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Performance evaluation of biosand filter modified with iron oxide-coated sand for household treatment of drinking water

M. Mansoor Ahammed *, Komal Davra

Civil Engineering Department, S V National Institute of Technology, Surat – 395007, India

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ABSTRACT

The biosand filter (BSF), intermittently operated household slow-sand filter, was modified by introducing a 10-cm thick layer of iron oxide-coated sand. Long-duration (about four months) tests were conducted to compare the performance of the modified BSF (MBSF) with the conventional BSF in terms of their efficiency in removing bacteria and turbidity under different operating conditions. Filters were charged daily with 20 L or 40 L natural canal water (turbidity 10.0 ± 1.2 NTU; faecal coliforms 365 ± 251 MPN/100 mL; pH 8.4 ± 0.4) or seeded tap water (turbidity 14.7 ± 4.3 NTU; *Escherichia coli* 3850 ± 736 CFU/mL; pH 7.9 ± 0.3). Results showed that the performance of MBSF in terms of faecal coliform and *E. coli* removals was better by at least one-$\log_{10}$ unit throughout the filter operation. The mean bacterial removal was low for BSF for the first month (90.0%), while it was 99.3% for MBSF during the same period. Bacteria and turbidity removals increased with time as filter ripening (maturation) occurred in both the filters. No significant difference was observed in turbidity removal between BSF and MBSF, and mean effluent turbidity was around 1 NTU for BSF and MBSF representing >90% removal. When daily charge was increased from 20 L to 40 L, a reduction in bacterial removal was noted in both the filters indicating the influence of operating conditions. Effluent physico-chemical quality remained within the guideline values for drinking water.

1. Introduction

Waterborne diseases continue to be a major cause of illness and death in communities with little access to safe drinking water. World Health Organisation estimates that globally, 1.8 million deaths occur per year due to a combination of inadequate sanitation and poor water quality [1]. Public water supplies in developing countries often fail to produce and distribute water safe for consumption which makes the responsibility of ensuring safe drinking water with the consumer. A number of household water treatment methods such as filtration, flocculation, chlorination and solar disinfection have been found to be effective in improving microbial quality of water [2].

One of the most promising and accessible technologies for household water treatment is biosand filtration. The biosand filter (BSF) is an intermittently operated slow sand filter (SSF) at small scale. The filter consists of a bed of fine sand supported by a layer of gravel enclosed in a box with appurtenances to deliver and collect the water [3]. The BSF, allows a SSF to be operated intermittently, thus making it more suitable for household applications. This is achieved in the design by making the highest point of the outflow tubing above the sand, thus ensuring that water covers the sand at all times. A diffuser plate placed above the level of the water protects the sand below from damage when water is poured into the system. A "clean in place" technique minimises the need for sand bed removal, simplifying maintenance and increasing continuity of performance [4,5]. As in conventional SSFs, during the ripening process a biolayer (*schmutzdecke*) forms, head loss increases and performance improves. Since the filter is generally charged once daily, a portion of the charged water remains in the BSF until the next charge. It is reported that approximately 143,000 BSFs were in operation as of June 2007, serving an estimated 858,500 users in 36 countries. For the year, they produced nearly 1.3 billion litres of drinking water (at 25 L/unit/day) [5]. Recently, based on performance and sustainability criteria, Sobsey et al. [6] identified biosand filters as most effective method among the five different household treatment technologies, and as having the greatest potential to become widely used and sustainable for improving household water quality to reduce waterborne disease and death. Health impact studies in different countries have shown substantial reduction in childhood diarrhoeal diseases in households using biosand filters [7,8].

Several studies have been reported on the performance of the BSFs in reducing bacteria, viruses and turbidity from feed water. Bacterial removals have been reported to vary from no apparent removal to 99% depending on operating conditions and filter ripening [9,10]. Elliott et al. [11] demonstrated that reductions of bacteria and viruses tend to be lower than those reported for traditional SSF. While slow sand filters have been shown in the laboratory to reduce faecal bacteria by 2–3 $\log_{10}$, viruses by 1.5–2.0 $\log_{10}$ and *Cryptosporidium* oocysts by more than 5

* Corresponding author. Tel.: +91 98258 75162.
E-mail address: mansoorahammed@gmail.com (M.M. Ahammed).

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$\log_{10}$ [12], tests of the biosand filter both in the laboratory and in the field achieved a mean reduction of *E. coli* of less than 2 $\log_{10}$ [11,13]. Baumgartner et al. [10] reported total coliform removal by biosand filter in the range 58.3–99.7% under different operating conditions and at different sample collection points. Murphy et at. [14] reported *E. coli* removal in the range 0–99.99% in a field study in Cambodia. Bacterial removal generally increases substantially with repeated charges and time in use as filters matured, and increased retention time of water in the filter bed. Ripening (maturation) typically takes 4 to 6 weeks. It is also known that cleaning the biofilter also diminishes its microbial removal efficiency possibly because the disturbed biofilm is less efficient or because cleaning helped bypass microbially active zones of the filters [15]. The impaired performance of the filters persisted for approximately 4–6 weeks following cleaning. These findings raise questions about the assurance of safe water provided to users of BSF before ripening and after cleaning [11], and indicate the need for modification of BSF in order to improve the performance of the BSF during the ripening period and also after cleaning the filter.

Metallic oxides/hydroxides are good sorbents of bacteria and viruses. This has led to the development of metal hydroxide-coated sand as a filtration/adsorption medium in water and wastewater treatment. Iron oxide-coated sand (IOCS) was shown to be highly efficient in removing different microorganisms and turbidity [16–20]. For example, column packed with sand coated with ferric and aluminium hydroxides removed greater than 99% of *E. coli, V. cholerae,* poliovirus and coliphage MS-2 from dechlorinated tap water [18]. Ahammed and Chaudhuri [16] reported that IOCS removed 80–84% heterotrophic bacteria, 94–96% *E. coli* and 73–83% poliovirus from canal water.

A few attempts have been made to modify the BSF to improve its performance. These include introduction of pre-filter as a pretreatment unit, and use of smaller size filter media to reduce the filtration velocity. However, the results were not very promising [21]. In the present study, the biosand filter was modified by introducing a thin layer (10 cm) of IOCS in the sand bed. Performance of the modified BSF was compared with a BSF in a long-duration study spanning about four months, during which bacteria and turbidity reduction, flow rate variation, physico-chemical characteristics and other relevant parameters were monitored. A canal water and a spiked tap water were used as feed.

2. Materials and methods

2.1. Filter installation

Locally available river sand was selectively sieved, using a set of sieves for sand analysis and the portion passing through 1.18 mm sieve and retained on 0.150 mm was used in the present study as filter media. The filter media had an effective size of 0.23 mm and a uniformity coefficient of 3.1. The sand was washed several times using tap water until the wash water became clear. Two biosand filters were used in this study, a conventional BSF (BSF) and a modified BSF (MBSF). Plastic containers obtained from the local market were used for constructing the filters. The containers were first cleaned with tapwater, and were filled with 5 cm deep underdrain gravel (4.75–12.0 mm size), 5 cm of coarse sand (1.18–4.75 mm size) separation layer and 40 cm of sand (0.150–1.18 mm size) layer in succession. In the case of MBSF, the 40-cm sand layer included a 10-cm iron oxide-coated sand (IOCS) layer in the middle of the sand layer. Water was present in the containers before loading the filter media to avoid any occurrence of air spaces and short circuiting. The outlet pipe was provided in such a manner that a water depth of 5 cm is maintained over the filter media. A plastic diffuser plate was placed on the lip of the filter to avoid disturbance to the top layer of sand during daily charging of the filter with raw water. Schematic diagram of the filter is presented in Fig. 1. The filters had a pore volume of 19.1 L.

2.2. Preparation of iron oxide-coated sand

The sand used for coating had similar specifications as that used in BSF. The sand was soaked in 8% nitric acid solution, rinsed with deionised water to pH 7.0, and dried at 105 °C in preparation for surface coating. In the present study the method suggested by Liu et al. [22] was employed for coating the sand with iron hydroxide. In order to produce iron hydroxide-coated sand, 500 g of ferric chloride was dissolved in 1 L of deionised water. The iron solution was mixed with 3 L of acid-washed sand. This was then dried for 48 h at 90 °C. Coated sand was neutralised in 5 L of 5 M sodium hydroxide solution for 24 h and then dried at 90 °C for 24 h. After drying, the coated sand was rinsed with deionised water to pH 7.0, redried at room temperature.

2.3. Water

Water from two different sources was used in the study: i) Tap water collected from tap of Environmental Engineering Laboratory of the Civil Engineering Department of Sardar Vallabhbhai National Institute of Technology, Surat, India and ii) canal water from an irrigation canal near ONGC Colony, Surat, India. Since the tap water had no/very little bacterial concentration, spiking of the microorganism was necessary. Further, since turbidity and the total organic carbon concentration were also low in tap water, sterilised sewage and locally available clay were added to the feed water. It was thought that addition of sewage would simulate the presence of wastewater in typical drinking water sources of developing countries and accelerate the ripening process [11]. However, since the canal water had sufficient levels of turbidity and microorganisms no spiking of microorganisms or turbidity was needed. Canal water was collected weekly and stored at 4 °C until one day prior to feeding. Spiked tap water was prepared daily. Characteristics of the two feed waters during the study period are presented in Table 1.

2.4. Filter operation

Two filtration experiments, one with spiked tap water (Run 1) and the other with canal water (Runs 2) as influent were conducted consecutively. BSF and MBSF were operated in parallel under identical conditions. The filters were charged once a day with raw water prepared daily. The schedule of the filter operation is presented in Table 2. In the case of 40-L charge, since the reservoir of the filters could hold only about 25 L, the second 20 L was poured one hour after the first 20 L water was poured. The filters were cleaned after Run 1 as described in Section 2.6. The test was conducted at room temperature, and water temperature varied in the range of 26–34 °C during the testing period.

2.5. Sample collection

Different types of samples were collected at different intervals for analysis: (1) influent water; (2) grab samples of the filtered water taken throughout a daily charge, and (3) composite sample of the filtered water to measure the daily average concentration of different water quality parameters. Grab samples were analysed for microbial quality and dissolved oxygen concentration while composite samples were analysed for all relevant water quality parameters including turbidity, pH and microbiological quality. Sample bottles of volumes of 1 L were used to collect water samples from each filter. Water samples for microbiological testing were collected in sterilised bottles. Tests showed insignificant die-off rates for challenge microorganisms after overnight storage at room temperature. Thus, the effects of time on microbial survival were regarded as negligible in this study.