

Arsenic in African Waters: A Review

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Abstract The review of studies on arsenic in African waters shows that arsenic can be found in high concentrations in both surface water and groundwater. Arsenic concentrations in African groundwater range between 0.02 and 1760 $\mu\text{g L}^{-1}$, whilst the level of arsenic in surface water is ranged up to 10,000 $\mu\text{g L}^{-1}$. This high level of arsenic in surface water is related to mining operations, agricultural drains, local sediments, disposal, and incineration of municipal and industrial wastes. However, mining activities remain the main source of surface water pollution. They have thereby a strong impact on the concentration of arsenic in the environment. As for groundwater, high levels of arsenic occur in natural conditions. It is due to the presence of iron oxides; sulphide minerals such as pyrite, arsenopyrite, and chalcopyrite; volcanic rocks; and geothermal

waters. Few studies in Africa make the link between human health problems and high levels of arsenic in water. Only two articles were found dealing with arsenic remediation. This shows that arsenic, which constitutes a major public health issue in the world, has less interest in Africa although high concentrations of arsenic have been found in both surface water and groundwater in some African countries. Most of the studies carried out on arsenic issues in Africa are dedicated to the characterization and the quantification of the pollution, but studies on the risk to human health and treatment systems are limited. The arsenic issue in Africa needs special attention in order to avoid the problems experienced in some areas mainly in Asia.

Keywords Arsenic · Groundwater · Surface water · Africa

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1 Introduction

Arsenic is a ubiquitous element that can be found in rocks, water, air, animals, and plants. It is a metalloid which can have both inorganic and organic forms (Matschullat 2000). Arsenic species can be converted into different forms or transformed into insoluble compounds in combination with other elements, such as iron and sulphur (Mandal and Suzuki 2002). Most arsenic compounds are odorless and tasteless and readily dissolved in water, which creates an elevated health risk (Wang and Mulligan 2006). Long-term exposure to inorganic arsenic may cause a wide range of health

effects, including skin lesions such as hyperkeratosis and pigmentation changes and blackfoot disease, circulatory disorders, diabetes and cancers of the bladder, lung, kidney, and liver (Smith et al. 1992; Gbaruko et al. 2010). In 1993, the World Health Organization (WHO) reduced provisionally the guideline value from 50 to 10 $\mu\text{g L}^{-1}$. Above this value, the water is considered unfit for human consumption. Due to its high toxicity and widespread occurrence in the environment, several studies concerning source, behavior, and distribution of arsenic in the environment as well as its removal technique were performed in the world. These studies have shown high levels of arsenic in water in many areas like parts of USA, China, Chile, Bangladesh, Taiwan, Mexico, Argentina, Poland, Canada, Hungary, Japan, Ghana, and India (Amasa 1975; Chen et al. 1994; Karim 2000; Chakraborti et al. 2002; Ning 2002; Smedley and Kinniburgh 2002; Wang and Mulligan 2006; He and Charlet 2013). These high levels of arsenic result from both natural and anthropogenic occurrences (Mandal and Suzuki 2002; Smedley and Kinniburgh 2002; Nriagu et al. 2007). The anthropogenic sources are constituted mainly by mining activities, fossil fuel processing, and incineration of municipal and industrial wastes. As for natural sources, arsenic is present in sulphide ores associated with other metals like copper, lead, silver, and gold. Arsenic can be released from these natural sources by the combined effects of mineral weathering and high-evaporation rates. It can also come from desorption of mineral oxides and reductive dissolution of iron and manganese oxides in reducing conditions. Although all these environmental conditions can be found in African countries, and that Africa harbors the world's largest mineral reserves of gold and other minerals (platinum, diamonds, chromite, manganese, and vanadium) (Economic Commission for Africa ECA 2009), the existing review articles speak very little of arsenic in Africa. It may be because arsenic was not found in a large scale in African countries or there are very few studies on arsenic in Africa. The aim of this paper is to build a map of arsenic distribution in African waters using existing data and to highlight the lack of data comparing to the probable magnitude of the problem. It is also important to show what the arsenic threat represents for human health in Africa and to provide an overview of the methods studied to remove arsenic from water in Africa. In this document, all values

of arsenic in water greater than 10 $\mu\text{g L}^{-1}$ will be considered high.

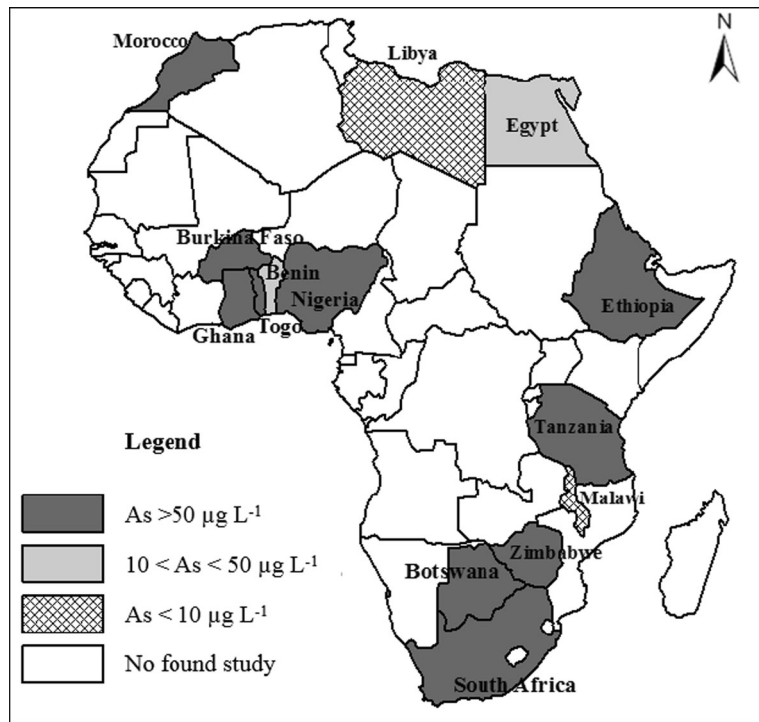
2 Arsenic Distribution in Water in Africa

Generally, arsenic in Africa is found in a low concentration in natural water. Occurrence of arsenic in natural water is dependent on the local geology, hydrogeology, and geochemical characteristics of the aquifer and climatic factors as well as human activities. Arsenic concentrations above WHO guidelines for drinking water have been recorded in different African countries (Fig. 1). This figure shows for the first time, to our knowledge, the distribution of arsenic in African waters and brings out the issue of arsenic in the African continent. The details of values of arsenic concentration in the contaminated countries are reported in Table 1.

2.1 Arsenic in Surface Water

The concentration of arsenic in natural African surface water is very different depending on the country, and even in the same country, it depends on the area. Low concentrations of arsenic have been noticed in some areas of Tanzania, Botswana, and Burkina Faso (Taylor et al. 2005; Huntsman-Mapila et al. 2006; Ouédraogo and Amyot 2013) whereas high concentrations were recorded in Ethiopia, Ghana, Morocco, other areas of Tanzania, Togo, and Zimbabwe (Bowell et al. 1995; Jonnalagadda and Nenzou 1996; El Hachimi et al. 2005; Serfor-Armah et al. 2006; Rango et al. 2010; Rezaie-Boroon et al. 2011). For example, Rango et al. (2013) indicated that there was 566 $\mu\text{g L}^{-1}$ of arsenic in the surface water in the Rift Valley in Ethiopia. Whilst Serfor-Armah et al. (2006) have reported a range of concentrations from 150 to 8250 $\mu\text{g L}^{-1}$ in the surface waters in Prestea in Ghana. These high levels of arsenic in the surface water are usually related to the mining operation (Amasa 1975; Jonnalagadda and Nenzou 1996; Serfor-Armah et al. 2006; Kusimi and Kusimi 2012). Indeed, areas devoid of mining activities like Okavango Delta (Huntsman-Mapila et al. 2006) have generally low values of arsenic in the surface water, whereas in mining activity areas the surface waters have high levels of arsenic. However, Rango et al. (2010) have found high levels of arsenic in the surface water in the Rift Valley which is devoid of mining activities. According to them, local sediments were the main source of arsenic in water in

Fig. 1 Distribution of arsenic in African waters



the Ethiopian Rift Valley. Rezaie-Boroon et al. (2011) have also highlighted high concentrations (6460 µg L⁻¹) of arsenic in the surface water in the vicinity of Lomé and other big cities. This high concentration of arsenic was due to the impact of the effluents from the industrial activity as well as hazardous waste dumping. Surface waters have generally a higher level of arsenate [As (V)] than arsenite [As (III)]. Ahmad and Carboo (2000) who worked on speciation of As (III) and As (V) in some Ghanaian gold tailings observed the absence of As (III) in riverbed sediments. This low value of As (III) in surface water may be attributed to the fact that As (III) has been oxidized to As (V) by dissolved oxygen. However, Smedley et al. (1996) found some streams which have high As (III) content ($[As(III)]/[As_{total}] > 0.5$), probably as a result of methylation and reduction reactions mediated by bacteria and algae.

2.2 Arsenic in Groundwater

Background concentrations of Arsenic in groundwater are less than 10 µg L⁻¹ in most African countries (Asubiojo et al. 1997 in Nigeria; El-Ghawi 2005 in Libya; Taylor et al. 2005 in Tanzania; Asante et al. 2007 and Yidana et al. 2008 in Ghana; Pritchard et al.

2008 from Malawi). However, the values quoted in the African literature show a very large range from 0.02 to 1760 µg L⁻¹ (Table 1). In contrast to surface waters, the origin of the high levels of arsenic in groundwater is mainly natural. So, the high concentrations of arsenic reported in the groundwater by Smedley et al. (2007) in Burkina Faso (1630 µg L⁻¹) and Kusimi and Kusimi (2012) in Ghana (1760 µg L⁻¹) have for origin weathered rocks of the underlying geology and are not due to mining activities. When considering the concentrations of arsenic in surface waters (0.5 to 73 µg L⁻¹) and in groundwaters (<0.1 to 4 µg L⁻¹) from Tarkwa (Asante et al. 2007), or the ones in Obuasi ranging from <2 to 175 µg L⁻¹ and from <2 to 64 µg L⁻¹, respectively, in surface waters and groundwater (Smedley 1996), two gold mining areas in Ghana, it can be noticed that mining activities affect less the groundwaters than surface waters. In this way, the highest concentration of arsenic in groundwater from 801 µg L⁻¹ in the Obuasi gold mine area is more probably due to the presence of sulphide-bearing rocks such as pyrite, arsenopyrite, and chalcopyrite (Akabzaa et al. 2009a). The natural occurrences of high levels of arsenic in groundwater have been highlighted by several other studies in the world (Mandal and Suzuki 2002; Smedley and Kinniburgh 2002). Moreover, contrary to the remark made by

Table 1 Arsenic concentration in African waters

Locations	Type of system (number of samples)	As concentration range or average ($\mu\text{g L}^{-1}$)	% of sample >10 $\mu\text{g L}^{-1}$	Study area	References
Benin	Groundwater (42)	<30	-	Borgou	Higy and Cordey (2011)
Botswana	Surface water (09)	1.1 to 3.1	0	Okavango Delta	Huntsman-Mapila et al. (2006)
	Groundwater (20)	3.2 to 116.6	30		
Burkina Faso	Surface water	<1 to 188	-	Okavango Delta	Mladenov et al. (2013)
	Groundwater				
	Surface water				
Burkina Faso	Surface water	0.31 to 0.74	0	Nakambe	Ouédraogo and Amyot (2013)
	Groundwater (34)	1 to 87.8	11.76	North region	Nzihou et al. (2013)
	Groundwater (45)	<0.5 to 1630	<50	Yatenga and Zondoma provinces	Smedley et al. (2007)
Egypt	Groundwater (31)	1 to 124	52	Yatenga province	Somé et al. (2012)
	Surface water	1.2 to 18.2	-	Nile Delta	Abdel-Moati (1990)
Ethiopia	Surface water (05)	0.02 to 96	6.5	Rift Valley	Reimann et al. (2003)
	Groundwater (120)				
	Spring water (14)				
	Surface water (14)	<0.1 to 405	21.43		
	Groundwater (25)	<0.1 to 278	40		
	Spring water (14)	<0.1 to 156	57.14		
	Surface water (09)	0.21 to 3	0		
	Surface water (11)	2.39 to 566	-		
	Groundwater (94)	0.6 to 190	-		
	Spring water (29)	3.79 to 167	-		
Ghana	Groundwater (10)	<1 to 141	60	Obuasi and Boltanga	Smedley (1996)
	Surface water (02)	1400 and 2250	100	Obuasi	Amasa (1975)
	Surface water and groundwater (230)	<0.003 to 170	0.5	All Ghanaian country	Rossiter et al. (2010)
	Surface water (12)	0.5 to 73	33	Tarkwa	Asante et al. (2007)
	Groundwater (19)	<0.1 to 4	0		
	Surface water	2800 to 10,400	100	Obuasi	Amonoo-Neizer and Amekor (1993)
	Groundwater (40)	<5.2 to 69.4	5	Tarkwa	Bhattacharya et al. (2012)
	Surface water (10)	1 to 18,910	-	Obuasi	Akabzaa et al. (2009a)
	Groundwater (15)	1 to 801	-		
	Surface water (13)	150 to 8250	100	Prestea	Serfor-Armah et al. (2006)
	Surface water	<2 to 175	-	Obuasi	Smedley et al. (1996)
	Groundwater	<2 to 64	-		
	Groundwater (150)	<2 to 39	2	Accra, eastern region, and Volta region	Kortatsi et al. (2008a)
	Groundwater (148)	<0.05 to 39	19	Lower Offin Basin	Kortatsi et al. (2008b)
	Surface water, groundwater, and water from mine pits (161)	1 to 28,950	-	Ankobra River Basin	Akabzaa et al. (2009b)
	Groundwater (290)	-	5 to 12	Ashanti, western, and Brong-Ahafo regions	Buamah et al. (2008)
	Surface water, groundwater and water from mine pits (161)	1 to 28,950	-	Ankobra River Basin	Akabzaa and Yidana (2012)
	Surface water (10)	<1 to 1130	40	Tarkwa	Kusimi and Kusimi (2012)

Table 1 (continued)

Locations	Type of system (number of samples)	As concentration range or average ($\mu\text{g L}^{-1}$)	% of sample >10 $\mu\text{g L}^{-1}$	Study area	References
	Groundwater (16)	<1 to 1760	68.75		
Malawi	Groundwater (26)	<2	0	Balaka, Chikwawa, and Zomba	Pritchard et al. (2008)
	Groundwater (26)	<3	0	Blantyre, Chiradzulu, and Mulanje	Pritchard et al. (2007)
	Groundwater (09)	3	0	Blantyre	Mkandawire (2008)
Morocco	Surface water (14)	50.08 to 199.6	100	Upper Moulouya	El Hachimi et al. (2005)
	Surface water (12)	38.9 to 199.6	100	Upper Moulouya	El Hachimi et al. (2007)
Nigeria	Groundwater (250)	0.4 to 6.88	0	Parts of southern Nigeria	Asubiojo et al. (1997)
	Groundwater (20)	40 to 160	100	Ogun state	Gbadebo (2005)
South Africa	Surface water (20)	119	-	Koekemoerspruit	Dzoma et al. (2010)
	Groundwater (20)	12.3	-	Mafikeng	
	Surface water (10)	<1	0	Limpopo province	Ogola et al. (2011)
	Surface water	0.62 to 2.03	0	Cape Town	Akinsoji et al. (2013)
Tanzania	Surface water	-	41	Lake Victoria Basin	Kassenga and Mato (2009)
	Surface water and groundwater	0.13 to 2.4	0	Geita District	Taylor et al. (2005)
	Surface water and mine drainage waters (28)	30 to 324	100	Serengeti National Park	Bowell et al. (1995)
Togo	Surface water (23)	3000 to 6460	-	Lomé coastal region	Rezaie-Boroon et al. (2011)
Zimbabwe	Surface water (20)	1 to 96	55	Eastern plains of Zimbabwe	Jonnalagadda and Nenzou (1996)

Wang and Mulligan (2006) in their study, arsenic concentrations in groundwater are often higher than those measured in surface waters. Table 1 shows that arsenic concentrations in the surface waters in Africa are higher than those measured in groundwaters. This underlines the fact that mining activities have a strong impact on the environment in Africa. Huntsman-Mapila et al. (2006) and Smedley (1996) have noticed that As (III) is more predominant than As (V), respectively, in the Okavango Delta and Obuasi gold mine groundwater. Whilst Smedley et al. (2007) have found high levels of As (V) comparatively to As (III) in the Burkina Faso groundwaters. This difference may be explained by pH and redox conditions. In the Smedley et al. (2007) studies, the pH of groundwaters ranges from 5.18 to 7.78 and the redox potential (Eh) ranges from 97 to 447 mV, which corresponds mainly to oxidizing conditions. According to Lombi et al. (1999) and Smedley and Kinniburgh (2002), under oxidizing conditions at a pH lower than 9.2, As (V) is the dominant species. This reveals that, in the less deep groundwaters where oxidizing conditions are present, As (V) is predominant

whereas, in the deeper groundwaters where the conditions reduce, As (V) is converted to As (III), and As (III) is the predominant species.

3 Source of Arsenic in Water

Analysis of works on arsenic performed in different African countries highlights two main sources of arsenic release in water.

3.1 Anthropogenic Sources

The main anthropogenic activities that may release arsenic into the environment in Africa include mining activities, agricultural drains, fossil fuel processing, combustion, and disposal and incineration of municipal and industrial wastes. Several studies have shown the impact of mining activities on water quality (Amasa 1975; Jonnalagadda and Nenzou 1996; Serfor-Armah et al. 2006; Dzoma et al. 2010; Kusimi and Kusimi 2012). According to Golow et al. (1996), gold ore is

usually associated with different combined forms of arsenic such as pyrites, arsenopyrite, and chalcopyrite. During the processing of the ore of gold, poisonous gaseous arsenic compounds are released in the atmosphere and may settle on soil, vegetation, and water in the neighborhood during precipitation or any other process. The same observation has been done by Amonoo-Neizer and Amekor (1993) and Amasa (1975). Their studies have shown the deposit of large quantities of arsenic in soil and vegetation in locations near the mine. This process leads mostly to the enrichment of surface water with arsenic (Amonoo-Neizer and Amekor 1993; Serfor-Armah et al. 2006). In the same way, waters from tailings leaching into water bodies contribute to increase the levels of arsenic. Jonnalagadda and Nenzou (1996) have also highlighted that mine wastes contribute to surface water pollution by arsenic. Adaikpoh et al. (2006) who have assessed the level of heavy metals in sediments and coal from the Ekulu River in Nigeria have highlighted that the coal mine introduced heavy metals especially arsenic in water. Dzoma et al. (2010) have also noticed that mining activities around Koekemoerspruit in South Africa have contributed to higher heavy metal presence in the environment. Koekemoerspruit water samples had arsenic levels with several magnitudes higher than WHO maximum permissible levels for drinking. As for other anthropogenic sources of arsenic, they were highlighted by the Abdel-Moati (1990) and Rezaie-Boroon et al. (2011) studies. Abdel-Moati (1990) reported that about 413 t yr^{-1} of arsenic entered into the northern Nile delta lakes via agricultural drains and wastewater discharge. According to him, phosphate fertilizers, detergents, herbicides, and loamy Nile deposits are the main arsenic sources to the drainage system. Concerning the Rezaie-Boroon et al. (2011) study, they noticed that the effluents of industrial activity as well as hazardous waste dumping contributed to a higher arsenic presence in Lomé's and other big cities' surface waters. Although there are several sources that may release arsenic into the environment in Africa, the most widespread source which greatly affects natural water remains mining activities and this source more affects surface water than groundwater.

3.2 Natural Sources

The ubiquity of arsenic in the environment originates from natural enrichments. The most common sources of arsenic in the natural environment in Africa are iron

oxides, sulphide minerals, volcanic rocks, and geothermal waters. Huntsman-Mapila et al. (2006) have highlighted that the occurrence of elevated arsenic in the groundwater of the Okavango Delta is attributed to the reductive dissolution of Fe oxides and hydroxides in the sediments. However, the real mechanism of arsenic release in groundwater seems more complex. Indeed, the complementary study performed by Huntsman-Mapila et al. (2011) shows that the enrichment of As in the island groundwater of the Okavango Delta is a result of a complex interplay between (1) concentration by evaporation/transpiration; (2) reductive dissolution of Fe oxyhydroxides, masked by reprecipitation; and (3) competitive interaction between HCO_3^- and As for the same sorption sites as pH increases. According to them, the predominant process controlling the very elevated levels of arsenic in the island center groundwater is probably the effect of the evapotranspiration. Reductive dissolution of oxide and hydroxide of minerals containing Fe and Mn is the initial step for the release of arsenic from the sediment into the groundwater. Fe oxides are considered the most likely sources of As by other studies (Smedley 1996; Smedley et al. 2007; Kortatsi et al. 2008a; Bhattacharya et al. 2012). Smedley et al. (2007) noticed that arsenic-bearing sulphide minerals are also sources of arsenic release in groundwater in zones of mineralized Birimian volcano-sedimentary rocks. The same remark has been done by Kortatsi et al. (2008b). According to them, pyrite and arsenopyrite oxidation is the plausible process for arsenic mobilization. Baioumy (2005) has also observed in his study a relatively strong positive correlation between arsenic and sulphur, which suggests the occurrence of arsenic as sulphide. The occurrence of arsenic in volcanic rocks and geothermal waters has been underlined by Reimann et al. (2003) and Rango et al. (2010, 2013). Their studies indicate that sediments coming from volcanic rocks are a major reservoir and source of arsenic and a hydrothermal component can contribute to the high concentrations of arsenic in water.

4 Probable Extent of As Contamination in Africa

Arsenic presence and issues concern a small number of African countries (Fig. 1). That could be explained by a lack of studies in other countries or arsenic has been investigated in these countries, but not found. Moreover, in affected countries, high-As concentrations were

found only in some areas. For example, in Burkina Faso, high-As concentrations were found only in the northern region (Smedley et al. 2007; Somé et al. 2012; Nzihou et al. 2013). In Botswana and Ethiopia, only the Okavango Delta and Rift Valley, respectively, seem to be concerned with arsenic pollution (Reimann et al. 2003; Huntsman-Mapila et al. 2006; Rango et al. 2010; Dsikowitzky et al. 2013; Mladenov et al. 2013; Rango et al. 2013). It is certainly clear that the arsenic issue seems to be limited compared to other continents in the world, e.g., Asia or America (Smedley and Kinniburgh 2002), but the arsenic issue in Africa is not well defined. Indeed, when considering Burkina Faso, high-As concentrations were found in the Birimian lithologies. A major part of this country is constituted by the similar Birimian lithologies as well as other countries as Côte D'Ivoire, Mali, Guinea, and Niger (Smedley et al. 2007) where high-As concentrations were not found yet. That supposes that high-As concentrations could be found in other parts of Burkina Faso and other cited countries, even if current studies have not revealed it. In the same way, Amini et al. (2008) used the statistical rule and physical data to delineate two process regions for arsenic mobilization: "reducing" and "high-pH/oxidizing." Their results showed that under reducing conditions, the Congo and neighbor countries have a high probability to be contaminated by arsenic, and under high-pH/oxidizing conditions, arsenic could be found in northern Mali, Zambia, Nigeria, Angola, and Kenya. Otherwise, it is now evident that high-As concentrations in groundwater can be associated with reducing conditions, particularly in alluvial and deltaic environments, e.g., Bangladesh and West Bengal alluvial basin and deltaic aquifers where As concentrations in groundwaters can reach $3200 \mu\text{g L}^{-1}$ (Smedley and Kinniburgh 2002). The same alluvial basin and deltaic environments (e.g., Chad basin, Congo basin, Limpopo basin, Niger basin, Nile basin, North interior basin, Okavango basin, Orange basin, Senegal basin, South interior basin, and Zambezi basin (Rebello et al. 2010; Goudie 2005)) are occurring all over the place in the African continent. These areas are appropriate in reducing conditions to release high amounts of arsenic in groundwater. As a result, the arsenic issue in African countries could be more extensive than what current studies highlight. Additional studies need to be carried out in order to get more knowledge on the spread of arsenic in Africa, also recommended by Fatoki et al. (2013), especially as groundwaters are usually used for human consumption.

5 Health Hazard Linked to High-As Water in Africa

Generally, arsenic contamination in drinking water is a major public health issue. But, studies in Africa do not always make the direct link between health problems and arsenic in drinking water. Adverse effects of arsenic on human health reported in some African countries are usually associated to mine smoke and food crops grown in mining-contaminated areas. Already in 1975, some of the villagers at Nainti and Anyinabrem close to the Obuasi gold mine in Ghana, claim to have developed chronic eye inflammation as a result of the mine smoke (Amasa 1975). Furthermore, Amasa (1975), Amonoo-Neizer and Amekor (1993), and Adomako et al. (2010) have reported high concentrations of As in food items such as orange, sugar cane, cassava, and rice from mining regions in Ghana. According to Obiri et al. (2006), high arsenic in food crops grown in mining-contaminated areas of Ghana can cause adverse effects to human health. In this way, in Ghana, Asante et al. (2007) who found the same high concentrations of arsenic in human urine samples from residents of the mining town of Tarkwa and from non-mining town of Accra suggested that human contamination of arsenic has another source, possibly foods. Indeed, the waters from Tarkwa had very high concentrations of arsenic comparatively to those from Accra. Despite this, drinking water remains the significant human exposure way of inorganic arsenic contamination. Smedley et al. (1996) had highlighted a link between the concentrations of inorganic urinary arsenic from sample populations and drinking water in Ghana. They found that a rural stream-water-drinking community has a mean value of $42 \mu\text{g L}^{-1}$ of urinary arsenic whilst a suburb of Obuasi community using groundwater for potable supply has $18 \mu\text{g L}^{-1}$. In Burkina Faso, health surveys have also identified in the Ouahigouya area, northern Burkina Faso, skin lesions characterized by melanosis, keratosis, and ulceronecrotic tumor in patients from three villages where high-As groundwaters have been found (COWI 2005; Smedley et al. 2007). Recent reports have suggested that two deaths linked to high-As drinking water have occurred in this area (Ouedraogo 2006). Besides, Somé et al. (2012) identified that 29.26 and 46.34 % of the population (240 persons) in 20 villages in Yatenga province, Burkina Faso, were affected by melanosis and keratosis, respectively. According to them, this public health problem in Yatenga linked to arsenic is due to drinking water. Indeed, they found that 52 % of the

Table 2 Some examples of techniques used for removal of arsenic from water

Technologies	Initial As concentration	Removal efficiency or adsorption capacity	Advantages	Disadvantages	References
Oxidation	500 $\mu\text{g L}^{-1}$	90 %	Easy and cheap process; oxidants are readily available; applicable for large water volume	Relatively slow process; need technical knowledge; generate toxic residue; interfering substances decreases the removal; additional removal process is essential	Hug et al. (2001); Mondal et al. (2013); Baig et al. (2015)
Photochemical oxidation	40–200 μM	Able to remove As below 10 $\mu\text{g L}^{-1}$			Dutta et al. (2004); Mondal et al. (2013); Baig et al. (2015)
Phytoremediation	<200 $\mu\text{g L}^{-1}$	95 %	Very environmentally friendly; low-cost technique	-	Baig et al. (2010)
Coagulation-flocculation	100 $\mu\text{g L}^{-1}$	77 % As (III); 90 % As (V)	Low capital cost and simple to operate; effective in wide pH ranges; effective for the system with hard water and applicable for large water volume; removal for As (V) is high	Periodic replacement; high operation and maintenance costs; very high amount coagulant dose is required; additional separation step necessary; environmental recontamination of As-contaminated sludge may be of concern	Pallier et al. (2010); Mondal et al. (2013); Baig et al. (2015)
Adsorption	Activated alumina 10 mg L^{-1}	99.6 %	Comparatively cheap and commercially available; high removal efficiencies; not need a large volume and additional chemicals	Interferences from competitive anions (PO_4^{3-} , HCO_3^- , SiO_3^{2-} , SO_4^{2-}); problems regarding regeneration	Tripathy and Raichur (2008); Mondal et al. (2013); Baig et al. (2015)
	Iron-based sorbents 1.5 mg L^{-1}	96–99 %		and multiple uses of the adsorbents; As-spent adsorbent is often difficult to remove and further environmental contamination may be possible; need large area for treatment plant; periodic monitoring is required	Chowdhury and Yanful (2010); Mondal et al. (2013); Baig et al. (2015)
	Zero valent iron 5 mg L^{-1}	121 mg g^{-1} As (III); 125 mg g^{-1} As (V)			Du et al. (2013); Mondal et al. (2013); Baig et al. (2015)
Ion exchange	-	1.83 mmol g^{-1} As (V)	The removal efficiency does not depend on the pH and concentration of the influent; removal is moderately effective	The removal of As (III) is not possible and prior oxidation necessary; interferences from other anions; solid and Fe causes clogging; huge investment and operation costs required to install at large scale; not effective when used for a long time; produces large volume of toxic brine during regeneration of resins	Donia et al. (2011); Mondal et al. (2013); Baig et al. (2015)
Membrane	Nanofiltration 0.1–10 mg L^{-1}	99 %	Good purification and no toxic solid waste are produced; high removal efficiency for As (V) from water along with other contaminants	Removal efficiency is very low for As (III); high electrical energy needs to run the models; high operation and capital cost; pretreatment steps are often	Harisha et al. (2010); Mondal et al. (2013)
	Reverse osmosis 0.2–0.5 mg L^{-1}	99 %			Gholami et al. (2006); Mondal et al. (2013)

Table 2 (continued)

Technologies	Initial As concentration	Removal efficiency or adsorption capacity	Advantages	Disadvantages	References
Membrane distillation	40 mg L ⁻¹ As (III); 2000 mg L ⁻¹ As (V)	>99.95 % As (III); >99.99 % As (V)	High removal efficiency of both As (III) and As (V); removal does not depend on the solution pH	required; efficiency is very low with high-concentration As-contaminated water Increasing concentration of As has an adverse effect on the process, and removal decreases with increasing As concentration in feed water due to polarization effect	Qu et al. (2009); Mondal et al. (2013)
Forward osmosis	-	>90 %	Simple and cost effective method; low or no requirement of hydraulic pressure; the membrane has a high rejection; probability of lower membrane fouling and higher water recovery than other conventional membrane processes	High dilutive internal concentration polarization; increasing of the reverse draw solute flux	Zhao et al. (2011); Jin et al. (2012); Mondal et al. (2013); Singh et al. (2015)

water samples exceeded the WHO guideline value (10 µg L⁻¹) whilst no trace of arsenic was found in the samples of tomatoes, cabbages, and potatoes. Another publication (Nzihou et al. 2013) has focused on the health risk related to medium- and long-term exposure to drinking water contaminated by arsenic. They built an exposure factor based on the arsenic concentration in drinking water. Results show that, for arsenic concentration ranging from 1 up to 87.8 µg L⁻¹, the majority of the population in the northern part of Burkina Faso is at risk of arsenic-related diseases (cancerogenic or non-cancerogenic). Certainly, there is not enough studies performed in Africa putting a link between human health problem and high-arsenic water. But, the occurrence of arsenic in significant concentrations in African water remains a threat to human health in several countries.

6 Removal of Arsenic in Water

Drinking water contamination by arsenic is a threat for human health in Africa. However, only two articles have been found dealing with arsenic remediation. The first article (Ebina et al. 2003) examines the synthesis and arsenic adsorption capability of smectite-titanium oxide nanocomposite of tunable pore size. The results of laboratory experiments show that a clay-titanium oxide nanocomposite synthesized from smectite powder and titanium oxide powder has a good adsorption capability of As (III) and As (V) dissolved in water. The second article (Bowell 1994) deals with the sorption of arsenic by iron oxides and oxyhydroxides in soils. The results showed that the iron oxides and oxyhydroxides coming from neutral-pH oxidized clay-rich soils and oxidized surface portion of mine tailing soils at the Ashanti mine, Ghana, adsorb arsenic more than that coming from highly acidic soils or reducing conditions and the organic-rich soils. The sorption decreases in the order As (V) > dimethylarsinic acid (DMAA) = monomethylarsonic acid (MMAA) > As (III) below pH 7 and As (V) > As (III) > MMAA = DMAA above pH 7. That sorption would be controlled by Eh and pH and in the presence of other potential sorbents such as organic acids. Although few studies in Africa deal with arsenic removal from water, it can be found in the literature various treatment methods (conventional and advanced) for arsenic removal from water in the world (Table 2). All these technologies used for the removal of As from

water have some advantages, but they also have drawbacks and their by-products can be a further potential source for secondary As pollution. So, it would be interesting to develop, in the African context, new technologies with local materials in order to challenge the menace of arsenic.

7 Conclusions

Arsenic contamination of water resources is a real problem in African countries. Geological source and anthropogenic practices, such as mining operations, agricultural drains, and disposal and incineration of municipal and industrial wastes, release large amounts of arsenic into the environment and cause contamination of water resources. The adverse impact of arsenic on human health has been highlighted in some countries as Burkina Faso and Ghana. Remediation of arsenic in contaminated water focussed only on the sorption method by using clay-titanium oxide nanocomposite synthesized and iron oxides and oxyhydroxides in soils. Despite the fact that much research has been carried out on arsenic in the world, less than 100 articles deal with arsenic in African waters. Most of these studies are prospecting studies of arsenic in water and rarely make the connection between health problems and arsenic in drinking water. Moreover, only two articles have been found dealing with arsenic remediation. This shows that arsenic which constitutes a major public health issue in the world has less interest in African countries, whereas, high concentrations of arsenic have been found in both surface water and groundwater in some African countries. Moreover, the probability to occur high-As concentrations in other parts of the African continent, where current studies did not highlight, is real. Thereby, the arsenic issue in Africa needs special attention in order to avoid the problems experienced by some areas as mainly in Asia. Consequently, it would be interesting to develop, in the African context, new technologies with local materials in order to challenge the menace of arsenic.

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