Chemosphere 168 (2017) 155–162

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Comparison of sand-based water filters for point-of-use arsenic removal in China

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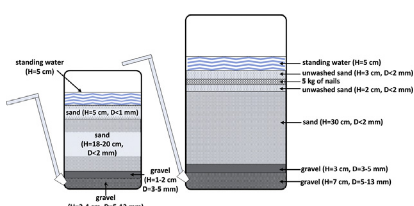
HIGHLIGHTS

- 5 filters were compared to find the most effective for an As-affected village.
- Iron-based filters can remove As, but removal is affected by filter design.
- Nails placed in biosand filter sand were more effective than those placed above.
- The arsenic biosand filter (nails above sand) rarely removed arsenic to <50 μg/L.
- The biosand filter with embedded nails removed arsenic to <50 μg/L for six months.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 March 2016
Received in revised form
26 September 2016
Accepted 7 October 2016
Available online 22 October 2016

Handling Editor: X. Cao

Keywords:
Biosand filter
Contamination
Drinking water
Iron
SONO filter

ABSTRACT

Contamination of groundwater wells by arsenic is a major problem in China. This study compared arsenic removal efficiency of five sand-based point-of-use filters with the aim of selecting the most effective filter for use in a village in Shanxi province, where the main groundwater source had arsenic concentration >200 μg/L. A biosand filter, two arsenic biosand filters, a SONO-style filter and a version of the biosand filter with nails embedded in the sand were tested. The biosand filter with embedded nails was the most consistent and effective under the study conditions, likely due to increased contact time between water and nails and sustained corrosion. Effluent arsenic was below China's standard of 50 μg/L for more than six months after construction. The removal rate averaged 92% and was never below 86%. In comparison, arsenic removal for the nail-free biosand filter was never higher than 53% and declined with time. The arsenic biosand filter, in which nails sit in a diffuser basin above the sand, performed better but effluent arsenic almost always exceeded the standard. This highlights the positive impact on arsenic removal of embedding nails within the top layer of biosand filter sand and the promise of this low-cost filtration method for rural areas affected by arsenic contamination.

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http://dx.doi.org/10.1016/j.chemosphere.2016.10.021
0045-6535/

1. Introduction

Presence of unsafe levels of arsenic in drinking water is a major problem in China. Arsenic is a carcinogen so excessive exposure through drinking water leads to increased risk of cancer of the skin, lungs, bladder and kidney (Kapaj et al., 2006). To avoid this risk, the World Health Organisation (WHO) recommends arsenic levels in drinking water be lower than 10 μg L^{-1} (WHO, 2011). It has been estimated that around 20 million people in China are exposed to water containing arsenic higher than this level (Rodriguez-Lado et al., 2013).

Shanxi province is one of the top three provinces in China for exposure to arsenic in drinking water (Yu et al., 2007). A study conducted between 2001 and 2005 found that over 12% of wells in Shanxi had arsenic levels over 50 μg L^{-1} (Yu et al., 2007), which is China's national standard for small-scale distributed water supply (PRC, 2007). Datong and Taiyuan basins are the two areas most affected by arsenic poisoning (Zhang et al., 2013).

Arsenic occurs naturally in the Earth's crust and can leach into groundwater if conditions are favorable. Exposure to arsenic in drinking water in China is most common where water is supplied untreated from groundwater wells, which tends to be in rural areas. The Chinese government has been working to improve coverage of centralized water supply networks (Xinhua, 2013), but many villages still rely on water sources with arsenic over China's national standard. In these cases, it is important for households to have access to a point-of-use filtration method that removes arsenic. This method should ideally be low cost and simple to install. It should also consistently reduce arsenic to below 50 μg L^{-1}.

Arsenic can be removed using a number of different methods and materials, which are categorized under oxidation, coagulation/flocculation and adsorption and described in detail by Kowalski (2014). Iron-water systems generally remove arsenic through adsorption and co-precipitation (Ghauch, 2015) and are popular for use by households because they remove contaminants and have good reactivity under natural conditions, while also being low energy, low cost and low maintenance (Tepong-Tsinde et al., 2015). Iron is not only used for removal or arsenic or limited to household scale. It was applied at water treatment plant scale by Kowalski and Søgaard (2014) with an aeration unit separating the iron and sand components and has been used for removal of uranium from drinking water wells (Gottinger et al., 2013) and a number of positively charged species (Noubactep, 2015). Issues do exist with the use of iron in filters. One of the major flaws is loss of permeability (Noubactep, 2014). For this reason, household filters like the SONO filter are described as using the next generation of filter materials (Rahman et al., 2013). This filter uses porous iron composite to overcome the rapid decrease in water flow rate that characterized earlier generations of iron-based household filters (e.g. 3-Kolshi filter) (Noubactep, 2009; Noubactep et al., 2009). Since the creation of the SONO filter, other iron-based porous materials have been tested for use in filters (Rahman et al., 2013). Nails can still be used as the active iron material (as shown in Chaudhari et al. (2014)), with periodic agitation of the iron nails to dislodge the build-up of iron oxides.

This study tested the ability of a number of sand and iron-based household filtration devices to remove arsenic from influent groundwater, with the aim of identifying the most effective filter for use in a village in Shanxi province. The location of the controlled field study was Liangjiabu village in Taiyuan basin, where the main village well had an arsenic concentration of over 200 μg L^{-1}. The following sand-based filters were chosen for this study: the biosand filter, the arsenic biosand filter, a close adaptation of the SONO filter, and a modified version of the biosand filter with nails embedded in the sand. These low-cost filters were operated by households for approximately five months. As iron is known to assist arsenic removal, the biosand filter with no added iron acted as a control. All other filters contained 5 kg of iron.

The biosand filter (control filter) is an adaptation of the traditional slow sand filter that removes microbial contamination from water, as described in Ngai et al. (2007) with the most significant element being the biologically active biofilm that forms on the top layer of sand (Chiew et al., 2009). The arsenic biosand filter (a conventional filter also known as the Kanchan arsenic filter) employs the same design, with the addition of a diffuser basin filled with rusting nails placed in the top of the filter. Arsenic in water flowing through the nails is adsorbed by rust and precipitates, with removal being achieved when precipitate is trapped in the sand (Ngai et al., 2007). The original SONO filter is a successful innovation in the area of sand-iron household filters. It consists of two buckets. The bottom one contains layers of sand and activated carbon or charcoal and the top one contains layers of sand and a porous layer of loose rusted iron filings (also called the composite iron matrix (CIM)), which are prepared through a process of wetting and drying (Hussam, 2010; Neumann et al., 2013). In the SONO filter, water is poured into the top bucket and filters down through the iron filings. This causes corrosion of the iron and the formation of iron phases that remove arsenic from the water and trap it within the iron matrix (Neumann et al., 2013). The SONO-style filter used in the current study was an adaptation of the SONO filter constructed by following the SONO filter patent (Hussam, 2010) as closely as possible. The final filter used for comparison in this study was an innovative modification of the original biosand filter. In this system, nails were embedded just under the top layer of sand in the biosand filter so as to investigate the impact of increasing contact time between the iron and water as suggested by Chiew et al. (2009) and Noubactep et al. (2009). A total of five filters were installed in five different households using the same influent water. These included two identical arsenic biosand filters, with one household instructed to filter all water twice through to increase contact time between the nails and water.

The arsenic biosand filter, SONO-style filter and the use of iron in sand filters to remove arsenic have separately been the subject of previous studies, both in the field and the laboratory (Leupin and Hug, 2005; Hussam and Munir, 2007; Ngai et al., 2007; Chiew et al., 2009; Neumann et al., 2013; Singh et al., 2014; Wenk et al., 2014). A number of theory-based studies are available that introduce the concept of embedding iron nails in the biosand filter (Noubactep et al., 2010, 2012; Tepong-Tsinde et al., 2015) and a study by Bradley et al. (2011) applies this construction for virus removal. To the knowledge of the authors, this is the first study to compare and provide experimental results on arsenic removal efficiency of the biosand filter, biosand filter with embedded nails, arsenic biosand filter and a SONO-style filter for influent water originating from the same high arsenic groundwater source.

2. Materials and methods

2.1. Filter construction

The biosand filter and two arsenic biosand filters (also known as Kanchan Arsenic Filters) used in this experiment were built according to Ngai et al. (2007) Each filter was made using a large washed plastic bucket of height 70 cm and estimated capacity 80 L. Groundwater was added and the following layers were loaded into each bucket in order and leveled: 7 cm of large washed gravel with diameters 5–13 mm; 3 cm of small washed gravel with diameters 3–5 mm; 30 cm of washed sand sieved through a 2 mm screen; and 5 cm of unwashed sand (<2 mm) as the final layer. The outlet pipe was cut so that a 5 cm layer of standing water remained above the