µg/L	
Kishanganj	Kishanganj	NA	0.0–11µg/L	(Kumar 2015a)
Kishanganj	Bahadurganj	NA	0.0–21µg/L	
Kishanganj	Thakurganj	NA	0.0–20µg/L	
Kishanganj	Kochadaman	NA	0.0–21µg/L	
Kishanganj	Terhagachh	NA	0.0–22 µg/L	
Supaul	Raghopur	NA	20–100 µg/L	(Nath et al. 2012a)
Supaul	Basantpur	NA	10–100 µg/L	
Supaul	Supaul	NA	10–100 µg/L	
Supaul	Nirmali	NA	5–50 µg/L	
Supaul	Saraigadhbhaptiyahi	NA	5–50 µg/L	
Supaul	Triveniganj	NA	5–25 µg/L	
Samastipur	Mohanpur	NA	> 50 µg/L	(MOWR, 2013)
Samastipur	Patori	NA	> 50 µg/L	
Samastipur	Vidyapatinagar	NA	> 50 µg/L	
Samastipur	Mohaddinagar	NA	> 50 µg/L	

Source: Compiled by the authors, * NA-Not Available

District	Block	Village	Concentration	References
West Champaran		Khap Tola	10–50 µg/L	(Bhatia et al. 2014a)
Source: Compiled by the authors, * NA-Not Available				

Bihar has experienced a significant and concerning rise in arsenic contamination since its initial case in 2002. The number of affected areas has expanded dramatically over the years. In 2005, there were only two blocks in one district affected, but by 2010, the contamination had spread to 16 districts and 60 blocks (Ghosh and Singh 2009c). According to Ghosh's report, by 2009, approximately 10 million people in Bihar had been impacted by arsenic contamination. In 2018, the Ministry of Drinking Water and Sanitation reported that 815 habitation areas, with a population of 1,223,387, were affected by arsenic contamination in Bihar. This data highlights the scale of the problem and its impact on the local communities. Furthermore, in 2019, the Ministry of Water Resources, River Development, and Ganga Rejuvenation conducted a study to identify arsenic hotspots across the country. According to the report, Bihar has the highest number of districts in India suffering from arsenic contamination, with levels ranging from 0.01 to 0.05 mg/L.

According to the mentioned report, a total of 21 districts in Bihar are affected by arsenic contamination. Among these districts, 19 experience arsenic contamination within the range of 0.01–0.05 mg/L (as per Table 3). However, two districts, namely Godda and Dhanbad, have arsenic contamination levels exceeding 0.05 mg/L (as per **Table 4**). It is crucial to address the varying levels of arsenic contamination in different districts to implement appropriate mitigation measures and ensure the safety of the affected population.

Table 3

Locations with Arsenic levels between 0.01 to 0.5 mg/litre in Ground Water in districts of Bihar

Sr.No	**District**	**Block**	**Location**	**Arsenic concentration 0.01 to 0.05 mg/L**
1	Begusarai	Teghra	Naya Nagar,Dularpur	0.02
2	Bhagalpur	Nathnagar	Satasnagar	0.03
3	Bhagalpur	Sabour	Masadhu	0.01
4	Bhagalpur	Sabour	Shankarpur Basti	0.01
5	Bhojpur	Ara	Baghakol	0.05
6	Bhojpur	Ara	Barki Singhi	0.04
7	Bhojpur	Ara	Jarawarpur Milki	0.02
8	Bhojpur	Ara	Kalyanpur	0.02
9	Bhojpur	Ara	Pipra	0.02
10	Bhojpur	Ara	Tenua	0.04
11	Bhojpur	Barhara	Ekuana	0.01
12	Bhojpur	Barhara	Farhda	0.01
13	Bhojpur	Barhara	Simaria	0.03
14	Bhojpur	Barhara	Sirisia	0.02
15	Bhojpur	Koilwar	Giddha	0.03
16	Bhojpur	Koilwar	Inglishpur	0.03
17	Bhojpur	Koilwar	Mokhlisa	0.02
18	Bhojpur	Sahpur	Sahjauli	0.01
19	Bhojpur	Udwantnagar	Bargain	0.02
20	Bhojpur	Udwantnagar	Bibiganj	0.02
21	Bhojpur	Udwantnagar	Sasaram Chota	0.01
22	Buxar	Buxar	Garhani	0.02
23	Buxar	Buxar	Parasiya	0.02

Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)

http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf

Sr.No	District	Block	Location	Arsenic concentration 0.01 to 0.05 mg/L
24	Buxar	Simri	Manikpur Simri	0.04
25	Darbhanga	Biraul	Dumri	0.01
26	Darbhanga	Biraul	Mahavir Nagar	0.01
27	Darbhanga	Biraul	Shekhpura	0.01
28	Darbhanga	Biraul	Supaul	0.01
29	E.Champaran	Belai	Chairah	0.01
30	E.Champaran	Motihari	Lakhwara	0.01
31	E.Champaran	Paharpur	Bishnupur Matirwan	0.01
32	E.Champaran	Patahi	Patahi	0.04
33	Gopalganj	Manjhwa	Bangra	0.01
34	Gopalganj	Manjhwa	Bishambharpur	0.01
35	Katihar	Ahmabad	Kishanpur	0.01
36	Katihar	Ahmabad	Police Station	0.04
37	Katihar	Ahmabad	Primary School Birpur	0.02
38	Katihar	Kursela	Ayodhya Gani Bazar	0.03
39	Katihar	Kursela	Debipur	0.01
40	Katihar	Kursela	Near Petrol Pump	0.02
41	Katihar	Kursela	Parbati Line Hotel	0.01
42	Katihar	Kursela	Sutara Mahi Mission School	0.04
43	Katihar	Manhasi	Manhasi Gohar Tola	0.01
44	Katihar	Manihari	Madhya Vidmaheshpur	0.01
45	Katihar	Manihari	Banipur	0.04
46	Katihar	Manihari	Panchayat Bhawan, Bauliya	0.02
47	Katihar	Sameli	Durga Mandir Chowk	0.01

Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)
http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf

Sr.No	District	Block	Location	Arsenic concentration 0.01 to 0.05 mg/L
48	Katihar	Sameli	Haricharan Mandal	0.03
49	Katihar	Sameli	Kushwaha Nagar	0.01
50	Katihar	Sameli	Purbi Chandpul	0.01
51	Katihar	Sameli	Tufani Line Hotel	0.02
52	Khagaria	Chautham	Basantpur	0.01
53	Khagaria	Gogri	Chakla	0.04
54	Khagaria	Gogri	Gauchari	0.01
55	Khagaria	Gogri	Gauchari Basti	0.01
56	Khagaria	Gogri	Mushkipur Bhuri Atari	0.04
57	Khagaria	Gogri	Pitaunjhia(Anganbari)	0.03
58	Khagaria	Khagaria	Harijantola Choti Kothiya	0.02
59	Khagaria	Khagaria	Kumar Chakki	0.03
60	Khagaria	Parbatta	Baisia	0.01
61	Khagaria	Parbatta	Sirajpur	0.02
62	Khagaria	Parbatta	Srirampur Thuthe	0.02
63	Khagaria	Parbatta	Temtha	0.03
64	Khagaria	Shahpur Kamal	Bhaloria	0.02
65	Khagaria	Shahpur Kamal	Pancbir Bazar	0.03
66	Lakhisarai	Barhaiya	Tarfar	0.02
67	Lakhisarai	Pipariya	Surji Chak	0.04
68	Lakhisarai	Surajgarha	Rampur	0.05
69	Lohardaga	Lohardaga	Patra Toli	0.01
70	Madhepura	Muraliganj	Muraliganj	0.02
71	Muzaffarpur	Bochahan	Sukarhat	0.04

Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)

http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf

Sr.No	District	Block	Location	Arsenic concentration 0.01 to 0.05 mg/L
72	Purnea	Purnea East	Andeli Hut	0.01
73	Purnea	Purnea East	Chotki Majhua	0.01
74	Purnea	Purnea East	Rajwara Brahampur	0.02
75	Saharsa	Saharsa	Saharsa 1	0.05
75	Saharsa	Simri Bakhtiyarpur	Simri Bakhtiyarpur	0.01
76	Samastipur	Mohanpur	Ala Chowk	0.01
77	Samastipur	Mohanpur	Dumri	0.04
78	Samastipur	Mohanpur	Jalalpur	0.02
79	Samastipur	Mohanpur	Mohanpur	0.02
80	Samastipur	Mohanpur	Rasalpur Purvi	0.02
81	Samastipur	Mohiuddinnagar	Chhapar	0.03
82	Samastipur	Mohiuddinnagar	Dubaha Paschim Tola	0.03
83	Samastipur	Mohiuddinnagar	Kursaha	0.01
84	Samastipur	Vidyapatinagar	Maniarpur	0.02
85	Siwan	Mairwa	Mairwa	0.02
86	Vaishali	Desri	Krishna Chauk More	0.01
87	Vaishali	Raghopur	Block Office Raghopur	0.01
88	Vaishali	Raghopur	Fatehpur Road	0.02
89	Vaishali	Raghopur	Kabir Chauraha	0.02
90	Vaishali	Raghopur	Malikpur	0.02
91	Vaishali	Raghopur	Police Station	0.04
92	Vaishali	Raghopur	Rustampur	0.04
93	Vaishali	Shahdai Buzurg	Tatma Toli	0.02

Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)
http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf

Sr.No	District	Block	Location	Arsenic concentration 0.01 to 0.05 mg/L
94	W.Champaran	Lauria	Sishwania	0.02
95	W.Champaran	Narkatiyaganj	Korigawa Chowk	0.01
Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)				
http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf				

Table no 4: **Locations Having Arsenic > 0.05 mg/litre in Ground Water in Different districts of Bihar**

Sr .No.	District	Block	Location	Arsenic (As) > 0.05 mg/l
1	Godda	Godda	Godda	0.06
2	Dhanbad	Dhanbad	Sijua	0.057
Source: The Ministry of Water Resources, River Development and Ganga Rejuvenation (MOWR, Rd& Gr)(2019)				
http://jalshakti-dowr.gov.in/sites/default/files/arsenic.pdf				

Sources of contamination

There are primarily two sources of arsenic contamination: geogenic (natural) or anthropogenic (man-made). Arsenic is naturally present in minerals such as arsenopyrite, orpiment, realgar, claudetite, arsenolite, pentoxide, scorodite, and arsenopalledenite, among others. However, arsenopyrite is often cited as the most common natural source of arsenic. Man-made sources of arsenic contamination include industrial waste, coal combustion, oil, cement, phosphate fertilizers, mine tailings, smelting, ore processing, metal extraction, metal purification, chemicals, glass, leather, textiles, alkalis, petroleum refineries, acid mines, alloys, pigments, insecticides, herbicides, and fungicides (Smedley and Kinniburgh 2001)In India, several geological sources have been identified as arsenic sources, such as Gondwana coal seams in the Rajmahal Basin in eastern India, the Bihar mica belt in eastern India, pyrite-bearing shale from the Proterozoic Vindhyan range in central India, the Son River Valley gold belt in eastern India, and isolated outcrops of sulphides in the eastern Himalayas. Studies by Bhattacharya et al. (2020b) indicate the release of arsenic and its transport from these locations.

Although there is still no concrete evidence of the source of arsenic contamination in Bihar, it is observed that the contaminated aquifers consist of Holocene sediments comprising sand, silt, and clay. This leads us to believe that the source of contamination in Bihar is mostly geogenic. The most commonly believed hypothesis is that arsenic in Bihar migrates with fluvial sediments from the Himalayas (McArthur et al. 2004). Although the source is believed to be geogenic, various anthropogenic activities such as groundwater exploitation, fertilizer use, coal burning, and the leaching of metals from coal-ash tailings can also partly contribute to arsenic contamination of groundwater and soil (McArthur et al. 2004).

Effect of Seasons on levels of Arsenic in ground water and in soil

It is generally observed that the levels of arsenic in groundwater are highest during the summers, decrease during the monsoon, and then increase again in the winters. However, there isn't a consensus in the literature about the effect of seasons on arsenic concentrations in groundwater. In Kishanganj, the arsenic concentration in groundwater was found to be at its maximum during the summers (Kumar 2015b)A study by Kumar et al.(2010) in Bhagalpur showed a non-significant effect of season on arsenic levels, with pre-monsoon levels at 118 µg/L and post-monsoon levels at 114 µg/L. There is a lack of sufficient studies in Bihar to support these results, although other studies in India and other countries have reported a potential effect of seasons on arsenic levels. In the Murshidabad district of West Bengal, a decline in mean arsenic concentration was reported from pre-monsoon (63.2 µg/L) to monsoon (59.2 µg/L) to post-monsoon (54.9 µg/L) (Farooq et al. 2011a)A study in Chhattisgarh also showed higher levels of arsenic in the pre-monsoon compared to the post-monsoon (Patley et al. 2017a). Similar results were observed in the Nawalparasi district of Nepal, where 66% of the samples showed higher arsenic concentrations in the pre-monsoon season compared to the post-monsoon season (Shrestha et al. 2014a).

Various reasons can be attributed to the seasonal variations of arsenic levels in groundwater. Some of these reasons include:

1. **Arsenic desorption**: Arsenic can desorb from the solid phase and enter the standing water, where it may undergo lateral removal or transport.
2. **Erosion and runoff**: During heavy rainfall, erosion of the topsoil layer can occur, leading to the runoff of arsenic-contaminated sediments.
3. **Volatilization and leaching**: Prolonged periods of flooding can result in the volatilization of arsenic as well as the leaching of standing water, which can desorb and transport arsenic from the topsoil to deeper layers (Islam et al. 2005).

It is important to note that the seasonal variations of arsenic levels can differ in different regions. Some reports indicate a reverse phenomenon for arsenic levels in the post-monsoon season compared to the pre-monsoon season. Examples include Silchar, Assam, where an increase in arsenic levels was reported (Kanungo 2016); Dhemaji, Assam, where higher arsenic levels were observed in the post-monsoon season (Buragohain 2018); Ballia District, Uttar Pradesh, where high arsenic concentrations were observed post-monsoon compared to pre-monsoon (Ali et al. 2012); and South 24 Parganas, West Bengal, where the maximum arsenic concentration was seen in the monsoon season and the least concentration was observed in the summers (Mazumder et al. 2020a).Table 5 attempts to indicate the arsenic levels in the pre-monsoon and post-monsoon seasons in some districts of India.

Table 5
Seasonal variation in Arsenic concentration in ground water and *soil

State	District	Pre-monsoon	Monsoon	Post-monsoon	References
Bihar	Kishanganj	0–22 μg/L	0–9 μg/L	0–10 μg/L	(Kumar 2015a)
Bihar	Bhaghalpur	118μg/L		114μg/L	(Kumar et al. 2010)
West Bengal	Murshidabad	63.2μg/L	59.2μg/L	54.9μg/L	(Farooq et al. 2011b)
Chhattisgarh*		3.13–5.83 mg kg-1		2.743–5.436 mg kg-1	(Patley et al. 2017b)
Nepal	Nawalparasi	0.73ppm		0.59ppm	(Shrestha et al. 2014b)
West Bengal	South 24 Parganas	694 μg/L	906 μg/L	794 μg/L	(Mazumder et al. 2020a)
Uttar Pradesh	Ballia	S*: 14–820 μg/L		S*:**13–950μg**/L	(Ali et al. 2012)
Uttar Pradesh	Ballia	M*: 30–450 μg/L		M*: 10–600 μg/L	(Ali et al. 2012)
Uttar Pradesh	Ballia	D* : 6-300μg/L		D *: 2-500 μg/L	(Ali et al. 2012)
Assam	Silchar	188 μg/L		161 μg/L	(Kanungo 2016)

Source: Compiled by the authors. (*in soil: shallow; M:medium; D:deep)

Levels of Arsenic in Groundwater

The groundwater in Bihar exhibits significant spatial variation in arsenic levels, leading to patchiness observed in the water from affected hand pumps. Arsenic concentrations in Bihar can vary by a factor of 90 over distances as small as 150 meters (Saha et al. 2011a). Geologically, Bihar is stratified into a "two-tier aquifer system" within a depth of 300 meters below ground level. This system consists of a shallow aquifer system (< 50 meters depth) and a deeper aquifer system (120–300 meters depth), separated by a 15–32-m thick clay and sandy clay aquitard (Saha et al. 2011a). The upper or shallow aquifer system is found to be arsenic-contaminated, while the deeper aquifer system exhibits low arsenic contamination, with maximum levels of 0.0035 mg/l (Saha et al. 2011a). A hydrogeochemical study identified several factors affecting groundwater chemistry in Bihar. These include the hydraulic conductivity of water, the presence of irrigation water charged with fertilizers, and recharge from rainfall infiltration. The groundwater in the deeper aquifer remains in a semi-confined to confined condition due to the poor hydraulic conductivity of the middle clay layer (Saha et al. 2011b). In these deeper aquifers, the factors affecting groundwater chemistry include leakage from shallow aquifers, ion-exchange processes, and the presence of silicate minerals. The middle clay layer acts as a protective barrier, safeguarding the deeper aquifer from arsenic contamination. Tube wells with a yield capacity of 150 m3/h can be installed in these areas, utilizing the deeper aquifer for drinking water supply (Saha et al. 2011b). Several studies have observed similar phenomena in Bihar. In Kishanganj, the level of arsenic was high in shallow hand pumps up to approximately 55 meters but reduced to negligible quantities at a depth of about 210 meters (Kumar 2015a).

In Darbhanga, similar results were observed, where shallow hand pumps exhibited higher levels of arsenic compared to deeper ones (Kumar and Singh 2020a). This indicates that the contamination of arsenic is more prevalent in the shallow aquifer regions. While the government in Bihar has installed hand pumps to address waterborne diseases like diarrhoea, privately installed hand pumps in shallow aquifer regions have become popular due to their cost-effectiveness. Installing deeper aquifers for socioeconomically backward groups can be expensive, leading to the widespread use of shallow hand pumps. This predisposes the local population to a higher risk of arsenic-contaminated water. In Khap Tola village, West Champaran, it was reported that more than 50% of the hand pumps with arsenic levels greater than 200 μg/L were privately owned and located in the shallow aquifer zone of 15–35 meters (Bhatia et al. 2014b). This highlights the need to educate the village communities about avoiding drinking water from shallow hand pumps. The authors of this review aim to draw attention to this issue and emphasize the importance of educating village communities about the risks associated with drinking water from shallow hand pumps.

Entry of Arsenic in food chain

Bihar, being one of the main agricultural states in India, relies heavily on agriculture for its economy, with approximately 80% of the population employed in agricultural production. The state is known for its vegetable and fruit production, ranking fourth in vegetable production and eighth in fruit production in the country.

The primary source of irrigation in Bihar is rainwater, but due to irregular rainfall patterns, people often rely on groundwater sources for irrigation. This is particularly important as crops such as rice, wheat, and maize, which are extensively cultivated in Bihar, require a significant amount of water for their growth. However, the presence of arsenic in groundwater poses a significant concern. The maximum allowable range of arsenic through food consumption is 0.2 mg/kg/day (Singh and Ghosh 2014). On average, children and elderly people in Bihar consume arsenic levels ranging from 398 μg/L to 945 μg/L through water used for drinking and cooking (Singh and Ghosh 2011a). This indicates a substantial exposure to arsenic through the consumption of contaminated groundwater. Moreover, there is a potential risk of arsenic contamination reaching consumers in arsenic-contamination-free areas through the export of food products from Bihar. If crops cultivated in arsenic-affected regions are exported to other areas, there is a possibility of arsenic being transferred through the food chain. The high reliance on groundwater for irrigation and the consumption of arsenic-contaminated water in Bihar present challenges for both agriculture and public health. Addressing the issue of arsenic contamination in groundwater is crucial to ensure the safety and well-being of the population as well as preventing potential contamination of food products reaching consumers outside the affected regions.

The case study conducted in Maner Block of Patna in 2011 revealed the presence of arsenic contamination in grains and lentils. The arsenic concentrations in the grains ranged from 0.024 to 0.015 mg/kg (Singh and Ghosh 2011a). Among the tested crops, wheat grain exhibited the highest concentration of arsenic, followed by rice husk, rice grain, lentils, and maize. It is important to note that arsenic contamination was observed not only in the grains themselves but also in various parts of the crops, such as the husk. The contamination occurs because plants irrigated with arsenic-contaminated water can uptake arsenic during the phytoextraction process and accumulate it in different plant parts. This poses a significant threat as grain husks, which may contain arsenic, are often used as general fodder for animals. The consumption of these feeds by animals puts them at risk of arsenic poisoning. Consequently, there is an indirect threat to the population that consumes eggs, meat, milk, and dairy products derived from these animals. Unfortunately, there are limited studies focused on the concentration of arsenic in food products. Given the current scenario, there is an urgent need for detailed studies to assess the arsenic concentrations in various parts of grains and other food crops. This information is crucial to understanding the extent of arsenic contamination in the food chain and implementing appropriate measures to mitigate the risks associated with arsenic exposure through food consumption.

According to Dubey et al. (2018b), the study found higher levels of arsenic concentration in vegetables compared to cereals (maize) and forage crops (Faba/Fava beans). The arsenic concentrations in vegetables ranged from 50.8 to 289.1 μg/L, while forage crops exhibited concentrations ranging from 90.3 to 241.5 μg/L, and cereals showed concentrations ranging from 40.1 to 265.4 μg/L. Among the vegetables tested, brinjal (eggplant) had the highest concentration of arsenic at 289.1 μg/L. Other contaminated vegetables included lady's finger (okra), sponge gourd, tomato, bottle gourd, cowpea, and ash gourd. In the study conducted in Buxar in 2019 (Kumar and Upadhyay 2019b), it was found that arsenic levels were higher in the cores of vegetables, particularly in areas where the moisture content is high. The study revealed a wide range of arsenic concentrations, from 0.02 to 586 μg/kg, in various vegetables grown in arsenic-contaminated villages. Specifically, the core of brinjal (eggplant) showed arsenic levels of 450 μg/kg, while the peel had a lower concentration of around 200 μg/kg. The gourd core exhibited arsenic levels exceeding 350 μg/kg, while the peel showed levels of approximately 180 μg/kg. In tomatoes, the core had arsenic levels of 200 μg/kg, whereas the peel had a higher concentration of 465 μg/kg. Chilli seeds contained around 160 μg/kg of arsenic, and bean seeds had approximately 200 μg/kg, while bean peels had a lower concentration of 50 μg/kg. The core of potatoes had arsenic levels of 500 μg/kg, while the peel exhibited levels of 10–20 μg/kg. Similar results were observed in Bhagalpur in 2019, where various vegetables showed arsenic levels ranging from 0.02 to 586 μg/kg (Arya et al., 2019). The core parts of vegetables had higher concentrations of arsenic, with the potato core containing 348.88 μg/kg, brinjal core having 290 μg/kg, and the gourd core exhibiting 226 μg/kg of arsenic levels.

These findings indicate that certain vegetables, especially brinjal, have a higher tendency to accumulate arsenic compared to cereals and forage crops. The presence of arsenic in vegetables is concerning, as they are a significant part of the diet in Bihar, and the consumption of arsenic-contaminated vegetables can contribute to higher arsenic exposure among the population. It emphasizes the need for continued monitoring and mitigation strategies to ensure food safety and reduce the risks associated with arsenic contamination in agricultural produce.

Effects on Arsenic on human health

The effects of arsenic exposure on humans depend on various factors such as age, gender, nutritional status, duration of exposure, and other individual characteristics. Among vulnerable populations, children, pregnant women, and infants are particularly susceptible to the adverse health effects of arsenic contamination. Arsenic poisoning can manifest in two forms: acute poisoning and chronic poisoning. Acute poisoning occurs when a high dose of arsenic is ingested over a short period of time, leading to immediate symptoms and potentially life-threatening effects. Chronic poisoning, on the other hand, results from prolonged exposure to relatively low levels of arsenic, which can cause the gradual accumulation of the toxin in the body and the development of various health problems over time. The Agency for Toxic Substances and Disease Registry (ATSDR) has defined the minimal lethal dose of inorganic arsenic as 1–3 mg/kg, while a daily intake of 600 μg/kg is considered fatal for humans. These values highlight the potential toxicity of arsenic and emphasize the importance of avoiding exposure to high levels of the toxin. In the context of Bihar, the population's exposure to arsenic is likely due to multiple factors, including the consumption of contaminated drinking water from shallow hand pumps, the consumption of locally grown food in areas with high arsenic contamination, and the use of shallow aquifers for irrigation. These factors, coupled with the poverty level and the lack of knowledge about water quality, have resulted in the entry of arsenic into the bodies of newborn babies, leading to life-threatening diseases such as various types of cancer (e.g., skin, bladder, lungs, kidneys, and liver) (Kumar et al. 2021).

1. Effects on the Skin

Acute symptoms of arsenic poisoning include the delayed appearance of Mee's lines in nail beds, dermatitis, melanosis, and vesiculation. In chronic cases, hyperpigmentation, pigment changes on the face, neck, and back (resembling a "raindrop" appearance), skin lesions, skin hyperpigmentation, and hyperkeratosis can be observed. Previous reports by Singh and Ghosh (2011b) indicate cases of body itching and skin pigmentation in Rampur Diara and Haldichapra of the Maner block in Patna district. In Kishanganj, cases of arsenical dermal lesions were diagnosed (Kumar 2015a). In Shahpur block of Bhojpur, out of the 1,422 villagers tested, 161 reported cases of arsenic lesions, with a prevalence rate of 11.3%. Additionally, it was found that 82% of hair, 89% of nails, and 91% of urine samples tested from the study area had arsenic levels above normal, indicating sub-clinical effects in many individuals (Chakraborti et al. 2011a). In Darbhanga, Kumar and Singh (2020a) reported cases of hyperkeratosis in the sole, palm melanosis, and leuco-melanosis. Blackening of teeth and nails was also observed in many individuals exposed to arsenic, along with hyperpigmentation (spotted pigmentation) on their whole body, in Chaukia, Terahrasiya village of Vaishali, and Masharu and Mamalkhan village of Bhagalpur. Typical symptoms of arsenicosis, such as hyperkeratosis in the sole and palm, hyperpigmentation, nodular keratosis of the skull, and hyperkeratosis of the skin, were observed. In Gyaspur Mahaji Patna village, typical symptoms of arsenicosis, including hyperkeratosis in the sole and palm, hyperpigmentation in the palm, spotted pigmentation on the whole body, melanosis, cervical nodes on the neck region, and a tumour lump at the back, were reported (Ghosh et al. 2007b). In rural areas of Buxar, the population exhibited typical symptoms of arsenicosis, such as hyperkeratosis in the palm and sole, melanosis in the palm and sole, blackening of the tongue, skin irritation, and anemia (Ms et al. 2019a). In Simri village, Buxar, reports indicated the presence of arsenic in children's hair, with a maximum value of 12.609 mg/kg (Ms et al. 2019a). In 2020, cases of arsenicosis were reported in villages along the Gangetic plains of Bhagalpur, particularly in Dildarpur, Gosaidaspur, and Srirampur (Kumar et al. 2020a). These findings highlight the significant impact of arsenic exposure on the skin and the various symptoms and conditions that can arise as a result.

2. Gastrointestinal effects.

Acute symptoms of arsenic poisoning can include a garlic odour on the breath, severe abdominal pain, nausea and vomiting, thirst, dehydration, anorexia, heartburn, bloody or rice-water diarrhoea, and dysphagia. On the other hand, chronic symptoms typically manifest as gastritis, colitis, abdominal discomfort, anorexia, malabsorption, and weight loss. In specific regions, various gastrointestinal symptoms have been reported due to arsenic contamination. In the Rampur Diara and Haldichapra villages of the Maner block in Patna, cases of diarrhoea and gastric problems were observed (Singh and Ghosh 2014). (Singh et al. (2014b) reported cases of gastric problems and diarrhoea in the Mamal Khan and Mashrau villages of Bhagalpur. In Terahrasiya and Chaukia villages of Vaishali, cases of diarrhoea, gastric problems, jaundice, dysentery, and piles were reported (Kumar and Singh 2020a). Additionally, in Gyaspur Mahaji village, Patna, 75.52% of the population reported gastritis and flatulence, while 73.10% reported constipation (Kumar and Singh 2020b). Gastritis, constipation, and loss of appetite were also reported in the Buxar district (Kumar et al. 2021).

3. Cancerous effects.

The International Agency of Research on Cancer (IARC) has described arsenic as a class 1 carcinogen.

Prevalence of prostate cancer was linked to arsenic hotspots in Gangetic-zone of Bihar (Nath et al. 2012b). In Patna, high incidences of breast, skin, liver, and gall bladder cancers were recorded in arsenic hit areas (Nath et al. 2012b). In West Champaran it was identified that children are at a high risk of developing cancer (Bhatia et al. 2014a). Singh et al. (2014b) reported cases of skin cancer, gallbladder cancer, and breast cancer in Bhojpur. Arsenical neuropathy was observed in 48 % of 102 arsenicosis patients in the Shahpur block of Bhojpur (Chakraborti et al. 2016). In Darbhanga, afew cases of skin, liver, and bladder cancer were observed in the population of the study area (Abhinav et al. 2016). In 2019, Gyaspur Mahaji village in Patna reported cases of squamous cell carcinoma of skin and the other with medullary breast cancer (Kumar et al. 2019b).

In a recent study carried out by (Kumar et al. 2021), a correlation was found between the geospatial map of the demographic area of the Gangetic plains in Bihar and blood arsenic levels in relation to cancer types. This study also specifies that the majority of the cancer patients with high blood arsenic concentrations were from districts near the river Ganges. Further studies also indicate a correlation between the occurrence of gallbladder cancer and increased levels of arsenic in Bihar (Kumar et al. 2022; Shridhar et al. 2023).

4. Respiratory, neurological, cardiovascular, hormonal, haematological and

One district in Bihar, Buxar, reported a mean blood arsenic concentration of 83.04 µg/L, with a maximum blood arsenic concentration of 706.1 µg/L. Along with the arsenic concentration, elevated levels of MDA and GPx, representing anti-oxidative stress, were also found. Additionally, all haematological parameters such as WBC count, RBC count, haemoglobin percentage, and other RBC indices were significantly abnormal (Ms et al. 2019a). In Gyaspur Mahaji village, Patna, arsenic concentration was measured in 58 blood samples, of which 59% reported arsenic levels exceeding the permissible limit. The highest concentration recorded was 64.98 µg/L (Ms et al. 2019b). Cases of bronchitis, tuberculosis, asthma, cough, breathlessness, neurological disorders, mental disability, hormonal imbalance, and heat problems have been reported in Buxar (Fig. 2) (Kumar and Upadhyay 2019c; Rahman et al. 2019), Darbhanga (Abhinav et al. 2016), Vaishali (Abhinav et al. 2017), and Bhagalpur (Abhinav et al. 2017). The rural population in Bhojpur exhibited elevated levels of serum estrogen while decreasing levels of serum testosterone, indicating the adverse effects of arsenic in contaminated groundwater (Singh and Ghosh 2014). Only a few studies have been conducted in Bihar to examine the health effects of arsenic contamination, highlighting the need for further research. In 2020, Simri village in Buxar reported impaired memory and intelligence among school children. A recent study by Kumar et al. (2022) attempted to explore the mental health aspects and the role of perceived social support in arsenic-induced cancer among the population from the middle Gangetic plain of Bihar.

Steps taken by the Government

In 2006, the National Rural Drinking Water Quality Monitoring and Surveillance Programme (NRDWQM&S) was launched with the main objective of increasing community participation and creating awareness about arsenic contamination (Shrivastava 2016). In addition to raising awareness, the NRDWQM&S also undertakes several other functions. This includes providing field test kits for arsenic testing and establishing district and sub-district drinking water quality testing laboratories for routine analysis of drinking water in rural India (Shrivastava 2016). Furthermore, the government has implemented various measures to address arsenic contamination. One such measure involves coloring the affected hand pumps to indicate that water from these sources should not be consumed (Shrivastava 2016). The government has also sealed off water sources that were found to have arsenic contamination above 0.05mg/L. Proactive steps have been taken to install new hand pumps at deeper levels and ring wells at upper levels. Additionally, arsenic treatment units have been installed, and the government provides assistance to states regarding arsenic treatment technologies (Shrivastava 2016). The government has also implemented groundwater-based piped water supply schemes and a surface water-based piped water supply scheme that utilizes rivers and ponds as water sources. As part of the National

Aquifer Mapping Programme (NAQUIM) led by the Central Ground Water Board (CGWB), efforts have been made to reduce or mitigate the levels of toxic substances in groundwater. In Bihar, approximately 40 wells tapping into arsenic-safe aquifers have been constructed (Ministry of Jal Shakti, December 2022). In addition to these initiatives, the government promotes research and development activities. It has identified seven specific areas for research and provides significant funding for studies undertaken in these areas. The World Health Organization (WHO) also suggests household water treatment and Safe Storage (HWTS) as solutions. HWTS involves the use of various technologies, either individually or in combination, such as filtration (biosand, ceramic pot, membrane, and candle filter) and disinfection methods (boiling, chlorine, UV, SODIS, and more). Household water treatment technologies are advantageous as they reduce the risk of secondary infections compared to community-level technologies (Kushawaha and Aithani 2021).

The non-government organization Sehgal Foundation has developed an innovative and sustainable technology called JalKalp and Matkikalp, which involves the use of bio-sand filters. These filters are specifically designed and optimized for the natural oxidation of As (III) into As (V), which helps remove arsenic from water. Additionally, the technology incorporates zero-valent iron (ZVI) for the removal of arsenic through the adsorption of As (V) on hydrous ferric oxide (HFO) produced by ZVI placed in a diffuser. This innovative approach, using low-cost biosand filters and ceramic pot filters like JalKalp and MatiKalp with the integration of ZVI, provides a sustainable solution for providing safe drinking water in households, particularly in states like Bihar where arsenic contamination is prevalent (Verma et al. 2021).

Problems with implementation and suggestions

It is indeed true that despite the government's initiatives, there is still a lack of awareness among people in villages regarding arsenic contamination and its effects. A significant percentage of respondents in an arsenic-contaminated village were found to be unaware of arsenic poisoning and its health consequences (Thakur and Gupta 2020). This highlights the need for a more rigorous awareness campaign to educate people about the harmful effects of arsenic contamination, its sources, and available remedial procedures (Singh 2015). While the government has made efforts to provide simple and affordable arsenic testing kits, it has been observed that they are often not procured and distributed effectively by the relevant departments or authorities. Therefore, more emphasis should be placed on creating awareness among the population about the availability of such kits and how to procure and use them (Ghosh et al. 2007c). Furthermore, although the government has established laboratories, there are challenges such as a lack of equipment and well-trained personnel that hinder timely identification and resolution of the arsenic contamination problem (Chakraborti et al. 2011b). Maintenance of the installed arsenic treatment units is crucial for their efficient operation. Another area that requires attention is the research on arsenic uptake in food, its health effects, and its impact on various multidisciplinary fields. While the government encourages and provides funds for research, there is a lack of comprehensive studies in these areas. Additionally, the absence of a common repository for arsenic contamination data in Bihar makes it difficult to monitor research progress and develop effective mitigation policies **(**Fig. 3 **and** Fig. 4**)** (Singh 2015).

Various technologies for Arsenic remediation.

Non-microbial based remediation methods

There are various technologies available for the remediation of arsenic in groundwater. Conventional methods such as coagulation, flocculation, adsorption, ion exchange, and membrane processes have been widely used (Kumar 2015b). Additionally, in-situ methods, including combinations like coagulation and flocculation, the use of zero-valent iron, adsorption methods using natural materials, and photochemical technologies, have been explored (Kumar 2015b). However, both conventional and in-situ methods have their limitations. Conventional methods are associated with drawbacks such as the generation of harmful by-products and sludge, the need for regeneration of adsorbents in adsorption techniques, the requirement of pH adjustment in coagulation, and the presence of dissolved solids and other inorganic ions in the ion exchange process. Economically, conventional methods may be less viable (Litter et al. 2010). Similarly, in-situ methods also have limitations, including interference from various compounds like oxides, sulphides, carbonates, and hydroxides, the production of toxic wastes by zero-valent iron, and the influence of microbial and geochemical processes (Litter et al. 2010). These drawbacks highlight the need for continuous research and development of arsenic remediation technologies to overcome these limitations and improve the effectiveness, efficiency, and economic feasibility of the methods used."

Arsenic resistant bacteria-based bioremediation: Unlike conventional technologies, there are certain biological processes that can be used for the treatment of arsenic in groundwater. Studies have been conducted utilizing arsenic-resistant bacteria to either remove arsenic or convert the more harmful arsenite to arsenate. Bioremediation is considered better than conventional arsenic removal technologies because of its environmental compatibility. Since arsenic is a ubiquitous metal, certain microorganisms have developed various strategies to withstand relatively large amounts of arsenic or detoxify it for survival processes. Microbes can detoxify arsenic in three ways: by uptaking or extruding arsenic, by arsenate reduction, and by arsenite oxidation.

The structural similarity between transporter proteins and arsenate and arsenite enables the uptake of these compounds in bacteria. Arsenate uptake is facilitated by the phosphate transporter proteins Pst and Pit, while arsenite uptake is facilitated by the glycerol transporter GlpF. The extrusion of arsenate or arsenite is mediated by either a three-gene operon, arsRBC, or a five-gene operon, arsRDABC (Yang et al. 2012). Several bacterial species have been reported for their ability to uptake and remove arsenate and arsenite. *Bacillus flexus*, isolated in West Bengal, demonstrated the potential to remove 25.6% of arsenate and 30.4% of arsenite (Majumder et al. 2012). Another isolate, *Bacillus licheniformis*, was found to uptake and remove arsenate and arsenite in Patna(Tripti et al. 2014) In 2015, two bacterial strains, *Pseudomonas sp*. and *Acinetobacter sp*., were reported to tolerate 7 and 17.5 mm of arsenite, respectively, and remove it in the range of 1.54–5.95% from contaminated water in West Bengal (Pandey et al. 2015).Dey et al. (2016) reported two bacterial strains, *Bacillus sp*. and *Aneurinilyticus sp*., which could tolerate arsenate levels up to 4500 ppm and arsenite levels up to 550 ppm, respectively. In

Chhattisgarh, *Exiguobacterium sp*. was reported in 2016 for its uptake and removal abilities of arsenate and arsenite, demonstrating the capability to remove up to 99% of arsenic (Pandey and Bhatt 2016). Furthermore, a study by Tyagi et al. (2018) indicated that three bacterial isolates, *Bacillus macerans, Bacillus megaterium*, and *Corynebacterium vitarumen*, exhibited arsenite resistance and effective arsenite removal capabilities. These studies highlight the potential of various bacterial species to uptake and remove arsenate and arsenite, providing promising avenues for bioremediation strategies targeting arsenic-contaminated water sources.

Prokaryotes have been found to possess two arsenate reduction systems: cytoplasmic arsenate reduction and periplasmic arsenate reduction. In the cytoplasmic arsenate reduction pathway, when As (V) is taken up by the Pst and Pit membrane transporters, the arsC gene is involved. The arsC gene encodes for the enzyme arsenate reductase (ArsC). ArsC catalyzes the reduction of As (V) to As (III). The reduced As (III) is then extruded from the cell through the ArsAB pump, which is responsible for the efflux of arsenite. In the periplasmic respiratory pathway, the enzyme arsenate reductase (ArrA) is utilized. ArrA is present in the periplasmic space and is involved in the reduction of arsenate. This pathway is specific to certain prokaryotes that possess the periplasmic respiratory system. Homologues of the arsC gene can be found in both plasmids and chromosomes of prokaryotes. In the cytoplasmic reduction pathway, ArsC utilizes glutaredoxins as a source of reducing potential. The reaction cascade starts with arsenate binding to the anion site in ArsC. It then forms an arsenate thioester intermediate with the active site, Cys12. The intermediate is subsequently reduced in two steps by glutaredoxin and glutathione, resulting in the production of the Cystic-S-As(III) intermediate. This intermediate hydrolyzes to release arsenite. The reduced As (III) can be extruded from the cell or sequestered in intracellular compartments. It can exist either as free arsenite or form conjugates with glutathione or other thiols, allowing for intracellular storage or detoxification of arsenic (Yang et al. 2012) These arsenate reduction systems provide prokaryotes with the ability to convert the more toxic arsenate form to the less toxic arsenite form and subsequently extrude or sequester it, contributing to their arsenic resistance mechanisms.

In Begusarai district, Bihar, two bacteria capable of tolerating 150 mM of arsenate were identified as Paracoccus sp. strain NC-A and Alcaligenes faecalis strain NC-B (Tripti and Shardendu 2018). These bacteria demonstrate a high tolerance to arsenic concentrations. Additionally, an isolate named *Stenotrophomonas sp*. NC-C was reported to tolerate 30 mM of arsenite in the same study (Tripti and Shardendu 2018). This bacterium shows resistance to arsenite, which is the more toxic form of arsenic. In the Bhojpur district of Bihar, two gram-positive bacteria, *Bacillus infantis* and *Bacillus litoralis*, were reported in 2018 for their ability to oxidize arsenite to arsenate (Biswas and Sarkar 2019). This oxidation process helps in the detoxification of arsenite. Furthermore, three arsenic hyper-tolerant bacteria, namely *Acinetobacter calcoaceticus* J1, *Agrobacterium tumefaciens* J2, and *Bacillus cereus* DAS3, were isolated and identified as efficient arsenic removers. They were capable of removing both As (V) and As (III) from the growth medium (Tripti et al. 2017). In 2018, two bacteria belonging to the genus *Pseudomonas* with the ability to resist arsenite concentrations of 13 mM and 15 mM were reported (Satyapal et al. 2018). These bacteria exhibit resistance to arsenite and have the potential for arsenic removal. These findings highlight the presence of bacteria with varying capabilities to tolerate and detoxify arsenic in different regions of Bihar and Uttar Pradesh, contributing to the exploration of bioremediation strategies for arsenic-contaminated environments.

Conclusion

The arsenic contamination in Bihar poses a significant threat to the lives of millions of people. The contamination, which was initially detected in 2002 in two blocks of a single district, has now spread to a total of 21 districts as of 2019. However, it is important to note that other regions in Bihar are not necessarily safe from arsenic contamination. The presence of arsenic in the environment has led to its entry into the food chain, putting people at risk of indirect contamination through food grains, meat, poultry, and other sources. Numerous cases of arsenicosis and deaths related to arsenic poisoning have been reported in Bihar over the years. Malnourished children and pregnant women are particularly vulnerable to arsenic poisoning due to their compromised immunity. Despite efforts by the government, the steps taken so far seem inadequate for controlling and preventing the spread of arsenic contamination in Bihar. In this context, bioremediation appears to be a cost-effective and environmentally friendly solution among the various technologies available to mitigate arsenic contamination. Further research should be undertaken to explore the potential of bacteria in mitigating arsenic and developing effective bioremediation strategies. The research conducted in Bihar has primarily focused on identifying arsenic-contaminated locations. However, in recent years, with the increased awareness of the harmful effects of arsenic poisoning, research has also been directed towards understanding the entry of arsenic into the food chain and taking proactive measures to mitigate its effects on the soil, water, and health of the people in Bihar. It is crucial to continue and expand research efforts in Bihar to better understand the extent of arsenic contamination, develop effective mitigation strategies, and protect the health and well-being of the population at risk.

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Conflict of Interests

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Consent to Participate

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by **Ruchi Dube, Sunita Singh, Arpita Gupte** and **Akhilesh Modi.** The first draft of the manuscript was written by Ruchi Dube. All authors read and approved the final manuscript.

RD: Collecting the literature, Compilation of data, Executing and planning of the different sections of the review article and Manuscript drafting.

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Figures

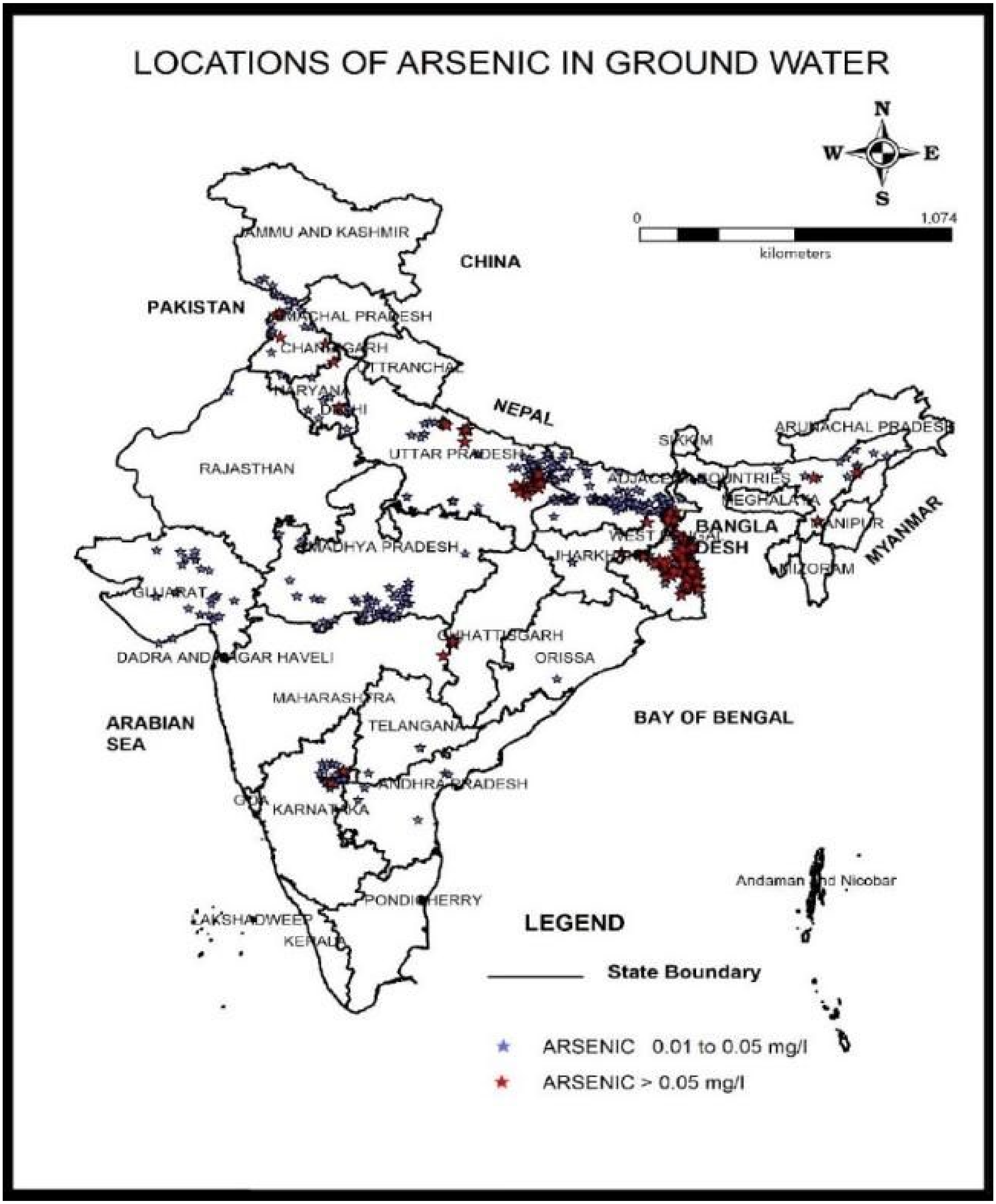

Figure 1

Arsenic hotspots in groundwater in India

Source: Ministry of Water Resources, River Development and Ganga Rejuvenation(2019)

Figure 2

(a) Hyperkeratosis of sole in an 80-year-old female. **(b)** Cervical enlarged node (Lymphoma Cancer) in a 68 years old male. **(c)** Enlarged thyroid gland growth (Thyroid cancer) in a 72 years old female. **(d)** Hyperkeratosis of the palm in a 60 years old male. (e) Lesion in the head region in 65 years old female

Figure 3

Non-functional arsenic-removal unit in Bhawani Tola

Figure 4

An abandoned arsenic-free open dug well in Ansari market, Kesath, Bihar, India