An overview of carcinogenic pollutants in groundwater of India

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ABSTRACT

Groundwater is the major source of freshwater for irrigation, drinking, and sanitation in India. 50% of urban water requirement and 85% of rural domestic water requirements are fulfilled by groundwater. Industrialization, unmanaged dumping of waste, extensive application of pesticides and other geological metamorphic activities have led to the contamination of freshwater resources. Consumption of such polluted water poses a threat to the ecosystem and human health and also, has the potential to cause cancer. Globally as well as nationally, cancer is emerging as a high-risk disease. Scientific community worldwide faces a crucial challenge in finding its possible prevention measures and cures. Reducing the exposure to carcinogens offers the most cost-effective and long-term strategy for control of cancer. Therefore, this study aims to discuss the prevalent carcinogenic contaminants and their sources reported throughout the country in groundwater and to ponder upon the associated health risks. The possible remedial measures are also critically reviewed, which may help in finding a sustainable methodology for mitigating carcinogenic groundwater pollutants.

1. Introduction

Aquifers are the main sources of potable water, which is essential for human health. Groundwater is less vulnerable to anthropogenic pollution as compared to surface water because the sediments tend to act as filters to remove the contaminants. Broadly, there are two major groups of water contaminants namely, inorganic contaminants and organic contaminants (Kumar et al., 2017,d, 2017c, 2019; Jacob et al., 2018). Inorganic water contaminants include trace metals, inorganic salts, mineral acids, sulfates, cyanides, etc. (Jacob et al., 2018; Lu and Astruc, 2018; Yadav et al., 2015; Jain and Ali, 2000). High concentrations of heavy metals (HMs) are detected in mine drainage waters and in industrial effluents. Arsenic (As), Cadmium (Cd), Zinc (Zn), Copper (Cu), Nickel (Ni), Lead (Pb), Mercury (Hg), Iron (Fe), Selenium (Se), and Chromium (Cr) are often detected in industrial wastewaters, which originate from metal plating, mining activities, smelting, battery manufacturing, tanneries, petroleum refining, paint manufacturing, pesticides, pigment manufacturing, printing, photographic industries,

etc. (Kaur et al., 2019; Kumar et al., 2017b, 2019). Groundwater can be contaminated either geogenically or anthropogenically with the HMs such as As, Cd, Hg, Fe, Pb, and Se, etc., (Dash et al., 2017; Kumar et al., 2016b,c,d, 2017). Nowadays, pollution due to heavy metal contaminants is one of the most important environmental concerns due to their high toxicities and adverse impacts on human health. According to the report published by WHO (2006), drinking of contaminated water is responsible for 80% of all the diseases and deaths in the developing countries. Drinking water with a high concentration of HMs has the potential of causing critical diseases such as cancer (IARC, 2009). HMs have the potential to bioaccumulate in the adipose tissues of the human body, which may result in various diseases. HMs generally exist as cations in water and thus, the toxic species of lead, arsenic, mercury, chromium, and cadmium exist as Pb^{2+}, As^{3+}, Hg^{2+}, Cr^{6+}, and Cd^{2+}, respectively (Lu and Astruc, 2018). These toxic cations of HMs can be removed by physical, chemical, and biological processes (Fig. 1). In the last few decades, the application of excessive pesticides in Northern India has put groundwater at high risks. Assessment and monitoring of

pesticide residues have detected the presence of such compounds in sediments as well as in groundwater at certain places (Dev and Bali, 2018). Pesticide usage undoubtedly boosts up a country's economy, however, mismanaged pesticide practices result in the contamination of the environment, most importantly, the water resources. Leaching of pesticides contaminates the soil sediments and groundwater. These contaminated sources affect human health by creating an extra load in terms of medical expenses on the Indian economy. Lari et al. (2014) quoted that the first incident of pesticide contamination was detected in Kerala in 1958, in which, 100 people died due to the consumption of food having the residues of parathion. Since then, in the last few years, several cases of groundwater contamination with pesticides have been reported in different parts of India (Dev and Bali, 2018; Kumar and Mukherji, 2018; Lapworth et al., 2018; Lari et al., 2014; Shukla et al., 2006). Somashekar et al. (2015) detected the presence of methyl isocyanate in the water samples collected from the Mysore city of Karnataka state, India. Lari et al. (2014) found endosulphan, β-Hexachlorocyclohexane (HCH), dichlorvos, chlorpyrifos and parathion-methyl in Bhandara, Amravati and Yavatmal districts of Maharashtra, India. In Hyderabad, India, four pesticides, namely, lindane, α-endosulfan, β-endosulfan, and Dichlorodiphenyltrichloroethane (DDT) were reported in the range of 0.68–1.38 μg/L, 0.21–0.87 μg/L, 1.34–2.14 μg/L and 0.15–0.19 μg/L in groundwater, respectively (Shukla et al., 2006). Various sources, the pathway of entry into different environmental segments, and receptors of pesticides have been illustrated in Fig. 2.

Apart from organic and inorganic contaminants, some recent studies have revealed that at certain places in India, groundwater has also been polluted by radioactive elements such as uranium and radon (Bajwa et al., 2017; Dash et al., 2017; Saini et al., 2017; Sar et al., 2017; Singh and Poonam, 2014). Uranium gets deposited in the kidneys, bones, and livers of human beings and its radionuclide is carcinogenic in nature. Water polluted with radon may cause stomach cancer. Some of the researchers have reported radon contamination in the groundwaters of Punjab and Himachal Pradesh (Sharma et al., 2019; Bajwa et al., 2017; Walia et al., 2003). There are several studies related to groundwater pollution in India, however, there is a lack of studies discussing the carcinogens present in the water to the best of our knowledge. Hence, this work provides an insight into the sources, distribution, and possible remedial measures for various carcinogenic compounds with special reference to groundwater in India based on the data available in the literature.
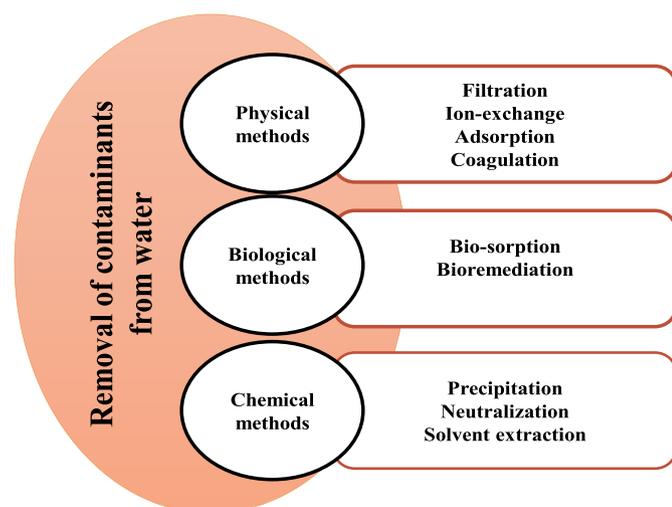

Fig. 1. Removal methods of heavy metals from water (Source: Lu and Astruc, 2018).

2. Sources and distribution of carcinogenic pollutants in Indian groundwaters

Uranium, arsenic, lead, cadmium, radon and pesticides are the primarily detected carcinogenic contaminants present in the Indian water and have been investigated and reported by various researchers (Duggal et al., 2017; Kumar et al., 2017; Saini et al., 2017; Garg et al., 2014). The permissible limits of some of the potentially carcinogenic compounds are presented in Table 1 along with their sources and the potential health hazards posed by them.

2.1. Uranium

In India, Guru Nanak Dev University, Amritsar, Punjab, has published the first report on the presence of uranium in groundwater in 1995 (Times of India, 2010). Uranium (U) is a naturally occurring radioactive element, abundant in rocks and on an average it is 10% by mass of the earth's crust (Dash et al., 2017). There are two sources of uranium in groundwater namely, geogenic and anthropogenic. The important anthropogenic sources of U pollution are phosphate fertilizer production from phosphate rocks having U, mining, and milling of U, U enrichment for nuclear weapons and fuels in nuclear power plants. U reaches the groundwater from sediments through leaching and from groundwater it enters the food chain, thus, causing toxicity at various trophic levels. The redistribution of U and its radionuclide into groundwater is governed by several factors and significantly takes place form soil to rocks (Dash et al., 2017). Some of the important redistribution factors are rock matrix, soil pH, water redox state, leaching capacity of the soil, and concentration of phosphate, fluoride, calcium, carbonate, and potassium (Dash et al., 2017). There are three naturally occurring isotopes of U i.e. U-234; U-235, and U-238 and all the three have very long halflives. The half-lives of U-234, U-235, and U-238 are 2.4×10^5 years, 7.0×10^8 years and 4.5 x years, respectively, therefore, they decay at very slow rates and even minor changes take very long periods. In India, U in groundwater is generally in the range of 1–100 μg/L but in certain regions, it has been detected at very high concentrations (Table 2) such as 5840 μg/L in the Kadapa district of Andhra Pradesh (Dash et al., 2017). The human health risks associated with U exposure are twofold including radiological hazards as well as chemotoxic hazards (Hakonson-Hayes et al., 2002). The radiation hazard from naturally occurring U in drinking water is low as the specific activity is low (7.1×10^{-7} curies g^{-1}) (Langmuir, 1978) but numerous degradation products of U (specifically, ^{223}Ra; ^{226}Ra; ^{228}Ra) that occur in groundwater are known carcinogens. Duggal and Sharma, (2017) reported that U concentration in Fatehabad, Haryana ranged from 1.1-113 ppb. U concentration in South-West Punjab (Bathinda, Mansa, Faridkot, Ferozpur) reported by Bajwa et al. (2017) varied from 0.5 to 571 ppb, 1.3–579 ppb, 2.4–476 ppb, 2.8–467 ppb, respectively (Table 2). In Kadapa district, Andhra Pradesh, the concentration of U was found to be 0.38–79.30 ppb by Rana et al. (2016). Kumar et al. (2015) analyzed four districts in Uttar Pradesh for U contamination and found that the minimum U contamination in Allahabad was 11.50 ppb while that of maximum uranium contamination was 11.30–63.33 ppb in Varanasi. Another study conducted (Singh et al., 2014) in the seven major districts of Haryana, India, observed that the concentration (ppb) of U ranged from 2.2 to 109.9 ppb, 2.3–47.9 ppb, 2.0–73.4 ppb, 2.7–32.4 ppb, 0.6–256.4 ppb, 6.7–40.3 ppb, 0.3–53.4 ppb in Kumharia, Kajalheri, Gorakhpur, Sabarwas, Siwani, Balanwali, and Khajuri, respectively. Garg et al. (2014) reported that U level in Hisar, Haryana was 5.3–113.5 ppb. A report published by the government of India in 2012, of Acid Mine Drainage in the Una district of Himachal Pradesh, noted the U concentration ranging from 2- 80 ppb.

2.2. Radon

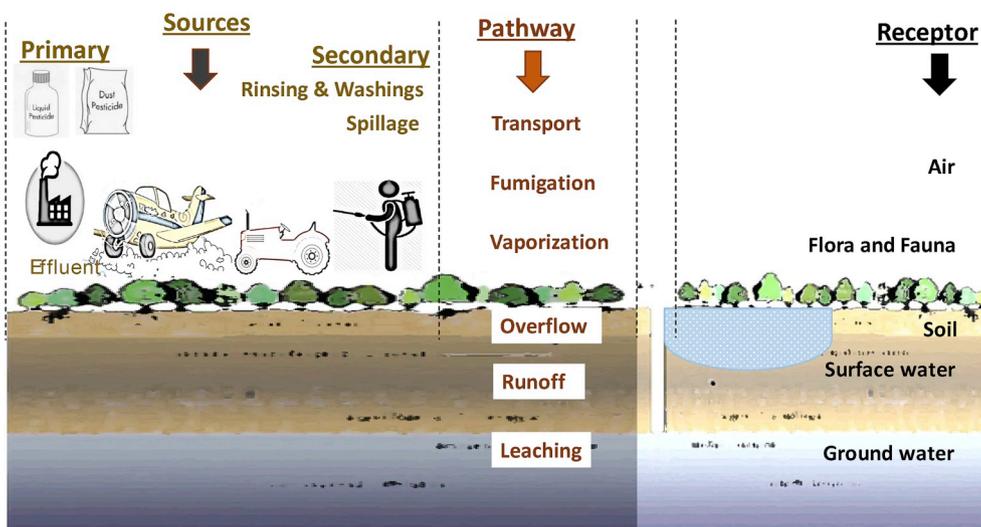Radon is a colorless, odorless, tasteless, radioactive noble gas

Fig. 2. Graphical illustration of primary sources, pathways, and receptors of pesticide pollution in the environment.

Table 1
Some of the potential sources of carcinogenic pollutants in groundwater, their permissible limits and associated hazard.

Pollutant	Sources to groundwater	Permissible limit (µg/L)		Potential health hazard
		BIS	WHO	
Arsenic	The geogenic process, pesticides, industrial waste, smelting of copper, lead, and zinc ore.	10	10	Acute and chronic toxicity of the liver and kidney damage which may result in carcinogenicity.
Cadmium	Rock and coal, Mining industries, landfill leaching, and cadmium batteries	3	3	May result in kidney cancer.
Lead	The industrial process, mining, plumbing, gasoline, and coal enrichment process.	10	10	Have lung, brain, kidney, and stomach cancer risk in humans.
Chromium VI	Industrial pollution or natural Sources	50	50	Stomach cancer.
Pesticides	Agricultural runoff, industrial effluent, and disinfectant	**	**	Liver, gall bladder and respiratory system cancers.
Uranium	Sediments and nuclear power plants	NA	NA	May causes cancer along with other carcinogenic pollutants.

**- Permissible limit varies from pesticide to pesticides; NA-Not allowed.
Source: WHO, 2006; BIS, 2012; USGS Water Science School; IARC M, 2015, 2009;

produced by two beta and three disintegrations from initial ^{238}U. Radiation of radon is natural as it occurs in the different spheres (water, soil, and air) of the earth. The successive decay of radon has produced progenies, which have carcinogenic potential. According to the International Agency for Research on Cancer (IARC) (2012), radon can cause lung and stomach cancers due to inhalation and ingestion (drinking of radon-contaminated water), respectively and therefore, classified as group 1 agents. Soil and rocks are the natural sources of radon and under high-pressure, radon would be readily dissolved in aquifer water (Srinivasa et al., 2019). The maximum permissible concentration of radon in groundwater as stated by the United States Environmental Protection Agency (US EPA) is 11 Bq. /L in. The radon concentrations in drinking water have been reported in several regions of India including Karnataka (Srinivasa et al., 2019; Ravikumar and Somashekar, 2018), Punjab

Table 2
Concentration of Uranium in groundwater of India.

Reference	District or region /State	Uranium concentration range (µg L^{-1})
Sharma et al. (2019)	Amritsar/Punjab	0.6–65.3
	Gurdaspur/Punjab	0.1–38.8
	Pathankot/Punjab	0.1–35.9
Prasad et al. (2019)	Garhwal/Uttarakhand	0.2–63.7
Sar et al. (2017)	Balod /Chhattisgarh	0.58–78.93
Panghal et al. (2017)	Jind/Haryana	2.65–34.05
	Rohtak/Haryana	1.07–37.84
	Sonipat/Haryana	5.79–40.25
	Panipat/Haryana	7.95–39.46
Saini et al. (2017)	South-west region/ Punjab	0.13–676
	Northern-east region/ Punjab	0.11–28.2
Duggal et al. (2017)	Fatehabad/Haryana	1.1–113
Manoj et al. (2017)	Yadgir/Karnataka	0.1–302
Adithya et al. (2017)	Central Tamilnadu /Tamilnadu	0.79–71.93
Bajwa et al. (2017)	Bathinda/Punjab	0.5–571.7
	Mansa/Punjab	1.3–579
	Faridkoy/Punjab	2.4–476
	Firozepur/Punjab	2.8–467.5
Singh et al. (2017)	Durg/Chhattisgarh	0.64–45.7
Kumar et al. (2015)	Varanasi/Uttar Pradesh	11.3–63.33
	Allahabad /Uttar Pradesh	11.50
	Kaushambi/Uttar Pradesh	11.00–12.08
	Fatehpur/Uttar Pradesh	11.95–35.84
Singh and Poonam (2014)	Kumhari/Haryana	2.2–109.9
	Kajalheri/Haryana	2.3–47.9
	Gorakhpur/Haryana	2.0–73.4
	Sabarwas/Haryana	2.7–32.4
	Siwani/Haryana	0.6–256.4
	Balanwali/Haryana	6.7–40.3
	Khajuri/Haryana	0.3–53.4
Garg et al. (2014)	Hisar/Haryana	5.3–113.5
AMD (2012)	Una/Himachal Pradesh	2–80
Giri et al. (2011)	Singhbhum/Jharkhand	0.5–11.2
Brindha et al. (2010)	Nalgonda/Andhra Pradesh	0.2–118.4
Babu et al. (2008)	Kolar/Karnataka	0.33–1443
Rani and Singh (2006)	Kangra/Himachal Pradesh	0.98–6.14
	Mandi/Himachal Pradesh	0.64–5.65
	Kullu/Himachal Pradesh	0.56–2.63
	Shimla/Himachal Pradesh	0.61–10.11

(Kumar et al., 2016c), Tamil Nadu (Singaraja et al., 2016), Uttarakhand (Garg and Krishan, 2017; Garg et al., 2015; Prasad et al., 2008), Rajasthan (Rani et al., 2013), Haryana (Duggal et al., 2018), West Bengal (Krishan et al., 2015; Naskar et al., 2018) and Jammu & Kashmir (Kumar et al., 2018), etc., (Table 3). Several regions of India, particularly rural areas are still consuming water having radon above the safe drinking water limits.

In 2008, the highest mean concentration of radon (510 Bq./L) in drinking water was reported by Prasad et al. (2008) in New Tehri, Garhwal, Uttarakhand (Table 3). Fig. 3a indicates the various concentrations of radon in Karnataka and Punjab, the states of India. In Karnataka, concentrations of radon in Chikmagalur city, Bangalore city, Kolar, Shimoga, Thirthathahalli taluk, Mysore, Udupi, and Belgaum had been reported (Table 3) with the radon contaminations in drinking water sources with the highest mean concentration of 91.39 Bq./L (Fig. 3a). In Karnataka, the Belgaum district showed the minimum radon concentration in drinking water whereas the highest concentration had been reported in Bangalore city (Table 3), which was above the US EPA threshold. Bathinda, Amritsar, Pathankot, Ropar, and Gurdaspur districts of Punjab had been reported with radon pollution in drinking water (Fig. 3b). Maximum and the lowest mean concentrations of 24.58 Bq./L and 3.75 Bq./L had been observed, respectively, in Pathankot and Amritsar districts of Punjab (Fig. 3b). Radon concentration ranged from 0.2 to 49.21 Bq./L in Punjab (Table 3). Though both Himachal Pradesh and Uttarakhand were situated in the Himalayan foothills, the radon concentration in Uttarakhand was much higher than Himachal Pradesh due to the differences in the compositions of rocks. The maximum mean concentration of 510 Bq./L had been reported in the Garhwali district of Uttarakhand and it was significantly higher than the maximum mean concentration of 8.47 Bq./L in Himachal Pradesh (Table 3). Few districts of Rajasthan, Haryana, Tamil Nadu, and West Bengal have also been reported to have a radon concentration in the range 0.05–85.7 Bq./L, 1.3–57.35 Bq./L, 0.07–40.7 Bq./L, and 1.9–803.8 Bq./L respectively (Table 3). Kumar et al. (2018), also reported the radon concentration in the range of 1.44–63.64 Bq./L in the Udhampur district of Jammu & Kashmir (Table 3). Thus, there is a frightening condition in a few regions of the country, which needs the minimization of the radon concentration in drinking water before direct or secondary consumption.

2.3. Arsenic

Arsenic (As) is an odorless and tasteless substance that is in controversy since long back. Epidemiological studies have indicated that exposure to arsenic through inhalation or drinking water causes cancers of lung, skin, and urinary bladder by oxidative DNA damage, genomic instability, aneuploidy, gene amplification, epigenetic effects, and DNA repair inhibition leading to mutagenesis. IARC (2015; 2009) has classified inorganic arsenic compounds as Group 1 carcinogens while organic arsenicals (monomethyl arsonic acid and dimethyl arsinic acid) have been categorized as possibly carcinogenic to humans (Group 2B). Apart from occupational exposure, As enters the body through food, drinking water, and beverages with the contribution through drinking water being major. In natural waters, As concentrations are generally less than 2 µg/L, however, the concentrations may be elevated up to 12 mg/L in waters, particularly groundwater. The provisional guideline value on the basis of treatment performance and analytical achievability is 10 µg/L. Signs of chronic arsenicism (a disease caused by gradual arsenic poisoning), including dermal lesions (hyperpigmentation and hypopigmentation), peripheral neuropathy, peripheral vascular diseases, and cancer, have been observed in population ingesting arsenic-contaminated water (WHO, 2011). The acute toxicity of As compounds in the human body are inversely proportional to the rate of removal from the body. The toxic inorganic forms of As, pentavalent as well as trivalent, are absorbed from the gastrointestinal tract, metabolized by reduction of the pentavalent form followed by oxidative methylation of the trivalent form into mono, di, and trimethylated

Table 3
Radon distribution in groundwater of India.

| References	The study area (District/City/region)	Name of the State	Mean (Bq./L)	Range (Bq./L)
Srinivasa et al. (2019)	Chikmagalur city	Karnataka	22.72	0.51–151.98
Divya and Prakash (2019)	Coastal region (Trivandrum, Kollam, Alappuzha, Eranakulam, Trissur, Malappuram, Kozhikode and Kannur)	Kerala	1.27	0.12–4.35
Srinivasamoorthy et al. (2018)	Sankarabarani River Sub Basin	Tamil Nadu and Pondicherry	1.8	0.14–7.87
Duggal et al. (2018)	Bhiwani	Haryana	NM	1.3–13.4
Kumar et al. (2018)	Udhampur	Jammu & Kashmir	28.73	1.44–63.64
Ravikumar and Somashekar (2018)	Bangalore City	Karnataka	91.39	3.05–696
Naskar et al. (2018)	Birbhum/Tantloi	West Bengal	106.8	3.3–803.8
Shilpa et al. (2017)	Thirthathahalli taluk	Karnataka	14.19	0.37–87.02
Garg and Krishan (2017)	Roorkee	Uttarakhand	2.16	0.55–3.39
Panghal et al. (2017)	Rothak, Jind, Sonipat and Panipat	Haryana	32.98	16.06–57.35
Reddy et al. (2017)	Kolar	Karnataka	46.9	3.3–122.9
Singaraja et al. (2016)	Tuticorin	Tamil Nadu	5.13	0.07–40.7
Kumar et al. (2016c)	Amritsar	Punjab	3.75	0.53–11.2
Singh et al. (2016)	Hamirpur and Kangra	Himachal Pradesh	NM	0.86–7.62
Mittal et al. (2016a)	Jodhpur and Nagaur	Rajasthan	NM	0.5–15
Mittal et al. (2016b)	Bikaner and Jhunjhunu	Rajasthan	4.42	0.5–22
Rangaswamy et al. (2016)	Shimoga	Karnataka	13.6	3.1–38.5
Krishan et al. (2015)	24 South Pargana & East Medinipur	West Bengal	5	1.9–9
Kumar and Sharma (2015)	Pathankot	Punjab	24.59	11.5–49.21
Garg et al. (2015)	Haridwar	Uttarakhand	6.24	2.64–9.25
Rani et al. (2013)	Sri Ganganagar, Hanumangarh, Sikar & Churu	Rajasthan	9	0.5–85.7
Chandrashekara et al. (2013)	Mysore	Karnataka	53.05	BDL-643.9
Somashekar and Ravikumar (2010)	Udupi (Varahi)	Karnataka	2.07	0.2–10.1
Somashekar and Ravikumar (2010)	Belgaum (Markandeya)	Karnataka	9.3	2.21–27.3
Prasad et al. (2008)	New Tehri, Garhwal	Uttarakhand	510	8–3050
Singh et al. (2008)	Ropar	Punjab	5.65	4.57–8.01
Walia et al. (2003)	Bathinda and Gurdaspur	Punjab	4.4	0.2–8.8
Walia et al. (2003)	Hamipur and Kangra	Himachal Pradesh	8.47	0.3–22.2
Choubey et al. (2003)	Doon Valley	Uttarakhand	53.5	25.4–92.5
Virk et al. (2001)	Gurdaspur	Punjab	5.08	0.2–8.8

Note: NM-not mention; BDL-below detection limit.
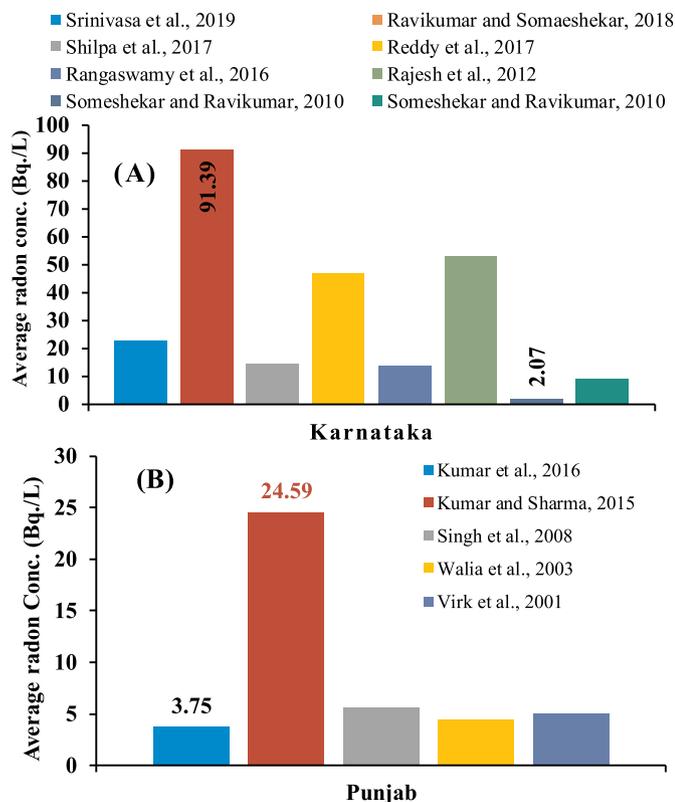
Fig. 3. The concentration of radon contamination in Karnataka and Punjab, India (Source: Adopted from Table 3).

Table 4

Arsenic distribution in groundwater of India.

District/State	Concentration (µg L^{-1})		Reference
	Range	Mean	
Saharanpur/Uttar Pradesh	1–36	9	Kumar et al. (2019c)
Barpeta/Assam	0.1–569	31	Jain et al. (2018)
Singhbhum/Jharkhand	1.02–5.15	2.42	Singh et al. (2018)
Gautam Buddha Nagar/Uttar Pradesh	0.7–237	9.1	Kumar et al. (2017)
Rajnandgaon/Chhattisgarh	148–985	505	Patel et al. (2017)
Nalgonda/Telangana	0.4–34.1	4.04	Purushotham et al. (2017)
Samastipur/Bihar	6.25–135	32.14	Kumar et al. (2016d)
Murshidabad/West Bengal	1.1–1219	262	Rahman et al. (2015)
Nadia/West Bengal	0.1–692.3	116	
North 24 Parganas/West Bengal	0.2–542.8	161	
South 24 Parganas/West Bengal	51.8–692.4	349	
Bathinda/Punjab	05–50	NM*	Sharma et al. (2013)
Faridkot /Punjab	10–100	NM	
Ferozepur/Punjab	10–50	NM	
Muktsar /Punjab	05–50	NM	
Sangrur/Punjab	05–50	NM	
Ballia/Uttar Pradesh	43.8–620.8	267	Srivastava and Sharma (2013)
Ghazipur/Uttar Pradesh	148.8–567.8	295	
Bishnupur/Manipur	1–180	27.17	Oinam et al. (2011)
Noida, Uttar Pradesh	3–119	28.3	Singh et al. (2011)
Kamrup/Andhra Pradesh	0.0–33.39	6.73	Chakrabarty and Sarma (2011)
Pasarlanka, Andhra Pradesh	NM	114.3	Mondal et al. (2010)
Medak/Andhra Pradesh	2.9–1257	146	Krishna et al. (2009)

*NM- not mentioned.

products, and finally excreted from the body in urine. There are large interindividual variations in arsenic methylation in humans, resulting in different levels of arsenic toxicity. Arsenic contamination was first reported in the Chandigarh region of north India (Datta and Kaul, 1976). The second arsenic incident was reported after eight years in the lower Gangetic plain of West Bengal (Garai et al., 1984). The main sources of As in the groundwater of West Bengal is unweathered alluvium sediments, which are derived from Himalayan sediments due to erosion. Arsenic gets mobilized due to the reductive dissolution of Fe (III) -oxyhydroxides in a reducing environment (Kumar et al., 2016d). The chemistry of arsenic in subsurface water is affected by redox potential, low dissolved oxygen, sulfate, and nitrate, etc. (Bhowmick et al., 2018). Contamination of As is widely prevalent in the delta and plains of Ganges-Brahmaputra in India (Table 4). Moreover, As concentration in different regions of India has been reported by some recent scientific publications (Table 4).

2.4. Cadmium and lead

The groundwater resources of India were affected by Cd and Pb in several regions. The high concentrations of Cd and Pb in groundwater have been reported in Punjab and Uttar Pradesh, India (Table 5). A part from Uttar Pradesh and Punjab, Pb contamination in groundwater was also reported in Bihar (Kumar et al., 2016d), Assam (Jain et al., 2018), Telangana (Purusthotham et al., 2017) and Maharashtra (Wagh et al., 2018), etc., (Table 5).

Cadmium concentrations in the groundwater's of Saharanpur, Noida, Ghaziabad, Lucknow, Gautam Buddha Nagar, and Varanasi districts of Uttar Pradesh were reported (Table 5). (Kumar et al., 2019a) investigated the Cd concentration in the rural region of the Saharanpur district, Uttar Pradesh (Table 5). Cd concentration in Saharanpur district ranged from 0.02 to 1.28 (Kumar et al., 2019a). The average concentration of Cd in Uttar Pradesh varied from 0.25 to 9.16 µg/L (Table 5).

The highest and the lowest average concentration had been reported in Varanasi and Saharanpur district, respectively (Table 5). The groundwater of Nalgonda district, Telangana, had an average Cd concentration of 9.28 µg/L, which was even higher than the average Cd concentration in Varanasi, Uttar Pradesh (Table 5). The average concentrations in the districts of Ghaziabad and Lucknow were 1.1 and 2.4 µg/L, respectively, which were below the safe drinking water guideline of WHO (2011). Cadmium concentrations in Barpeta-Assam, Garhwal-Uttarakhand, Bathinda-Punjab, Samastipur-Bihar, and Northern region-Rajasthan had been also reported within the permeable limits of BIS (2012) drinking water standards, and WHO (2011) guidelines (Table 5).

The average concentration of Pb in the Bathinda-Punjab, Ghaziabad-Uttar Pradesh, and Gautam Buddha Nagar-Uttar Pradesh is 157.8 µg/L, 130.2 µg/L and 10.4 µg/L respectively, and it was above the BIS (2012) drinking water standard and WHO (2011) guidelines (Table 5). The district such as Saharanpur, Garhwal, Nashik, Barpeta, Varanasi, Nalgonda, Nodia, and Medak had reported with Pb concentration lower than the BIS (2012) drinking water standard and WHO (2011) guideline (Table 5). In brief, the average groundwater contamination by cadmium in India is in the range of 0.9–157.8 µg/L (Table 5). The concentration of Pb in the city such as Ghaziabad and Bathinda may higher due to industrialization, urbanization, and other developmental activities.

3. Pesticides distribution in groundwater resource of India

Pesticides are a vast class of synthetic chemicals that include herbicides, insecticides, rodenticides, nematicides, etc., and are used to control insect-pests (Dev and Bali, 2018; Kumar and Malyan, 2016; Malyan et al., 2016; Yadav et al., 2015). Pesticide application increases crop yield through pest management. However, excessive application of these pesticides has an adverse impact on the environmental ecosystem (Kumar et al., 2019d). According to the Indian Agrochemical Industry report (Industry, 2016), India has a very low pesticide consumption rate as compared to other countries such as Taiwan, USA, China, UK, and

Table 5
Cadmium and Lead distribution in groundwater of India.

Reference	District/City/Region	Name of the State	Cadmium (µg/L)		Lead (µg/L)	
			Mean	Range	Mean	Range
Kumar et al. (2019a)	Saharanpur	Uttar Pradesh	0.25	0.02–1.28	5.47	0.68–19.86
Kumar et al. (2019c)	Saharanpur	Uttar Pradesh	NS	NS	15	2.5–37
Prasad et al. (2019)	Garhwal	Uttarakhand	0.1	0.001–0.9	0.9	0.003–11.3
Wagh et al. (2018)	Nashik	Maharashtra	0.027	0.005–0.051	0.998	0.29–1.96
Singh et al. (2018)	Bathinda	Punjab	0.6	0.12–3	NS	NS
Jain et al. (2018)	Barpeta	Assam	0.60	0–3.33	2.85	0.04–73
Chaurasia et al. (2018)	Varanasi	Uttar Pradesh	9.16	0.5–34.6	8.26	4–13.8
Kumar et al. (2017)	Gautam Buddha Nagar	Uttar Pradesh	0.9	0.02–7.5	10.4	0–200
Purushotham et al. (2017)	Nalgonda	Telangana	9.28	2.23–32.84	7.95	0.6–40.51
Chabukdhara et al. (2017)	Ghaziabad	Uttar Pradesh	1.1	0–12	130.2	47–254
Kumar et al. (2016d)	Samastipur	Bihar	0.08	0.03–0.12	3.19	0.59–8.4
	Lucknow	Uttar Pradesh	2.4	1.9–3	6.4	2.7–10
Duggal et al. (2014)	Churu, Sri Ganganagar, Sikar, Hanumangarh	Rajasthan	0.68	0.18–6.70	9	1–17
Singh et al. (2012)	Loni/Ghaziabad	Uttar Pradesh	0.43	BDL-0.5	9.27	5–23.5
Singh et al. (2011)	Noida	Uttar Pradesh	3.26	BDL-24.2	2.3	39–531
Krishna et al., 2009	Medak	Andhra Pradesh	NS	NS	2.3	0.4–7.2
Kumar et al. (2006)	Bathinda	Punjab	12.29	BDL-49.04	124.96	BDL–875

Note: NS-Not studied; BDL-Below detection limit.

Japan. In Taiwan, pesticide consumption per hectare is 13 kg but in India, it is just 0.6 kg per hectare (Industry, 2016) (Fig. 4). It is expected that the pesticide use in India will increase in the future to fulfill the food demand of the huge growing population (Malyan, 2017), which will become the major cause of groundwater contamination. In pesticide consumption, India ranks 8th in the world and its total consumption is around 500 million tones. Pesticides can get into the water via drift during pesticide spraying, by runoff from the treated area and leaching through the soil. In some cases, pesticides can be applied directly onto the water surfaces e.g. for the control of mosquitoes. Water contamination depends mainly on the nature of pesticides (water solubility, hydrophobicity), soil properties, weather conditions, landscape and also on the distance from the application site to the water source (Malyan et al., 2019; Yadav et al., 2015). Rapid transport to groundwater may be caused by heavy rainfall shortly after application of the pesticide to wet soils. A pesticide can leach to groundwater provided its absorptivity is below 300–500, half-life in the soil is lengthier than 6 months, solubility in water is greater than 30 mg/L, and its photolytic half-life is lengthier than 3 days. The parameters needed to study the movement of pesticides into groundwater include aquatic metabolism, field dissipation, hydrolysis, and leaching. Application of pesticides by unmanaged practices leads to groundwater leaching. Pesticide concentration has been reported by different authors in different regions of India (Table 6).

Pesticide poisoning is responsible for roughly 2 lakh of death per year and almost 95% of total death in developing nations (Yadav et al.,
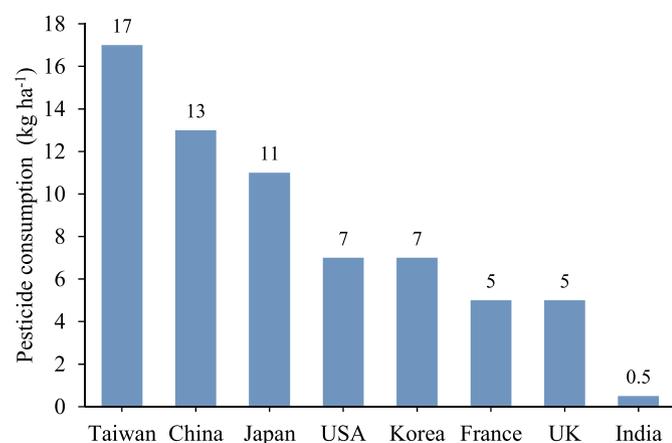
2015). Due to such health risks, pesticides such as DDT, Lindane, and Hexachlorocyclohexane (HCH) have been banned in several developing nations of the world (Yadav et al., 2015). Pesticide pollution in groundwater is of particular concern because groundwater is the main source of drinking water for the human population in India. It was observed that 90% of water samples were contaminated with more than one pesticides (Yadav et al., 2015). The pesticides DDT, lindane, parathion, and tetrachlorvinphos were classified as possible carcinogens to humans and were categorized into Group 2A, Group 1, Group 2B and 2B, respectively (IARC Monographs, 2015). During World War II, DDT was widely used to control malaria and insect-borne diseases. Lindane has been widely used to control insect pests in agriculture. Lindane is a lipophilic pesticide and agricultural workers especially, pesticide applicators are at high risk. Lindane application is now restricted or completely banned in many countries. There are only limited studies on the carcinogenic nature of the pesticide tetrachlorvinphos humans (IARC Monographs, 2015). In occupational studies, it was observed that parathion was associated with several types of tissue cancers but not authenticated for causing such cancers in human beings. Malathion is a Group 2A carcinogenic pesticide used to control insect pests as in agriculture. Occupational use of malathion has been associated with a high risk of Hodgkin lymphoma and prostate cancer (IARC Monographs, 2015). Lari et al. (2014) have reported pesticides in groundwaters of three districts namely, Amravati, Bhandara, and Yavatmal of Maharashtra (Table 6). In Amravati district, the concentrations of α-HCH and Parathion-methyl pesticides in groundwater were 0.39 and 0.09 ppb, respectively. Chlorpyrifos and α-endosulfan concentrations were 0.25 and 0.78 ppb, respectively in the groundwaters of Bhandara and Yavatmal region, Maharashtra, India (Lari et al., 2014). According to Kaushik et al. (2012), the concentration of α-endosulfan in the groundwater samples of two districts, Ambala and Gurgaon, were 0.013 and 0.27 ppb, respectively (Table 6). DDT concentrations in the groundwaters of Ambala and Gurgaon districts of Haryana were 0.94 and 0.36 ppb, respectively (Kaushik et al., 2012). According to Shukla et al. (2006), the DDT and lindane pesticides in water samples from the Hyderabad district of Andhra Pradesh (now in the Telangana State of India) ranged from 0.61 to 0.74 ppb and 0.68–1.38 ppb, respectively (Table 6). Pollution of α-HCH chemical species in the groundwater of the Kolkata district of theWest Bengal state was also observed by Ghose etal. (2009). Pesticides have been shown to display their effects by causing alterations in immunity, genotoxicity, and changes in the reproductive system and other physiological processes of different organisms, thereby, causing several critical diseases such as cancer.

Fig. 4. Pesticide consumption in different countries of the world (Source: Indian Agrochemical Industry report. 2016).

Table 6
Some reports related to pesticide contamination in groundwater.

Pesticide Name	Av. concentration (ppb)	Location/City	State	Reference
α-HCH	16.47	Hyderabad	Andhra Pradesh	Kata et al. (2015)
	0.39	Amravati region	Maharashtra	Lari et al. (2014)
	0.147	Ambala	Haryana	Lari et al. (2014)
	0.124	Gurgaon		
	0.1	Kolkata	West Bengal	Ghose et al. (2009)
Chlorpyrifos	0.25	Bhandara region	Maharashtra	Lari et al. (2014)
Parathion-methyl	0.09	Amravati region	Maharashtra	Lari et al. (2014)
α-endosulfan	18.05	Hyderabad	Andhra Pradesh	Kata et al. (2015)
	0.78	Yavatmal region	Maharashtra	Lari et al. (2014)
	0.013	Ambala	Haryana	Kaushik et al. (2012)
	0.266	Gurgaon		
	5.92–8.88	Hyderabad	Andhra Pradesh	Shukla et al. (2006)
	8.4	Unnao	Uttar Pradesh	Singh et al. (2005)
	12.27	Agra	Uttar Pradesh	Singh (2001)
DDT	19.94	Hyderabad	Andhra Pradesh	Kata et al. (2015)
	0.941	Ambala	Haryana	Kaushik et al. (2012)
	0.357	Gurgaon		
	0.01	Kolkata	West Bengal	Ghose et al. (2009)
	0.613–0.742	Hyderabad	Andhra Pradesh	Shukla et al. (2006)
	14.1	Unnao	Uttar Pradesh	Singh et al. (2005)
	383.27	Agra	Uttar Pradesh	(Singh 2001)
Lindane	0.68–1.38	Hyderabad	Andhra Pradesh	Shukla et al. (2006)
BHC	324.73	Agra	Uttar Pradesh	Singh (2001)
Aldrin	2.7	Unnao	Uttar Pradesh	Singh et al. (2005)
	254.47	Agra	Uttar Pradesh	Singh (2001)
Dieldrin	0.4	Unnao	Uttar Pradesh	Singh et al. (2005)
	53.13	Agra	Uttar Pradesh	Singh (2001)
Heptachlor	4.6	Unnao	Uttar Pradesh	Singh et al. (2005)
	29.40	Agra	Uttar Pradesh	Singh (2001)

Table 7
Remedial measure for carcinogenic pollutants from drinking water.

Type of pollutant	Treatment technology/method	References
Radon	Bioremediation (microalgae)	Pradhan and Sukla (2019)
Pesticides	Nano filtration and Ozonation	Patel et al. (2019)
Cadmium	Phytoremediation (*Pista stratiotes L.*)	Kumar et al. (2019)
Arsenic	Minerals (Clays, Iron oxides, Hydroxylapatite, and struvite)	Asere et al. (2019)
Arsenic	Biosorbents (Cellulose, Chitosan/chitin, Alginate, Biochar, Microalgal, and Fungal biomass)	Asere et al. (2019)
Cadmium	Through alumina nanoparticles	Koju et al. (2018)
Cadmium	Phytoremediation (aquatic plant-*Canna indica L.*)	Solanki et al. (2018)
Uranium	Polyethyleneimine modified activated carbon	Saleh et al. (2017)
Organophosphorus pesticide -malathion	Multi-walled carbon nanotubes	Dehghani et al. (2017)
Heavy metals	Phytoremediation	Kumar et al. (2017)
Uranium	Nano-magnetic iron oxide-urea-activated carbon nanolayer sorbent	Mahmoud et al. (2017)
Uranium	Nanostructure binary iron manganese oxy-hydroxides	Dimiropoulos et al. (2015)
Chromium and Lead	Magnetite nanospheres	Kumari et al. (2015)
Pesticides	Microfiltration followed by reverse osmosis	Rodriguez-Mozaz et al. (2015)
Arsenic	Nanofiltration	Elcik et al. (2016)
Uranium	Hydrogen-based membrane biofilm reactor	Zhou et al. (2014)
Uranium	Thermally activated sodium feldspar	Li et al. (2014)
Uranium	Copper oxide zeolite	Abdi et al. (2014)
Cadmium	Rice straw biochar	Han et al. (2013)
Pesticide	Nano-filtration	Plakas and Karabelas (2012)
Pesticide	Reverse Osmosis	Plakas and Karabelas (2012)
Arsenic	Anaerobic sludge of wastewater is used as biosorption material	Chowdhury and Mulligan (2011)
Lead	Rice husk biochar	Inyang et al. (2011)
Pesticide	Ozonation	Ormad et al. (2008)
Pesticide	Adsorption on activated carbon	Snyder et al. (2007)
Arsenic	Tea fungus (*Zygosaccharomyces sp.* and *Acetobacter sp.*) through biosorption	Murugesan (2006)
Arsenic	Electrocoagulation with Fe electrodes	Kumar et al. (2004)
Arsenic	Ion Exchange Resins	Ghurye et al. (1998)

4. Potential remedial measures for carcinogenic pollutants

In India and other parts of the world, groundwater resources have been contaminated by human activities, thus, imparting an adverse effect on drinking water quality. Presence of HMs, pesticides, radioactive compounds, etc., in drinking water, poses a significant health risk. A wide range of treatment methods such as filtration, bioremediation, adsorption, etc. have been used for the removal of these contaminants from drinking water (Table 7). The pesticides have been removed by activated carbon adsorption (Carpenter and Helbling, 2017; Stackelberg et al., 2007) from drinking water. Recently, Dehghani et al. (2017) also explored a multiwalled carbon nanotube-based process to remove pesticides from water. Ormad et al. (2008) studied the impact of chlorine or ozone peroxidation, chemical precipitation with aluminum sulfate and adsorption by activated carbon on the removal of 44 different pesticides. Chlorine and ozone oxidation could remove 60% and 70% of the total pesticides from water, respectively (Ormad et al., 2008). Chlorine oxidation process formed trihalomethane compounds, which are water pollutants. Oxidation and chemical treatment followed by an activated carbon absorption process removed up to 90% of the pesticides from water (Ormad et al., 2008).

Arsenic removal from groundwater is a challenging issue and recent studies have reported that it can be removed by nanofiltration, activated carbon and bioremediation methods (Table 7). Elcik et al. (2016) reported 97–99% removal of arsenic from water by nanofiltration method (Table 7). In Vietnam, arsenic, and iron contaminated drinking water is treated by the household sand filtration method. In this technique, arsenic is immobilized with Fe (II) and Fe (III) oxides are formed, which is removed from water by precipitation or sorption. Byrne et al. (2014) demonstrated up to 95% removal of arsenic from groundwater by this household sand filtration method. Zhou et al. (2014) reported that uranium contamination can be effectively removed from water (Table 8). They observed that the hydrogen-based membrane biofilm removed 94–95% of uranium (VI) from water continuously for an 8 months period when the pollution load of uranium was 6–11 mEq/m^2 day^{-1}. Other traditional technologies for the remediation of these

Table 8
Ideal condition for soil microbes for achieving optimal bioremediation (microbial degradation).

Factors	Optimal conditions for microbial activity
pH	5.5–8.8
Temperature	15° to 45°
Moisture	25%–28% of the soil water-holding capacity
Soil	Low clay or silt content
Oxygen	For aerobic, >10% of air-filled space of the soil
Nutrients	N & P for growth
Contaminants	<toxicity level
Heavy metals	Total 2000 ppm

substances include advance oxidation and adsorption. Still, these technologies are not able to achieve the complete removal of certain persistent organic pollutants, emerging contaminants, and HMs. In addition to all these physical and chemical strategies, different types of biobased approaches (known as bioremediation) have also been used for the removal of all these contaminants.

Bioremediation can be carried out with the help of suspended or immobilized reactors inoculated with (a) native flora/fauna, b) biostimulation of natural microflora, and c) bioaugmentation of the contaminated sites with suitable degrading strains of bacteria, fungi, plants, enzymes, etc. Microorganisms require a source of energy i.e. an electron donor and an electron acceptor to extract this energy from the donor according to the following equation:

Microorganisms + electron donor + nutrients + electron acceptor → oxidized or reduced end products + Microbes
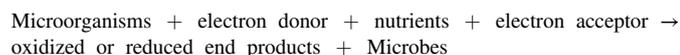
Biological systems generally treat contaminated media by using waste contaminants as the electron donors and supply microorganisms with the required electron acceptors and nutrients (Kumar et al., 2017a, 2017b, 2019a, 2019b). An additional supply of nutrients enhances the removal of pollutants by stimulating the production of enzymes and thus, in turn, accelerating the contaminant degradation. The addition of carbon and nitrogen sources, in particular, accelerates the microbial growth and activity and reduces the lag phase, thus, eventually increasing the rate of biodegradation. Several genetically engineered bacteria have also been developed for the purpose of bioremediation of a wide range of contaminants. Pesticide metabolism in soil depends significantly on the microbial population. The rate of pesticide degradation in the soil further depends on the soil microenvironmental conditions such as aeration, moisture, organic matter, and temperature. Extent and rate of degradation and removal efficiency of pesticides are significantly driven by factors affecting microbial growth including but not limited to inoculum size, culture conditions, pH, temperature, nutrient availability, moisture content, the concentration of cosubstrates, etc. Besides temperature, pH, and water holding capacity of the soil, the aging of pesticides in soil affects the microbial degradation of organophosphates (Deng et al., 2015). Table 8 enlists the key factors governing bioremediation and their optimum ranges. It has been observed that the biodegradation potential of *S. cerevisiae* for the removal of diazinon from water was 96% (Ehrampoush et al., 2017). The highest removal of diazinon was obtained at 3.88% of *S. cerevisiae* concentration, pH of 5.5, and 22.75 h of retention time. The removal of diazinon (an organophosphate pesticide) with *S. cerevisiae* is a highly cost-efficient methodology.

Microbial fuel cells (MFCs) have recently emerged as a promising technology in order to treat pollutant load from a vast range of wastewaters due to the simultaneous generation of energy along with the biodegradation of organic matter present in wastewaters (Kumar et al., 2016a). Electrochemically active microorganisms form the core of an MFC process, which can directly affect the performance in terms of treatment efficiency and bioelectricity generation (Kumar et al., 2017a). It is well known that MFCs involve some electron transfer mechanisms for electricity generation, and the knowledge of how the

bacteria interact with the insoluble electron donors and acceptors has been increasing rapidly (Kumar et al., 2019b). Therefore, the anode chamber of MFCs can facilitate the biodegradation of organic carcinogenic compounds while the heavy metals can be removed in the cathode chamber.

Regular contamination of surface water and its scarcity has exerted heavy pressure on groundwater resources near highly populated areas. As already stated, the concentrations of most of the carcinogenic compounds, which have been detected in groundwater at various places all over India, were higher than permissible limits set by European countries and the Bureau of Indian Standards. Health risk assessment studies have also revealed various alarming results for living organisms including human beings. In light of the discussions made in this review, it is suggested that an integrated management program should be designed on the basis of research reports to control the concentrations of these compounds in groundwater. Keeping in mind the geographic and cultural differences, more and more local research needs to be carried out with a robust scientific approach in support of the evidence-based policies so as to lessen the exposure to carcinogenic compounds. Moreover, it is recommended to employ a suitable pump and treat remediation technologies before the consumption of severely contaminated groundwater. Along with regular monitoring with respect to carcinogenic heavy metals and organic compounds, area-specific risk awareness programs need to be arranged for the general awareness of the local population.

5. Conclusions

Groundwater is a sustainable source for drinking water in India and other countries. Untreated wastewaters from industries, excessive applications of pest control, chemical and geological activities, are the important causes for the contamination of the potable groundwater. Concentrations of trace metals, pesticides and radioactive elements, which are Group I carcinogens, have been detected above the permissible limits in the groundwater, which is a matter of grave concern. Therefore, there is an urgent need for comprehensive analysis of groundwater with emphasis on carcinogens and development of a comprehensive strategy for limiting the ingress into the groundwater as well as treatment of the drinking water for the removal of these contaminants.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bcab.2019.101288.

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