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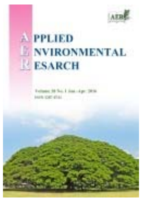

Biosand Filter (BSF): Types and Mechanisms behind Its Efficiency

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Abstract

More than 760 million people around the world lack access to clean drinking water. A biosand filter was developed through the collaboration of research groups in developing and developed countries. This type of filter is considered a point-of-use filtration system that can be easily installed at home, and has shown promising results. Thousands of these filters have been distributed and are currently in use in developing countries around the world, helping to alleviate poor water quality conditions. Although these filters have been proven to improve water quality in terms of biological contaminants, there are still concerns over their ability to remove heavy metal contaminants. This review will outline basic and current research that may pave the way for BSF improvement in terms of heavy metal removal from groundwater.

Keywords: Biofilms; Point-of-use systems; Iron-amended biosand filter; Drinking water; Arsenic removal

Introduction

Availability of, and access to, safe drinking water is one of the most significant problems of this era. The World Health Organization estimates that 760 million people around the world lack access to clean drinking water [1]. Many of these people are elders, children, or immunocompromised patients who are susceptible to water-borne diseases such as diarrhea [2]. In Thailand, it is estimated that only 30 percent of people in rural areas had access to safe drinking water in 2012 [3]. Most remote villages do not have a centralized water treatment system to treat and distribute water for the community. Point-of-use (POU) systems, where water is treated at the location of consumption, have been recently studied and proven to be effective in reducing diseases [4]. BSFs is considered as one of the most promising types of POU systems in providing safe, affordable, clean drinking water to individual households [4-5].

The BSF is a modification of a slow sand filter which uses sedimentation, filtration, and a bio-layer to treat water. It was developed by Dr. David Manz in the 1990s at the University of Calgary, Canada. Dr. Manz established the Centre for Affordable Water and Sanitation Technology (CAWST), and has been distributing BSF technology to many developing countries around the world. It is estimated that over 430,000 BSFs have been used in communities spread across 60 countries worldwide [6]. The BSF is smaller than a slow-sand filter, and is designed for intermittent use. Most household water treatment strategies focus on one to two specific technologies within: protection, sedimentation, filtration, disinfection, or safe storage [7]. A single BSF integrates several of these technologies (sedimentation, filtration, and disinfection) into a single unit. This integration improves and provides the best water quality possible within an affordable and sustainable means.

BSFs have been used in households to produce safe drinking water. In both laboratory and field studies, it has been shown that BSFs can improve water quality characteristics such as odor and turbidity [6-7]. In terms of biology, large-sized pathogens such as bacteria and protozoa are removed by the filtration sand layer as shown in Table 1 [8-11]. A recent study [12] showed that a ripened BSF can effectively remove virus particles to meet drinking water standards set by USEPA. Furthermore, field tests have shown that BSFs can remove up to 95% of iron in groundwater [6]. Most existing studies of BSF on heavy metal removal focused on arsenic removal, triggered by an arsenic contamination problem in Nepal. However, there are only limited studies to quantify BSFs' ability to treat arsenic efficiently; research into this area is still expanding [13-17].

This review will outline the modification of the conventional BSF system. Also, the mechanisms behind the filter's effectiveness in removing pathogens will be discussed. Although the original BSF is suitable for removing pathogens such as bacteria and protozoa, there is still a need to study removal of other contaminants such as inorganic and organic chemicals. The paper concludes with a summary of suggested future research.

In this review, we focus on different types of BSFs and their application in treating various contaminants: pathogenic particles, viruses, and heavy metals. A further review of the theories and mechanisms behind water treatment by BSFs will be addressed. Finally, a discussion on future research needed to expand BSFs' capability to treat diverse contaminants are also reported.

Types of BSF

1) Conventional Filters

The conventional BSF is designed for the purpose of economically producing safe drinking water to help reduce health risks such as diarrhea in developing countries [6-7]. The unit configuration adopts slow sand filtration technology with a modification to facilitate intermittent use in a household.

Table 1 Biosand filter efficiency in removing microorganisms and impurities

Test	Bacteria	Viruses	Protozoa	Helminths	Turbidity	Iron
Laboratory	Up to 96.5%	70 to >99%	>99.9%	Up to 100%	95% <1 NTU	NA
Field	87.9 to 98.5%	NA	NA	Up to 100%	85%	90-95%

Note: Adapted from "Household water treatment and safe storage factsheet", CAWST, 2012.

The conventional BSF consists of a hollow concrete or plastic structure filled with a filtration sand layer. Two base layers of gravel underline the filtration sand to provide drainage during the course of filtration. On top of the filtration sand, a diffuser plate is installed 5 cm above to protect the sand surface from disturbance while the unit is filled with water [6]. Because a BSF is a modified version of a typical slow sand filter, water is poured into the filter basin every 16-32 h. This water is filtered through the sand media by gravity, and displaces the same amount of water that has been sitting in the filter from the previous charge. Besides filtration, the BSF is designed such that the water level above the sand surface never falls below the filtration layer, thus providing a suitable space for a biologically active zone (Schmutzdecke or bio-layer) to mature or ripen. This bio-layer has been reported to help effectively remove virus from water [12, 18]. To date, there are 10 versions of BSFs designed by CAWST, with the two most recent being Version 9 and Version 10. The Version 9 has a shorter contact time between water and sand media than the Version 10. The Version 9 has a 45-cm filtration sand layer, while the Version 10 has a 55-cm filter layer. Charge volumes of Version 9 and 10 are 20 L and 12 L of water, respectively. Both the longer filter layer and smaller charge volume contribute to Version 10's longer contact time. Figure 1A shows the design and dimensions of a Version 10 BSF.

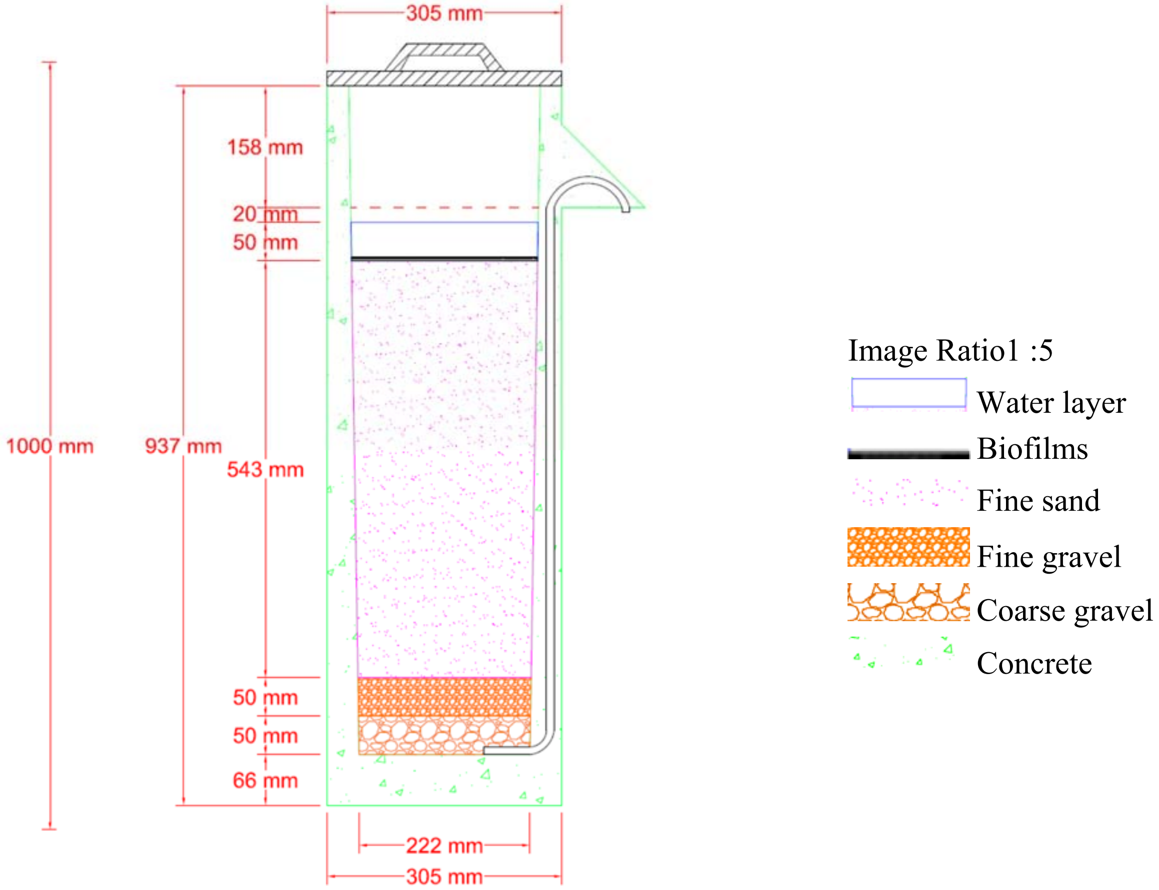

Figure 1A Biosand filter version 10 layout

2) Amended Filters

Following the successful implementation of conventional BSFs, research was carried out to modify the conventional unit to enable removal of both chemical and biological contaminants [17]. Inorganic contaminants in the form of heavy metals, such as arsenic or iron, are common groundwater contaminants. Previous studies [15-16, 19] have shown that Fe^0 has the potential to remove some heavy metals from groundwater. Thus, researchers began to modify the conventional BSF with iron particles to help remove inorganic metals, while still retaining the unit's ability to remove pathogens. So far, two main types of amended BSF models exist: the Kanchan arsenic filter (KAF), and the iron-amended filter.

3) Kanchan Arsenic Filter

The Kanchan Arsenic Filter (KAF^{TM}) is designed by a research collaboration from the Massachusetts Institute of Technology (MIT), Environment & Public Health Organization (ENPHO), and CAWST. Their group of researchers is comprised of scientists, researchers, economists, and social workers from the three organizations' home countries: the U.S., Nepal, and Canada. KAF^{TM} is a modification of the BSF to combat arsenic contamination in drinking water in Nepal. The filter is composed of two main compartments: with iron nails in the top layer, and a sand filter in the bottom layer. Five kilograms of non-galvanized iron nails are added to a container placed on top of the sand filter. The non-galvanized iron nails begin to rust and form ferric hydroxide, which can form an iron-arsenic precipitate with the arsenic dissolved in the water. The iron-arsenic precipitate will then filter out of the water in the sand layer. Unfortunately, a fundamental issue was recently found in this design [20]. The aerobic condition needed for *Schmutzdecke* to form is compromised with the presence of an active Fe^0 layer. This issue hinders the filter's ability to remove pathogens. Therefore, a further modification is proposed [7, 15, 18].

4) Iron-Amended Filters

The iron-amended filter is another modification of the BSF with iron nails or wool mixed within the sand layer [12, 18]. The design consists of a hollow concrete chamber filled with a 40-cm deep sand filtration layer. Within this filtration layer, the top 20 cm is amended with steel nails mixed with sand particles. Besides steel nails, zero-valent iron particles or extra fine steel wool are also sometimes used as amending materials. The uppermost surface of the filter contains 5 cm of pure fine sand. The filter runs intermittently and is charged with 20L water every 24 h. As in the conventional BSF design, a bio-layer develops on the sand surface, and continues to grow during usage. With the iron-amended BSF, more than 4-log removal of MS2 and rotavirus is observed [12, 18] due to the adsorption of virus onto iron oxides and the bio-layer after maturation. At this point, further research is still needed to investigate the role of the quantity and composition of iron materials added, the variables of water source compositions, and the competitive adsorption of arsenic in the presence of other contaminants. Figure 1B shows the design and dimensions of an iron-amended BSF.

Contaminant Removal Mechanisms of BSFs

Due to the BSF being a modification of a slow sand filter, these two filters share some basic mechanisms such as the development of *Schmutzedecke*, and their mechanisms of physical sedimentation, interception, and diffusion. However, since conventional treatment system is not effective enough in treating inorganic chemicals like heavy metals commonly found in groundwater, a modified filtration unit like the KAF or iron-amended BSF can perform better in concurrently removing both pathogens and inorganic chemicals. The KAF and iron-amended

BSF have both a bio-layer that works as a barrier to pathogens, and the presence of zero-valent iron, in forms such as non-galvanized nails, that acts as an adsorbent for arsenic and iron. This section reviews the mechanisms by which the BSF removes different groundwater contaminants.

Physical Treatment Aspect of BSFs

The high rate of physical removal of suspended solids and large-sized pathogens in a BSF is linked to the interception, sedimentation, diffusion, and adsorption in its sand filter layer and its bio-layer [18, 21-23]. These physical mechanisms are fundamental in filtration units similar to slow and rapid sand filtration systems.

In environmental systems, smaller particles (<1 μm) or colloids are usually ubiquitous. Colloid transportation in the environmental and engineered system has been studied intensively in the past decades [24-26]. The first groups of researchers to investigate and model colloid transport in the context of water filtration were Friedlander [27], Spielman and Goren [28], and Cookson [29]. The following section explains in detail the colloid transportation models found in the environmental system.

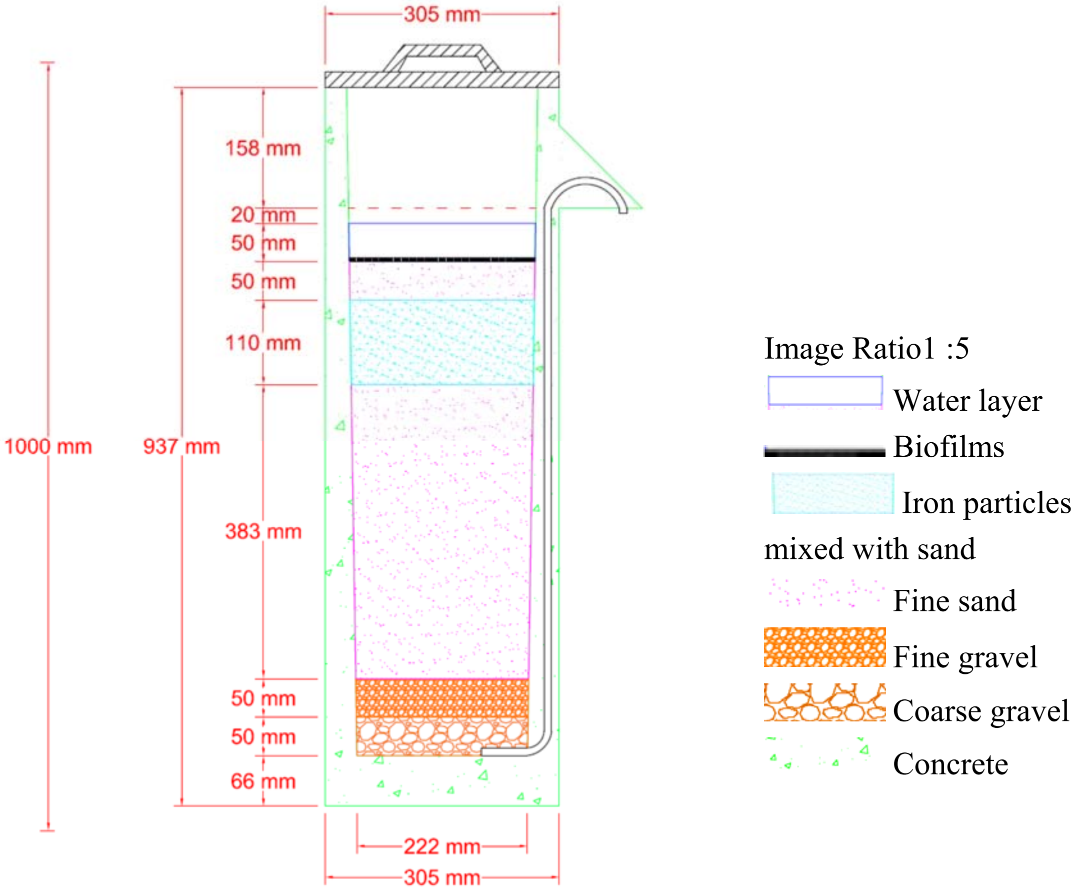

Figure 1B Iron-amended biosand filter layout

1) Classic transport model for a single collector

The classic transport model explains how a contaminant particle comes into contact with a sand particle, or a so-called collector. This model assumes that the flow around the sand particle, which is the collector medium, is laminar, and that all collectors are isolated from one another. Moreover, the collectors are assumed to be a spherical shape and to have a smooth surface.

This model focuses on the physical forces that govern transport of suspended solids in bulk water to the surface of the collector, which leads to the removal of the suspended solid from the water. In the aqueous phase, three basic mechanisms are responsible for the capture of suspended solids by sand particles [25, 30].

The first mechanism governs larger particles (>1 μm) where sufficient gravitational forces cause a particle to approach the collector along a streamline; this mechanism is known as *direct interception*. The suspended solid travels along a laminar streamline in *direct interception*, and comes into contact and collides with the collector.

The second mechanism governs smaller particles (<1 μm). Larger suspended solid particles are assumed to travel in a streamline perfectly in direct interception. However, the course of smaller particles is influenced by Brownian motion, which gives rise to the mechanism of *convective diffusion* in governing the transportation mechanism of smaller particles. Due to the randomness of Brownian motion, it is by chance that smaller particles randomly "wiggle" close enough to the collector surface to be attached in *convective diffusion*.

The third mechanism governs particles with a density greater than water. The transport path of such particles is influenced by buoyant weight and the drag force exerted by the water on the particle. When the settling velocity of the particle approaching the collector is great enough for the particle to settle on the collector surface, the mechanism of *gravitational deposition* or *sedimentation* occurs.

The three mechanisms described above can all take place in BSF units [6-7]. For example, bacterial cells are usually big enough to be removed by direct interception, while smaller virus particles diffuse to the collector surface by convective diffusion. Heavy clay particles are intercepted by the collector, and subsequently sediment. Besides bacteria and virus, other pathogens such as helminths and protozoa are reported to be effectively removed in a BSF due to their size [6-8, 17]. The overall efficiency of a BSF unit corresponds to *the efficiency of a single-collector* (η) as shown in Eq. 1. To calculate the overall filter efficiency, it is necessary to calculate η. Two studies: Yao [31], and Yao & O'Melia [32], used numerical models in predicting η. These two studies suggested a 4-step approach in solving filter efficiency: (1) determining the concentration of particles close to the surface of the collector surface; (2) calculating the rate at which particles collide with the surface; (3) using parameters from (1) and (2) to compute for a single collector efficiency; and (4) calculating the filter efficiency using equations from Iwasaki [33] and Ives [34]. Yao & O'Melia [32] also compared the result of single collector efficiency from numerical methods with experimental results. They found that η depends not only on filter velocity, media size, and water temperature, but also on the size and density of filtered particles.

$$\eta_T = \eta_{Sed} + \eta_{Int} + \eta_{Diff}$$

$$\eta_T = \frac{\Delta\rho g d_E^2}{18\mu_c V_{stream}} + \frac{3}{2}\left(\frac{d_E}{d_p}\right)^2 + 0.9\left(\frac{K.T}{\mu_c d_E d_p V_{stream}}\right)^{\frac{2}{3}} \qquad \text{(Eq.1)}$$

Where; d_p = media diameter (m), d_E = contaminant diameter (m), V_{stream} = flow velocity (m/s), K = Boltzman's constant = $1.38064852 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}, T = absolute temperature (K)

2) Collector surface roughness and its effects on colloid transport

Variations in the mechanism of colloid transport arise when the characteristic of the collector surface is not homogeneously smooth. Most of the time, interaction energy between microscopic contaminants and the collector surface is determined assuming perfectly smooth and geometrically regular surfaces [26, 35-37]. A basic theory often used in modelling and predicting attachment and filtration efficiency is Derjaguin-Lan-dau-Verwey-Overbeek (DLVO) [38], which combines the attractive Lifshitz-van der Waals (VDW) [39], and the electrostatic interaction (EDL). While DLVO theory is based on the assumption of a smooth and spherical particle, real colloidal systems in the environment may not fall into this homogeneous morphology and chemistry. In fact, discrepancies between DLVO predictions and experimental results have been noticed by many works [40-47]. These discrepancies lead to more in-depth investigations of the effects of surface topography and shape of the collector on particle interaction [40, 43, 45-46].

Hoek et al. [40, 45] investigated the interconnection between interaction energy and the surface roughness of the collector. Their study generated colloidal surfaces in various scenarios to produce different roughness and shapes. A typical way to model surface roughness includes a placement of regular asperities on a smooth surface [45, 47]. Asperities can be either protrusions or depressions, which represent surface roughness in a controlled way. Subir et al. [47] modelled a surface roughness of a sphere in heterogeneous circumstances. These rough surfaces were investigated using the surface element integration technique (SEI) to study their influence on DLVO interaction. From their study, the model suggested that the presence of roughness caused a significant reduction in repulsive interaction between the colloidal and the collector surfaces. Moreover, an interaction energy profile from DLVO indicates a derivation from those predicted solely from the smooth surface assumption. Therefore, the same author continued to investigate the effect of acid-base energy (as chemical effect) on colloid-collector interaction using an extended DLVO (xDLVO) theory [45]. An xDLVO mathematical model together with Derjaguin Integration (DI) were analyzed together. Sizes and space between particles were also addressed. The result suggested that surface chemistry was as important as collector surface roughness in nanoscale particle-surface interaction. And, the effect of VDW force was felt and rendered a collector surface more attractive when colloids were close to the surface. Additional work on xDLVO by Hoek et al. [40] also used the same SEI technique in predicting interaction energy between a spherical particle and rough substrate surfaces. In this work, a random size, location, and orientation of particle on the collector surface was investigated. They found that the overall xDLVO interaction energy decreased between the particle and the surface. Therefore, a rough surface was found to be more favorable for colloid deposition due to long-range attractive VDW force.

Besides colloidal particles, pathogen adhesion on surfaces in an aqueous system has been of interest to many researchers in the past years [21, 42, 48-49]. For example, bacteria attaching to the surface can lead to bio-layer formation. This bio-layer can be either beneficial or harmful to humans. For example, bio-layer or biofilms forming in wastewater treatment processes can be greatly helpful in removing nutrients and cleaning water. Moreover, biofilms layer on the top of BSF have been shown to help remove MS2 virus up to 7$\log_{10}$ [12, 18]. On the other hand, a bio-layer on pipe surfaces in drinking water distribution systems may lead to disinfectant depletion, and subsequently cause health risks [43, 50].

Transport of colloidal particles in the subsurface environment has been studied and applied with sand filtration in water purification process [51-53]. Biological, chemical and physical factors involving bacterial adhesion to sand particles are of interest. Morphology of a surface is an important factor for understanding bacterial adhesion characteristic and rate. Shellenberger and Logan [54] studied the effect of etching rough glass beads on latex microspheres and *E. coli* attachment. Each colloid was filtered through a column packed with rough-surface glass beads. The result demonstrated that the attachment of microsphere was higher on modified glass beads while no significance was observed with *E. coli* cells. They hypothesized that macromolecules on bacterial surfaces might play an important role in determining bacterial adhesion on smooth and rough surfaces. Confirming the findings of Shellenberger and Logan, Chen et al. [55], working on polystyrene latex particle deposition on bare and zeolite-coated stainless steel surface, found that rougher zeolite-coated stainless steel attracted more latex particles on the surface than smooth surfaces. However, these experimental results differ from those of Hoek et al. [40, 45], possibly due to methodological differences. While Shellenberger and Logan [54] employed a column system, Hoek et al. [40, 45] used DLVO theory to calculate interaction energy between colloid and a collector surface, then predicted the attachment. A theoretical prediction based on theory of a single collector may well be expected to differ from empirical results from a real filtration system.

Role of Bio-layer in BSF

The bio-layer or biofilm within BSF units is crucial to removing nano- and micro-sized pathogens such as MS2, rotavirus and *E. coli* [6-7, 12, 18]. This section reviews relevant work related to biofilms and their role in pathogen removal.

BSF units have been reported to be able to reduce both pathogenic bacteria and virus concentrations to levels safe for public consumption. Most studies agree on the effectiveness of BSF in bacteria reduction (>4$\log_{10}$) and turbidity removal down to 2 NTU after 6 to 8 weeks of operation. However, virus reduction efficacy over the same 6-8 weeks operational period varies widely amongst different studies [21-23]. The removal of suspended solids and large-sized pathogens is highly effective due to the physical and biological mechanisms of removal by the bio-layer [18], which involves enhanced sieving, adsorption, deposition, and predation [6-7]. Janjaroen et al. [36] found that drinking water biofilms found inside distribution system pipelines attracted more *E. coli* because of rougher biofilm surfaces developed under these conditions. The more that biofilms matured, the more bacteria cells were attached to the biofilms. Further studies by the same research group showed that hydrodynamic conditions within a rough biofilm surface provided a good place for *Legionella p.* to irreversibly deposit on the bio-layer [42-43]. This strong attachment between bacterial cells and biofilms was reversed by using high shear forces from aqueous flow, but not from chlorination [36, 42-43]. These above-mentioned studies suggest that biofilms may be vital in removing large-sized pathogens such as bacteria in matured BSF units as well.

Existing studies found that during the first 60 days of operation, the biological zone in BSF is not yet as effective as removing virus concentration [9, 23]. However, Bradley et al., [18] have shown that effective reduction of viruses by BSFs close to 4 $\log_{10}$ removal were achievable after a longer 200-day operational period. Several studies agreed on the physical factors such as ripening and maturation of biofilms in enhancing virus removal [9, 18, 23]. Only a few studies have investigated the biological factors such as identity of bacterial community on virus reduction. Elliot et al. [9] experimented on virus removal by intermittent BSF operation (every 18-22 hours). They found that after 50 days of operation, microbial activities within the bio-layer surface had an indirect effect on MS2 virus removal. They then added sodium azide to the filter to suppress aerobic bacterial growth, which led to a reduction in virus removal efficiency. These results hint at the role of aerobic bacteria in MS2 reduction. Further study of the effect of biological characteristics on the MS2 reduction was carried out by Wang et al. [12]. This research group collected several core samples of sand within the BSF to analyze for bacterial communities. They found that the highest reduction of MS 2 was located within the first 5 cm of the filter, while the average cumulative virus reduction throughout the entire filter was 5.6 $\log_{10}$ after 240 days. The high virus removal in the top 5-cm layer corresponded to a great diversity of microbial communities and elevated carbohydrate concentrations. This study was the first to closely investigate the microbial communities that may affect MS2 reduction within the BSF ecosystems. However, this study used only a single, well-characterized groundwater source in the experiment; as a result, the use of different water sources or contaminated waters is suggested for further study under field conditions.

Chemical Treatment Aspect of BSFs

1) Effect of ionic strength (IS), pH, hardness and natural organic matter on pathogen removal

Pathogens such as bacteria, protozoa, and viral bio-nanoparticles have been found to be responsible for waterborne diseases causing severe illness and fatalities; this problem is especially prevalent among those who are immune-compromised, and in developing countries where access to clean drinking water is limited [1]. Sand filtration has been found to be a natural process that can mitigate pathogen transportation to humans. In this process, water constituents play a key role in helping or preventing pathogen removal. Therefore, water chemistry characteristics related to pathogen removal in both the subsurface environment and a well-controlled filtration system have been studied intensively by several research groups in the past decade [18, 25, 37-38, 48, 56]. BSF involves filtration through a natural aquatic subsurface environment [6-7]. The previous section discussed the physical mechanisms that may be involved in colloidal removal. This section reviews the effect of water chemistry on pathogen removal.

We will review the fate and transport of viruses and protozoans in the natural subsurface environment. Viruses and protozoans are responsible for major and diverse health impacts [1], and are commonly detected in privately-owned wells, municipal wells, and even in deep confined aquifers [49, 57-58]. Due to their small size, viruses (20-80 nm) are generally more mobile than bacteria (0.5-3 μm) or protozoa (4-15 μm) [59]. Several studies have focused on the fate and transport of viruses under different scenarios of natural aquatic systems. These studies address interactions at the virus-virus and the mineral-water interfaces. Older studies employed bacteriophages such as MS2 as the enteric virus surrogates, while more recent studies have used real virus particles in investigating interactions between particles and collecting surfaces [9, 12, 18, 35, 38, 56, 60].

Studies of bacteriophage transport in the subsurface environment have suggested that, in field experiments where iron oxide coated sand is present, electrostatic interactions controlled virus mobility [61-64]. Yuan et al. [60] demonstrated that charge screening happens during virus deposition on a quartz surface in high IS, which increased the deposition rate coefficient of the virus. Moreover, with increased IS, Mylon et al. [56] found that bacteriophage MS2 exhibited high stability and did not aggregate in high concentrations of monovalent cations, suggesting influence by electrosteric stabilization. Stability (non-attachment) in interaction between virus-virus, or pathogen-sand particle were also observed by other researchers. Gutierrez et al. [35-37, 48, 65], Pham et al. [37] showed confirmatory results, where MS2 particles did not aggregate in high Na^+ concentration within a 4-hour time frame. Liu et al. [48] and Janjaroen et al. [36] also argued that *Cryptosporidium parvum* oocysts did not have as high an attachment to the quartz surface in a high ionic strength concentration as compared to that in a divalent cation environment [36, 48]. These previous works show that chemical properties in water such as monovalent salt concentration has an impact on pathogen aggregation, transport, and removal.

Further investigations have been conducted on the effect of water hardness on virus transport in the aquatic subsurface environment. Mylon et al. [56] suggested that divalent cations increased MS2 aggregation due to divalent cation complexation between charged moieties on the MS2 surface. Gutierrez et al., Pham et al. [35, 37] demonstrated that the classic DLVO theory underestimated a virus-virus, or a virus-collecting surface interaction in the presence of divalent cation, especially for Ca^{2+} concentration. Cation bridging was suggested to be responsible for unusually high virus aggregation, and attachment to the sand surface [35-37, 48, 56]. The effect of divalent cations in promoting pathogen removal was even enhanced in the presence of natural organic matter (NOM), which ubiquitously presents in natural aquatic environments [35-36]. NOM has been found to profoundly increase pathogen attachment to quartz or sand particle surfaces in the presence of calcium ion due to high complexation of Ca^{2+} between the proteins on the virus capsule and the functional groups in NOM [36-37, 48, 56].

Besides water hardness and ionic strength, pH has also been found to a controlling factor in pathogen attachment [26, 35]. When the pH approaches the isoelectric point (IEP), viruses carry no net electric charge. As a result, virus attachment or aggregation occurs due to reduced electrostatic repulsive interactions [35, 41].

The above-mentioned studies have paved the way to a better understanding of pathogen removal in a BSF under different water chemistry scenarios. Bradley et al. [18] experimented with a BSF amended with iron oxide to remove MS2 bacteriophages from groundwater. From their work, full-scale BSFs with iron particles possessed higher virus removal efficiency ($>4\log_{10}$) during the course of operation (287 days). However, the type of iron material added also affected the efficacy of virus removal. Their results suggested that iron wool had a more consistent effect on BSF performance than iron nails, due to its smaller size, the latter of which could cause flow channeling within the filter. Besides the iron oxide reaction helping to enhance virus removal within the BSF, the presence of a bio-layer after filter maturation is also an important component in virus reduction. Wang et al. [12] clearly demonstrated that in a matured full-scale BSF, the highest reduction of MS2 was found in the uppermost 5 cm of the sand media, where extensive microbial diversity was detected.

2) Effect of iron on arsenic removal in BSF

Many years of experience in using BSFs in Nepal and India to remove arsenic from groundwater [17, 66] have confirmed the need to modify approaches to arsenic mitigation depending on groundwater chemistry in the locality [67]. Pacini et al. [66] used a biological filtration system to treat arsenic and manganese in groundwater with control of pH and dissolved oxygen to limit abiotic iron oxidation. They observed a high efficiency of manganese and iron removal due to high solid retention times, and both biotic and abiotic processes. Their biological filter was colonized with Fe-Mn iron oxidizing bacteria to help remove iron and manganese.

In addition to biological processes in the filter, abiotic processes such as using zero-valent iron in removing manganese have been studied in many systems [14-16, 19]. Berg et al. [14] studied arsenic removal using a household sand filters both in laboratory and field. Their field experiment which involved the co-precipitation of arsenic with ferric iron found that the concentration of dissolved iron in groundwater had an effect on arsenic removal. Unfortunately, laboratory and field results did not agree on the adsorption model that explains arsenic removal; this variance was likely due to the presence of manganese, microorganism, and NOM.

Chiew et al. [19] examined the efficacy of using iron and phosphate for arsenic removal in an iron-amended BSFs using groundwater from Cambodia as a water source. They found that low levels of dissolved iron, and high influx of phosphate in groundwater drastically effected the removal of arsenic because phosphate can form a complex with iron leaving arsenate dissolving in water. The contact time between water and the nails inside the filter was not also long enough to oxidize arsenic. Besides, the presence of ammonia in groundwater might elevate nitrate concentration in the filter creating anaerobic conditions within the filter. Despite poor arsenic removal performance, removal of MS2 and *E. coli* bacteria remained effective throughout their experimental period. Therefore, they suggested that more studies are needed to ensure the efficacy of the filter in arsenic removal.

Mehta and Chaudhari [15] modified a household water treatment filtration system to treat arsenic from artificial groundwater. Their filter was amended with zero-valent iron (ZVI). They found that an appropriate ration of Fe/As was required to lower arsenic concentration under 10 μg/L. The removal of arsenic by zero-valent iron was attributed to adsorption of arsenic onto the iron oxide and/or co-precipitation with iron arsenate within the system. Additional work by Neumann et al. [16] also agreed with the result of Chaudhari [15]. The latter studied employed different filtration system configurations, but all of which zero-valent iron was still added. Their results suggested that arsenic removal occurred in the ZVI layer. Moreover, both new and 8-year old filters had the capacity to remove arsenic to less than 50 μg/L. Based on these experiments in both laboratories and field tests, BSFs have been implemented in several developing countries; several of these cases are presented in the next section.

BSF Implementation in Nepal

Since 1999, Ngai et al. [17] has led students from the Massachusetts Institute of Technology (MIT)'s Civil and Environmental Engineering Department working together with researchers from the Environmental & Public Health Organization (ENPHO) and Center for Affordable Water and Sanitation Technology (CAWST) to develop a sustainable water treatment system to tackle the problem of groundwater arsenic contamination in Nepal [67-68]. In their pilot study, they studied 3 different types of sustainable technologies including: a 3-Kolshi jerry can contain iron-oxide coated sand, activated alumina, and activated alumina manganese oxide; a 2-Kolshi; and a Kanchan^{TM} Arsenic Filter (KAF). The 3-Kolshi system was originally developed by the SONO Diagnostic Center in Bangladesh and consists of 3 clay plots containing adsorbent and iron filings. Arsenic is removed by adsorption onto the iron filings and subsequent filtration [69]. The 2-Kolshi was also designed in South Asia and consists of two pots containing ferric chloride as a coagulant, calcium hypochlorite as a disinfectant/ oxidant, and charcoal powder as an adsorbent. Arsenic was found to be removed by co-precipitation with iron [70]. Finally, the KAF was modified from a slow sand filtration system to have additional arsenic removal efficiency. The KAF contains an extra container than a slow sand filtration system filled with iron nails. Arsenic is removed by adsorption onto ZVI [13]. Overall, field studies suggest that the KAF was appropriate in removing arsenic to 10%, and iron and phosphate were also reduced by up to 90% as well as total coliform. However, caution must be observed regarding the appropriate operation of the BSF in order to maintain effectiveness. While the 3-Kolshi and 2-Kolshi systems were also able to remove arsenic, they were not popular among villagers.

Future Research

Previous research has focused on the basic principles of pathogen removal by BSF, which was the primary goal of the invention. Physical (collection surfaces), chemical (water characteristics), and biological (pathogen) effects have all been found to play major roles in pathogen removal. However, BSF may potentially be useful for removal of other contaminants such as heavy metals, and organic and inorganic substances. Further studies can lead to appropriate modifications that can enhance the suitability of BSF in removing other contaminants. Table 2 is a list of suggested research topics that can be carried out to improve BSF performance in this regard.

Table 2 Suggestions for future research on BSF

No.	Research Topic	Description
1	Removal of inorganic contamination by BSF	Evaluate the effectiveness of BSF in removing various types of inorganic contaminants such as manganese and fluoride
2	Removal of organic contaminants by BSF	Evaluate effectiveness of BSF in removing various types of organic contaminants such as herbicides and pesticides
3	Metal leaching from sand	Investigate the potential of heavy metals previously adsorbed on the sand surface to leaching back into water
4	Enhancing zero-valent iron benefits for arsenic removal by KAF	Compare the effectiveness of various types of zero-valent iron for arsenic removal when incorporated in a BSF/KAF
5	Effect of iron-nails washing on KAF performance	Explore the potential of enhancing iron corrosion and arsenic removal in a KAF by washing the iron nails which are used as the source of zero-valent iron in the KAF

Source: Table modified from CAWST document [6-7]

Conclusion

BSFs have shown promise as a POU water treatment system in rural areas, and have been distributed and used widely in developing countries around the world due to their effectiveness in treating pathogens such as bacteria, viruses, and protozoa. Particle removal mechanisms in BSF have been studied for many years. Large particles (>1 μm) were found to be removed by physical mechanisms such as filtration, sedimentation, and straining, while colloidal particles such as viruses were found to be removed by adsorption to the sand surface. Water chemistry also plays an important role in particle removal; water hardness was found to enhance pathogen removal in BSFs. In addition to physical and chemical factors, viruses are also inactivated and removed by the biological layer at the top of the BSF. Furthermore, a BSF amended with ZVI has been found to treat some heavy metals such as arsenic in groundwater; however, the removal mechanism still needs to be investigated. Although both conventional and iron-amended BSFs have been used and studied for some time, more in depth research into inorganic and organic contaminant removal should be carried out to evaluate and enhance the efficacy of the BSF.

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