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A new perspective on small-scale treatment systems for arsenic affected groundwater

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ABSTRACT

This work provides a new perspective on small-scale treatment systems to remove arsenic from groundwater for potable applications in low-income communities. Data corroborated from the literature highlight a significant challenge to providing potable water in a financially sustainable manner in arsenic affected areas. Analysis of the literature also reveals notable deficiency in the current practice, especially the over-focus on household-scale treatment systems for arsenic affected groundwater without adequate maintenance, monitoring, and a systematic cost–benefit analysis. Accurate and reliable analysis of arsenic in water samples at relevant health guideline values is costly and technologically demanding for low-income communities. Significant discrepancy in the performance of household-scale treatment systems can be attributed to the lack of maintenance and systematic monitoring. Moreover, data on the maintenance and compliance monitoring cost of small-scale arsenic treatment systems are very limited in the literature, and the available data show an exponential increase in maintenance cost per treatment capacity unit as the treatment size decreases. On the other hand, significant opportunities exist to increase performance reliability and reduce water treatment cost by taking advantage of the current digital transformation of the water sector. The analysis in this work suggests the need to reframe current practice towards commune-scale treatment systems as an interim step before centralised water supply is available.

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1. Introduction

Natural contamination of groundwater by arsenic is a vexing problem in many low-income communities around the world (Singh et al., 2015; Berg et al., 2007, 2001). Health issues associated with arsenic affected groundwater were first discovered in West Bengal and Bangladesh in the early 1990s (Saha, 1995). Since then, groundwater contaminated with arsenic has been identified in many regions of the world (Singh et al., 2015). Arsenic in groundwater used as a drinking water source poses a threat to human health. Indeed, arsenic has been recognised as the most serious inorganic contaminant in drinking water on a worldwide basis. Concern about the significant health risks due to chronic arsenic exposure via drinking water has resulted in many dedicated works to provide a safe and financially sustainable solution to affected communities (Kobya et al., 2020; Sodhi et al., 2019; Thakur et al., 2020).

Access to safe and clean water is essential for economic development in low-income communities. Empirical research has shown a relationship between economic growth and fresh water availability or water-related disasters such as floods and droughts in many countries (Borgomeo et al., 2018). It is widely acknowledged that water-related risks can impact development opportunities and can trap communities in a downward spiral of economic decline (Borgomeo et al., 2018). Moreover, while access to safe and clean water has been recognised as a human right according to the World Health Organisation (WHO), a large proportion of the world's pollution is still deprived of access to safe and clean water. In many areas, a safe and clean water source is either located at a considerable distance from their home or not available at all. The loss of productive time for water collection places a significant constraint on this population, inevitably affecting their income and the education of their children (Borgomeo et al., 2018).

Recognising the impact of water on economic development, many international organisations such as the United Nations Children's Emergency Fund (UNICEF), the United Nations Industrial Development Organization (UNIDO), and WHO together with philanthropies such as the Bill & Melinda Gates Foundation have provided generous support to improve access to safe and clean water for low-income communities around the world. Previous effort has focussed mostly on eradicating waterborne diseases in low-income countries, and the progress to date has been significant. Between 2000 and 2017, the proportion of the global population with access to safe and clean water increased from 61% to 71% (World Health Organization, 2019). Nevertheless, as the list of low-income countries gets shorter, it is clear that international aid and philanthropy cannot solve the problem without the self-investment from local communities. In the case of arsenic contaminated groundwater, international aid alone has been a part of the early problem. For example, the event of serious arsenic contamination in West Bengal and Bangladesh was linked to UNICEF tube well program to provide pathogen free water to the population to avoid water borne diseases (Saha, 1995). Moreover, there is a clear economic incentive for affected communities themselves to invest in water solutions. It is estimated that every $1 invested in water and sanitation resulted in a $5-6 economic return from lowering the cost of health care and increasing productivity (World Health Organization, 2019; Haller et al., 2007).

Extensive studies on treatment technologies for arsenic affected groundwater and its associated health and ecological effects have been conducted (Shafiquzzaman, 2021; Alkurdi et al., 2021; Chwirka et al., 2004; Lacasa et al., 2011; Song et al., 2006; Víctor-Ortega and Ratnaweera, 2017). These efforts, however, mostly rely on experimental works and largely focus on feasibility demonstration of lab-scale or small-scale treatment systems, but ignore to address the practical aspects of arsenic affected groundwater treatment technologies. The practical aspects including engineering, scalability, and economic constraints of treatment systems play a vital role in addressing the issues of arsenic affected groundwater and its health and ecological effects in low-income communities.

Previous lessons on small-scale treatment systems to improve access to safe and clean water and ultimately to achieve an economically independent status call for a rethink of the current approach. There is growing evidence of an overfocus on low-cost and small-scale treatment systems as a solution to arsenic in groundwater. There is also evidence of inadequate performance monitoring as well as discrepancy in the performance and cost–benefit analysis of these low-cost, small-scale treatment systems. This work aims to provide an analysis of the state of play of current efforts to address the problem of arsenic in groundwater in low-income communities. The occurrence, health effects, and the detection of arsenic in groundwater are firstly reviewed to highlight the need for effective treatment of arsenic affected groundwater in low-income communities. Then, common treatment technologies are critically assessed in a holistic social, economic, and technological context. The emerging digital capability is also discussed with respect to its potential to reduce cost, enhance performance, and improve maintenance and compliance monitoring.

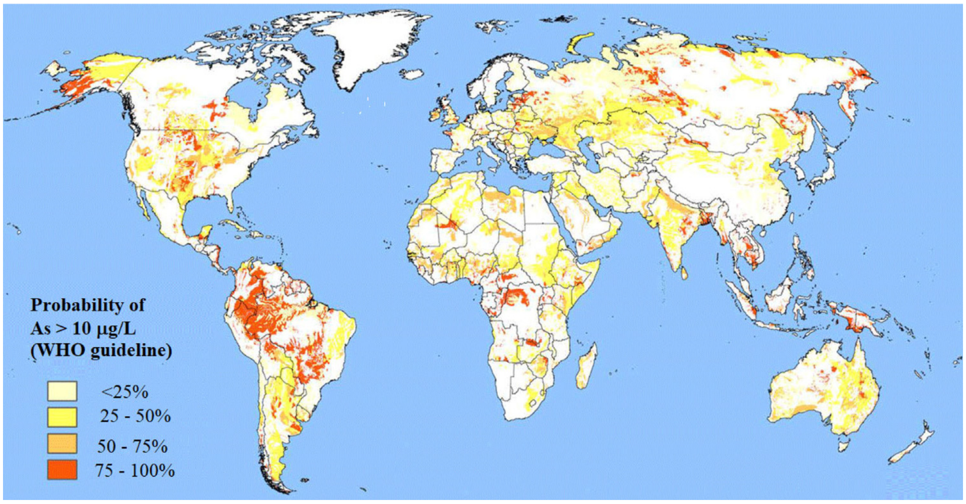

Fig. 1. Estimated geogenic arsenic contamination in groundwater over the world.
Source: Adapted from Amini et al. (2008).

Table 1
Examples of arsenic affected groundwater hotspots around the world (NEG = Negligible; GDP = Gross Domestic Product in 2019).
Source: Data from: The World Bank; Smedley and Kinniburgh (2002).

Location	Population exposed (million)	GDP per capita (US$)	Arsenic concentration in groundwater (μg/L)
Bangladesh	30	1,856	0.5–2,500
West Bengal	6	2,100	10–3,200
Vietnam	1	2,715	1–3,050
Thailand	0.015	7,807	1–5,000
Argentina	2	9,912	1–5,300
Northern Chile	0.5	14,897	100–1,000
Tulare basin (California, USA)	NEG	65,298	1–2,600
Moira Lake (Ontario, Canada)	NEG	46,190	50–3,000

2. Occurrence and health implication

2.1. Arsenic affected groundwater

Chronic arsenic poisoning is caused not just by a natural geological problem, it is also overwhelmingly underlined by social and economic conditions. As a common element in the earth crust, arsenic affected groundwater is ubiquitously distributed throughout the world (Amini et al., 2008). Data in Fig. 1 are from a combination of statistical analysis of about 20,000 data points of arsenic in groundwater and key geological and climatic properties worldwide. Contrary to the scale of arsenic affected groundwater in Fig. 1, the threat of chronic arsenic poisoning is limited to less than 100 million people in several hot spots around the world (Amini et al., 2008). Population in these hot spots relies almost exclusively on groundwater for water supply and does not have access to centralised water treatment (Amini et al., 2008). Table 1 illustrates some examples of these hot spots (where the threat of arsenic in groundwater is most pervasive), affected population size, and their economic status (measured by gross domestic product per capita). Arsenic affected groundwater can be a vexing problem in some remote communities in the developed world including the USA and Canada even though the affected population in these developed countries is negligible. Data from Fig. 1 and Table 1 highlight the need for a holistic techno-economic consideration to address the problem of arsenic in groundwater.

Arsenic affected groundwater almost always contains other contaminants of concern. Some of the most common co-contaminants include iron, manganese, and fluoride. In fact, major minerals binding arsenic in sediments are the metal oxides, especially those of iron and manganese (Smedley and Kinniburgh, 2002); and co-contamination by iron, manganese, and fluoride has been reported in most arsenic affected groundwater (Smedley and Kinniburgh, 2002; Jha and Tripathi, 2021; Kumar et al., 2018; Le Luu, 2019). When arsenic is present in shallow aquifers, there can also be co-contaminants from anthropogenic activities such as ammonia and pathogenic bacteria. Nga et al. (2003) reported clusters of several co-contaminants in all samples when assessing groundwater quality in eight separately located wells in the Red River Delta (Vietnam). These co-contaminants include arsenic (up to 110 μg/L), iron (up to 32 mg/L), ammonia (up to

Table 2
Arsenic co-contaminants in groundwater and their health and aesthetic guideline values.
Source: Data from the 2008 WHO Guidelines for Drinking Water Quality and the 2021 Australian Drinking Water Guidelines.

Co-contaminants	WHO Guideline		Australian Drinking Water Guidelines	
	Health	Aesthetic	Health	Aesthetic
Iron (mg/L)	NA	0.3	NA	0.3
Manganese (mg/L)	0.4	0.1	0.5	0.1
Fluoride (mg/L)	1.5	NA	1.5	NA
Ammonia (mg/L)	NA	NA	NA	0.5
Pathogens (e.g. E. coli)	0	NA	0	NA

NA: not applicable.

29 mg/L), and organic matter (up to 12.6 mg/L of dissolved organic carbon) (Nga et al., 2003). The high concentrations of ammonia and organic matter as well as the shallow Holocene alluvial nature of the groundwater aquifer in the Red River Delta suggest possible anthropogenic contamination from agriculture run-off, solid waste decomposition, and untreated wastewater discharge.

Co-contaminants in arsenic affected groundwater are regulated in drinking water guidelines for health (e.g. manganese, fluoride, pathogens) and aesthetic (e.g. iron and ammonia) reasons (Table 2). Thus, these co-contaminants must also be removed. Some co-contaminants such as iron and manganese can be conveniently removed with arsenic. Indeed, co-occurrence of arsenic and iron (and manganese) in groundwater allows for cost-effective removal of these contaminants by co-precipitation followed by simple sand filtration (Nur et al., 2019; Kameda et al., 2014). On the other hand, additional or separate treatment processes may be required for other co-contaminants such as fluoride, ammonia, and pathogens. Unfortunately, these co-contaminants are often overlooked when treating arsenic affected groundwater.

Another co-contaminant of arsenic in groundwater are pathogens which are common in private wells. While the disease burden is most significant in dug wells and shallow tube wells, even deep tube wells are not completely free of waterborne pathogens. Howard et al. (2007) examined thermotolerant coliforms (TTC) in arsenic affected groundwater in Bangladesh. In the wet season, they reported a median TTC value of 820 cfu/100 mL and 1.2 cfu/100 mL in dug wells and deep tube wells, respectively (Howard et al., 2007) (cfu stands for colony-forming unit). In Vietnam, Oh et al. (2021) reported co-contamination of groundwater with 376 μg/L of arsenic and 10.3 cfu/mL of total coliforms. It is noteworthy that studies on both arsenic and pathogens in groundwater are rare in the literature. Nevertheless, waterborne pathogens have been widely reported in water sourced from private wells (Bivins et al., 2020; Moreira and Bondelind, 2017; Nguyen et al., 2020). Data corroborated here heighten the need to look beyond arsenic when providing water supply solutions in communities with low social economic background. Thus, without appropriate disinfection, the risk of waterborne disease is unacceptable and may even overwhelm the chronic health risk of arsenic contamination.

2.2. Health and ecological effects

Arsenic poisoning at a high dose can be fatal. The lethal dose of arsenic is about 3 mg/kg or 210 mg for an average sized adult (Hughes, 2002). In general, this is an extreme dose that cannot be obtained from exposure to natural groundwater given the highest reported groundwater arsenic concentration of 5.3 mg/L shown in Table 1. Thus, arsenic affected groundwater is strictly limited to chronic health effects and WHO guidelines on drinking water have recommended the maximum allowable level of arsenic of 0.01 mg/L.

Arsenic exists in the environment in various forms and exerts a range of health effects. Arsenic can be found in solid form in minerals, gas phase (e.g. arsine), organic forms (e.g. arsanilic acid and methylarsonic acid), and as water-soluble inorganic salts such as arsenate and arsenide. Compared to inorganic arsenic, organic arsenic is significantly less toxic since the arsenic atom is covalently locked up in an organic molecule, rendering it biologically unavailable for interaction with other biomolecules in the host body. Gaseous arsenic can be extremely toxic but is beyond the scope of this work. Previous studies in the literature are mostly related to arsenic poisoning (i.e. called arsenicosis) due to chronic exposure to inorganic arsenic contaminated groundwater used for drinking water (Singh et al., 2015).

Arsenicosis has several symptoms and a range of possible health consequences. The appearance of black spots on skin is the most common and notable symptom of arsenicosis. It is called 'arsenical keratoses' and is often associated with skin lesions (skin damage) when those black spots become too large. Arsenic has a high affinity toward keratin, which is a type of protein found in hair, nails, and skin. In fact, arsenic poisoning can be forensically confirmed by analysing hair sample (Chen et al., 2018). Moreover, compared to the rest of the body, skin on soles and palms is subjected to much higher pressure, and hence it has higher keratin content. As a result, skin pigment changes caused by arsenic poisoning usually first occur on these areas of the body (Fig. 2).

To date, clinical reports of arsenical keratoses have been limited to India (West Bengal) and Bangladesh. The first incident of arsenical keratoses was reported by the Department of Dermatology, School of Tropical Medicine in Calcutta, India (Saha, 1995). Early patients were from West Bengal, but a few years later, there were also patients from neighbouring

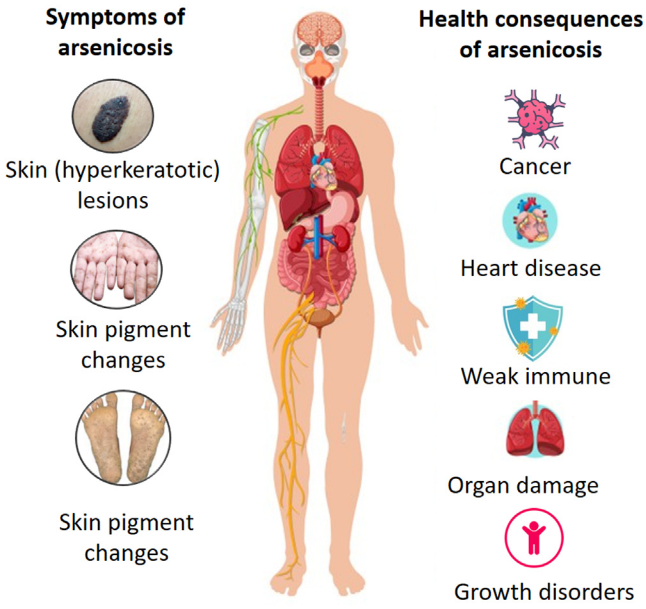

Fig. 2. Symptoms and health consequences of chronic arsenic poisoning from groundwater.

Bangladesh (Saha, 1995). A follow up investigation revealed arsenic contaminated water from tube wells as the cause, which was formally confirmed in 1993 (Smith et al., 2000). These tube wells were installed in the 1970s with support from the UNICEF to reduce acute gastrointestinal illness from bacterial contamination of stagnant surface water. In other words, exposure to arsenic contaminated groundwater by residents in West Bengal and Bangladesh had occurred over several decades. In 1990s, an emergency intervention programme was launched to address the problem of arsenicosis. Furthermore, in 1993 the WHO lowered the guideline value of arsenic in drinking water from 50 to 10 μg/L. Since 1990s, although many communities have continued to rely on arsenic affected groundwater for their daily need, they have used bottled water for drinking and cooking or had some forms of water treatment for arsenic removal. Thus, widespread arsenical keratoses have not been recorded since then.

Arsenicosis can even result in a range of serious health consequences. These include skin cancer and several other forms of cancer, irregular heartbeat, organ failure, weakened immune system, and development disorders (Fig. 2). These illnesses were prevalent and could be directly linked to arsenic affected groundwater among arsenicosis patients in West Bengal and Bangladesh (Smith et al., 2000). For other populations, they can be masked by other factors. It is noteworthy that arsenic affected groundwater is more pervasive in low-income communities. Thus, the populations in low-income communities often have other underlying social-economic issues together with the health problems caused by arsenicosis.

2.3. Quantitative and qualitative detection

As a common metalloid, arsenic can be detected and quantified in water, air, and solid samples using a broad range of analytical techniques (Sankararamakrishnan and Mishra, 2018). These techniques can be classified into three groups: laboratory instruments, portable devices, and test kits (Fig. 3). Their performance varies in terms of accuracy and reliability, requirement for laboratory infrastructure and technical skills, and cost. Despite the broad range of the analytical techniques in Fig. 3, none of them appears to be a perfect fit for quantitative and qualitative analyses of arsenic affected groundwater in low-income communities.

Laboratory instruments are cost-prohibited for decentralised arsenic treatment applications (e.g. household-scale treatment systems). There are many laboratory instruments for arsenic analysis in the market. Examples include inductively coupled plasma (ICP) with either optical emission spectrometry (OES) or mass spectrometry (MS) detector and atomic adsorption spectrometry (AAS) (Sankararamakrishnan and Mishra, 2018; Hung et al., 2004). These analytical instruments are highly accurate and reliable (Hung et al., 2004); however, they can cost more than a hundred thousand dollars each to purchase. They all require extensive laboratory infrastructure and hence have considerable operational costs. For examples, ICP-OES and ICP-MS instruments require instrument grade argon as carrier gas while acetylene and nitrous oxide are required as fuel and oxidant for AAS. In addition to the high operational expense, a highly skilled technician is required to operate these laboratory instruments. As a result, the cost of laboratory grade arsenic analysis is about 20$/sample or more. It is necessary to underline that this cost is inclusive of lab consumables and the capital cost of the instrument and exclusive of sample preservation, collection, and delivery. If this is passed on to individual households

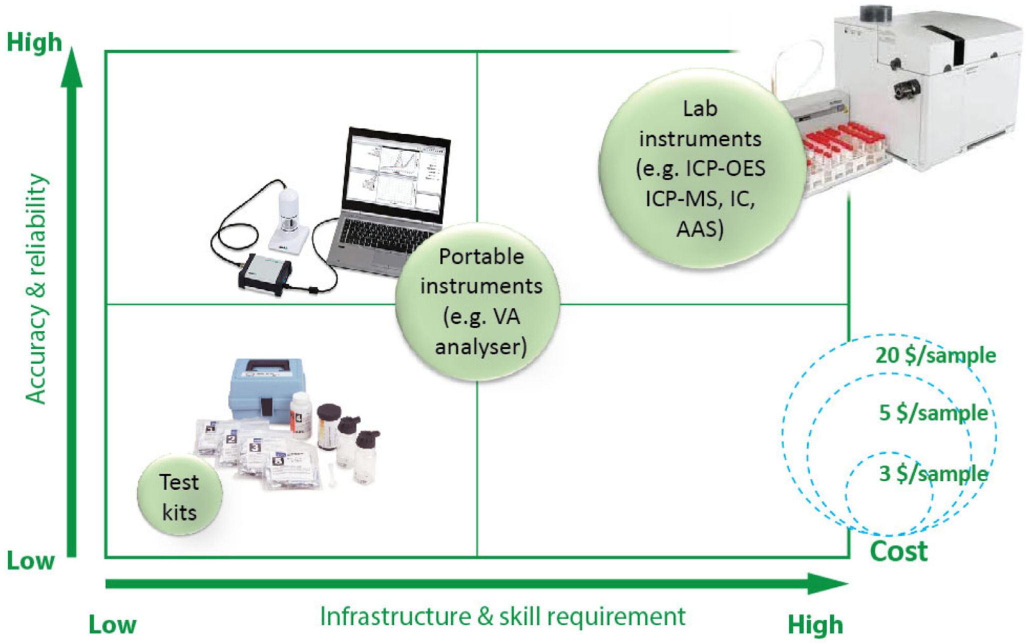

Fig. 3. Analytical techniques for quantifying arsenic in groundwater (the circle size is indicative of the cost of analysis).

as part of the on-going monitoring and compliance cost, arsenic treatment will become unaffordable in most cases, particularly in low-income countries.

Given the high cost of laboratory instruments, there have been some attempts to develop low-cost test kits for arsenic analysis. Most test kits in the market are based on the conversion of inorganic arsenic in the aqueous phase to gaseous arsine by adding zinc metal (Das et al., 2014). The arsine gas then reacts with mercuric bromide on the test strip to form a mixture of arsenic and mercury bromides that changes the test strip colour from yellow to brown depending on the content of arsenic bromide. By visual comparison of colours to a calibrated colour scale, arsenic concentration in the initial water sample can be obtained. These test kits require low up-front cost and the analysis can be performed according to the provided instruction. Commercial test kits for arsenic analysis are readily available at about 350 US$/pack for 100 samples. Several other mechanisms such as biosensing for test kit arsenic analysis have been reported in the literature (Devi et al., 2019; Zhang et al., 2019). Nevertheless, these biosensing techniques are not yet commercially available.

While test kits are inexpensive and easy to use, they are at best a semi-quantitative technique for determining arsenic concentration in water samples (Sankararamakrishnan and Mishra, 2018; Erickson, 2003). Concern about the lack of accuracy and precision of arsenic test kits has promoted a recent study by Reddy et al. (2020). In this study, performance of arsenic test kits from six major suppliers was compared to laboratory instruments. Reddy et al. (2020) reported that only two kits provided accurate and precise estimate of arsenic in the samples as claimed by the suppliers. The remaining four kits (including those from reputable laboratory suppliers) failed to achieve the stated level of accuracy and/or precision. As a result, Reddy et al. (2020) recommended the inclusion of internal standards in every test kit package. The authors also highlighted the need for cross checking test kit performance with calibrated laboratory instruments (Reddy et al., 2020).

The gap between high-cost laboratory instruments and unreliable test kits has been filled to some extent by a group of portable instruments. Examples include the PDV6000 Plus from Modern Water, the 946 Portable VA analyser from Metrohm, and the MetalGuard online analyser from Aqua Metrology Systems. These portable instruments have been widely used by the mining sector for monitoring arsenic and other heavy metals in groundwater. They rely on a voltammetric mechanism for arsenic quantification. In brief, a negative potential is first applied to reduce arsenic in the sample to its ground state on the electrode (Mays and Hussam, 2009). The process is then reversed to oxidise arsenic from the electrode back into the solution (Mays and Hussam, 2009). A voltammogram is obtained to confirm the presence of arsenic and quantify its concentration in the sample (Mays and Hussam, 2009). Portable instruments are less expensive than laboratory instruments. However, they still require skilled personnel to operate. There are several common interferences to voltammetric analysis in groundwater matrix, including organic matter, sulphide, and some metals (Lewtas, 2015; Lewtas and Wajrak, 2012). For example, organic matter can form complex with arsenic and sulphide can precipitate arsenic from the solution. Several metals such as copper and iron have similar voltammogram to arsenic that can deposit on the electrode, thus altering the voltammogram and the resultant arsenic quantification. Although the accuracy and reliability of portable instruments have not been systematically investigated in the context of low-income

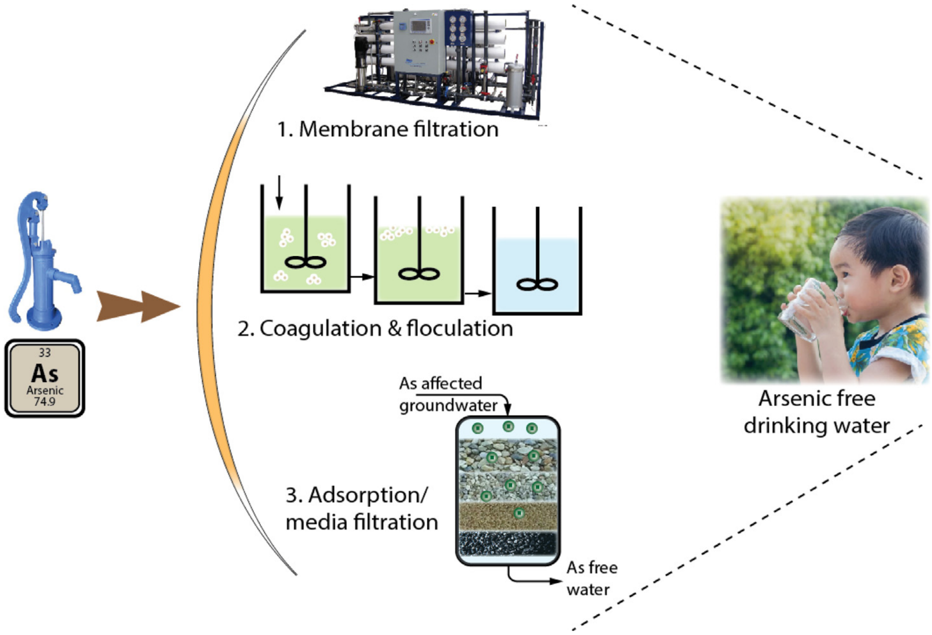

Fig. 4. Common technologies suitable for small-scale treatment of arsenic contaminated groundwater for potable water provision.

communities, these instruments present an exciting opportunity to lower the cost of arsenic analysis (Nsabimana et al., 2019).

3. Managing arsenic contaminated groundwater

3.1. Best drinking water supply practice

There is a long-standing principle that raw water destined for potable (drinking) usage should be drawn from the best available sources. In a typical setting, potable water is usually from a protective catchment or rechargeable aquifer that is undisturbed by and free of sources of both anthropogenic and natural contamination. In areas affected by arsenic contamination, the problem arises when centralised water supply is not available. This perhaps explains the contrast between widespread arsenic occurrence in groundwater throughout the world (Fig. 1) and the limited number of hot spots (Table 1) discussed in Section 2.1. Thus, the most cost-effective and safest strategy to address arsenic affected ground water is to provide potable water to the population from a centralised treatment plant. As history has demonstrated, this is unfortunately not always feasible to some low-income communities. It is nevertheless important to acknowledge that the provision of decentralised water treatment especially at household-level must only be taken as a last resort.

Good practice in potable water supply is based on a multiple barrier approach, where different barriers to contamination are put in place. They include source selection and protection, monitoring and maintenance, and treatment. These components, especially monitoring and maintenance, are often absent in low-cost decentralised water systems that have been provided to arsenic affected areas. Unlike other review works on this topic that descriptively list and describe technologies for removing arsenic from groundwater, the following sections focus on the applicability of available technologies and their interplay with key social economic factors to address the challenges of arsenic affected groundwater in low-income communities.

3.2. Arsenic removal technologies

Many treatment technologies are available for removing arsenic from contaminated water. They have been extensively discussed in several previous reviews (see for examples Le Luu, 2019; Ghosh et al., 2019; Mondal et al., 2013; Alka et al., 2021). However, only a few of them are suitable for small-scale water treatment in arsenic affected areas. As discussed in Section 2.1, arsenic is almost always present with other co-contaminants in affected groundwater. Thus, additional treatment steps may also be required if these co-contaminants cannot be removed together with arsenic. Given the focus of this work on arsenic, only arsenic treatment technologies are considered here. Technologies with proven track record for arsenic treatment in terms of removal efficiency, cost-effectiveness, and suitability for small-scale applications include membrane filtration, coagulation & flocculation, and adsorption/media filtration (Fig. 4).

Membrane filtration processes such as nanofiltration (NF) and reverse osmosis (RO) can be very effective for arsenic removal from groundwater (Chen et al., 2020; Gonzalez et al., 2019; Schmidt et al., 2016). NF/RO membranes can achieve 99% arsenic removal (i.e. in either As(V) or As(III)) (Gonzalez et al., 2019; Schmidt et al., 2016; Walker et al., 2008). Thus, in most cases, a compact membrane system is capable of meeting the drinking water guideline regarding arsenic with a single pass. Indeed, household-scale NF/RO systems have been deployed for water treatment for drinking water in many communities. It is, however, noteworthy that NF/RO cannot be used as a standalone treatment system. The feed water prior to NF/RO must be pre-treated to remove suspended solid particles and other foulants that can clog the membrane. Groundwater contaminated with arsenic is usually laden with a high content of iron and manganese that pose a high risk of fouling to NF/RO membranes (Gonzalez et al., 2019; Schmidt et al., 2016; Walker et al., 2008). In addition to pre-treatment, inline addition of chloramine and antiscalant may also be required to prevent biofouling and scaling. NF/RO systems must also be regularly cleaned by special chemicals to remove fouling and scaling. Overall, the logistic demand and technological expertise to support NF/RO treatment are often beyond the affordability range of low-income communities. The cost of an NF/RO treatment system is also out of reach for most of these communities. As a result, while NF/RO membranes are very effective for arsenic removal and have been widely used in remote communities in North America and other developed countries, they are deemed unsustainable and unsuitable for the low-income countries.

Coagulation & flocculation is a common and perhaps the simplest technique for the treatment of arsenic affected groundwater. Through chemical precipitation, coagulation & flocculation co-precipitate dissolved arsenic from groundwater with other co-contaminants such as iron and manganese to form insoluble flocs, which can then be removed by sedimentation or sand filtration (Singh et al., 2015). The addition of coagulants such as aluminium and ferric salts may be necessary to initiate the chemical precipitation and promote the formation of large flocs which absorb and co-precipitate with arsenic. When correctly applied, coagulation & flocculation has been proven as an effective method for removing arsenic from groundwater with low arsenic load (Lacasa et al., 2011). For heavily arsenic affected groundwater, additional treatment is required after coagulation & flocculation to achieve the permissible arsenic content in the product water (Chwirka et al., 2004; Song et al., 2006). Arsenic removal efficiency of coagulation & flocculation is highly sensitive to pH of the raw groundwater; thus, pH adjustment is required for optimum arsenic removal efficiency (Lakshmanan et al., 2010; Wickramasinghe et al., 2004). It is also important to optimise the coagulant doses. Over dosing the coagulant can cause charge reversal. In other words, suspended particles in the water can go beyond charge neutralisation to gain positive charge, and thus, become stable in the solution. Given its simplicity, coagulation & flocculation in combination with sand filtration has been promoted for arsenic treatment at individual household level. However, there appears to be a lack of training provision, maintenance, and monitoring to ensure performance reliability. A follow up survey of 43 households using coagulation & flocculation and sand filtration to treat groundwater showed that 60% of these systems could not meet the 10 μg/L guideline value of arsenic in drinking water (Berg et al., 2006). Many households were even unaware of the purpose of these systems to remove arsenic (Berg et al., 2006). Moreover, coagulation & flocculation treatment of arsenic affected groundwater results in sludge that has to be disposed safely to prevent arsenic escape into the environment.

Adsorption/media filtration is another technology that has been widely used for small-scale treatment of arsenic affected groundwater. Adsorption/media filtration relies on the ability of an adsorbent to adsorb and retain arsenic and other contaminants from groundwater. Most common adsorbents include activated carbon, alumina, iron oxides, laterite (i.e. a natural mixture of iron and aluminium oxides), and zeolites (Singh et al., 2015; Han et al., 2013). Several novel low-cost adsorbents such as biochar, rice-husk, and furnace slag have also been trialled for treatment of arsenic affected groundwater (Alkurdi et al., 2021; Kim et al., 2021; Nath et al., 2019; Shaikh et al., 2020). Overall, adsorption/media filtration is a low-cost, simple-to-operate, and sludge-free technology for treating arsenic affected groundwater. The adsorption/media filtration process has a small physical footprint, does not require any chemical addition, and can be easily integrated with other processes for pre-treatment or disinfection (Singh et al., 2015). Nevertheless, arsenic removal efficiency of adsorption/media filtration is strongly affected by the presence of co-contaminants such as iron, manganese, and silicate that can compete with arsenic for the adsorption onto the adsorbents (Giles et al., 2011; Zhu et al., 2013). These adsorbents also have a limited life time. Thus, the performance must be monitored, and adsorption column must be regenerated once the adsorption capacity is exhausted. Like coagulation & flocculation, most if not all arsenic adsorption/media filters at household scale are not monitored and provision for regeneration is not provided. The cost of single use disposable arsenic adsorption/media filter would be even higher than the cost of supplying water bottles for drinking and cooking. Furthermore, disposed adsorption/media filters become a secondary source of arsenic waste that needs to be dealt with to protect the environment.

While all three technologies reviewed above have been extensively used for small-scale arsenic treatment, membrane filtration appears to be more suited for remote communities in developed countries. They require special chemicals for scaling prevention and membrane cleaning (in the case of NF/RO). On the other hand, there have been many applications of coagulation & flocculation and adsorption/media filtration for arsenic removal for low-income communities in the literature (Singh et al., 2015). However, reports of successful low-cost and small-scale coagulation & flocculation and adsorption/media filtration systems for arsenic removal in the literature may have been too optimistic (Alkurdi et al., 2021; Song et al., 2006; Nur et al., 2019; Kameda et al., 2014). They usually focus exclusively on initial arsenic removal. The removal of other co-contaminants and post-treatment to ensure adequate disinfection are often ignored. More importantly, in many cases, they also fail to consider the cost of operation & maintenance (OPEX) and compliance monitoring (Alkurdi et al., 2021; Song et al., 2006; Nur et al., 2019; Kameda et al., 2014).

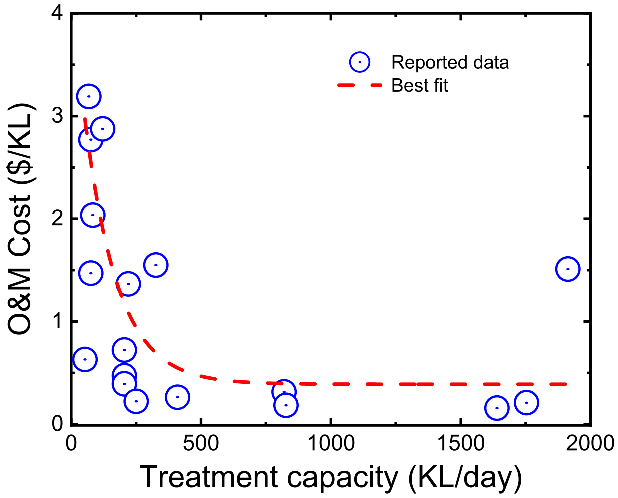

Fig. 5. Relationship between the unit cost of operation & maintenance and treatment capacity of adsorptive media filtration systems for arsenic removal in the US.
Source: Adapted from Sorg et al. (2015).

By not accounting for the cost of operation & maintenance, many previous works have distorted the economics of small-scale arsenic treatment. A thorough analysis of the literature reveals that OPEX is rarely reported or considered for small-scale arsenic treatment systems. There is only one notable exception which is a survey of 50 small-scale arsenic treatment systems purchased and installed by the US EPA in the USA (Sorg et al., 2015). Results from this survey show disproportionally high OPEX cost associated with small-scale treatment systems (Fig. 5). Previous studies often assume that the users can operate and maintain small-scale treatment system themselves. This assumption does not take into account treatment reliability. Indeed, there is significant temporal variation in water quality even when it is drawn from the same tube well. This assumption is also invalid since it omits the cost of time and materials provided by the users. Apart from the previously mentioned study by the US EPA (Sorg et al., 2015), there is a dearth of information regarding long term performance of low-cost and small-scale arsenic treatment systems.

It can also be inferred from Fig. 5 that there exists a minimum treatment capacity below which the treatment is economically unviable. In other words, while decentralised treatment can be an interim measure to address arsenic affected groundwater in low-income communities, it should be offered as a last resort and only at the commune level for a group of households. Some studies in the literature have reported point-of-use (POU) treatment devices such as household filters using laterite (a mineral that is rich in iron and aluminium oxides) or iron oxide for arsenic removal (Maiti et al., 2013; Mondal et al., 2017). However, it is noteworthy that the US EPA and many other water authorities do not accept POU treatment as a mean to comply with the drinking water standard due to the lack of performance monitoring and validation. This is because without pre-treatment, co-contaminants such as iron, manganese, and suspended particles can clog and quickly overwhelm the filter. Thus, the US EPA specifies that POU treatment devices should be connected to the tap (not arsenic affected groundwater) if the final water is intended for drinking and cooking.

There have also been some contradictory reports on the performance of household coagulation and sand filter treatment for arsenic removal. Ilmiawati et al. (2016) evaluated 77 household-level sand filters in the Red Delta River (Vietnam). They reported that these sand filters could effectively remove iron and manganese but were ineffective against arsenic (Ilmiawati et al., 2016). Discrepancy between the study by Ilmiawati et al. (2016) and several previous reports of effective arsenic removal by household-level sand filters could be attributed to several speculative reasons. Feed water characteristics may change over time, and arsenic removal was reported when the sand filter was operated by trained personnel at the beginning of the project.

3.3. A paradigm shift for managing arsenic affected groundwater

There has been an increasing realisation that the threat of arsenic affected groundwater can only be addressed by a holistic solution, one that is fully costed, financially supported by the end users, regularly maintained, and adequately monitored. Assessment of decentralised arsenic treatment systems should be based on both cost and reliability. Concurrently, among some of the worst affected countries such as Bangladesh, India and Vietnam, there is also an emerging digital capability that can change the costing structure and improve the performance reliability of these decentralised treatment systems. Rapid smart phone and 4G broadband penetration in developing countries is the foundation for this paradigm shift toward affordable and reliable decentralised water treatment. As an example, India and Vietnam were ranked 10th and 52nd in the 2019 Global 4G LTE penetration rankings, respectively. These are well ahead of several countries such as New Zealand (ranked 57th) and Ireland (ranked 79th) with a much higher GDP.

The Waterbox – AquaCheck package is a notable example of such digitally enabled and decentralised treatment systems. The package was developed from a joint venture between two German start-up companies Lavaris Technologies GmbH and AquaCheck GmbH (Siegfried et al., 2016). Waterbox is a compact drinking water purification plant consisting of several key treatment steps: filtration, precipitation or coagulation, and disinfection. The Waterbox treatment performance is monitored by AquaCheck which is a portable device for measurement of multiple water parameters including arsenic. Measurement results are automatically tagged with GPS coordination for data storage and transferred to a cloud database for future analysis and performance optimisation. Given these advanced digital features, the Waterbox – AquaCheck package has been trialled for arsenic removal in low-income communities in India, Mongolia, Mexico, and Argentina (Siegfried et al., 2016).

As the digital transformation continues to penetrate the water treatment sector, maintenance and monitoring cost will be further reduced, especially for decentralised systems (Hoolohan et al., 2021; Thomson, 2021). New capabilities such as remote commissioning and remotely assisted maintenance can also be expected (Thomson, 2021). However, similar benefits are clearly envisaged for centralised water treatment with respect to arsenic affected groundwater alleviation. Given the significant benefit from economic of scale, water supply to arsenic affected area should gradually transit toward centralised treatment and via a reliable supply network. Indeed, arsenic affected areas in developing countries usually have moderate to high population density, and thus are much more suited for centralised water supply. In other words, the role of digitally enabled decentralised water systems to provide potable water to low-income communities should be limited to a transitional period.

4. Conclusion

Natural contamination of groundwater by arsenic is a vexing problem that causes detrimental health and ecological effects to many low-income communities around the world. This review calls for a new perspective on small-scale systems for treating arsenic contaminated groundwater for drinking water. Drawing from previous lessons and recent data, this review highlights key issues and challenges in the current practice of arsenic affected groundwater treatment. It appears that the current focus on household-scale treatment systems is not supported by a holistic economic analysis and long-term performance data. Most previously reported studies involving household-scale treatment systems did not include the cost of maintenance and compliance monitoring (i.e. water sample analysis). Follow-up studies showed evidence of unreliable performance, possibly due to inadequate maintenance. Data corroborated in this review highlight the need to reframe current practice towards package treatment plants at commune scale and the phasing out of household-scale (point-of-use) treatment systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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