In-home performance and variability of biosand filters treating turbid surface and rain water in rural Kenya

Erica R. McKenzie, Marion W. Jenkins, Sangya-Sangam K. Tiwari, Jeanie Darby, Wycliffe Saenyi and Charles Maina Gichaba

ABSTRACT

Thirty low-income Kenyan households using turbid river and relatively cleaner rain water participated in a 6 month in-home Biosand filter (BSF) performance study comprised of surveys and monthly monitoring of BSF influent and effluent water for turbidity and fecal coliforms (FC). River–river (influent–effluent) sample pairs \( n = 155 \); 90% of observations resulted in average BSF instantaneous FC and turbidity removals of \( 1.41 \log_{10} (96.1\%) \) and 32.5%, respectively. Cumulative distributions of influent and effluent quality demonstrated unambiguous improvement of river water but rain water improvement was limited and less reliable. Filter performance varied considerably within and across units. A hierarchical set of hypothesized factors affecting filter bacterial performance variability was assessed. BSF effluent FCs were positively correlated with influent (flush water) FCs and influent and effluent turbidity, and negatively correlated with turbidity applied to-date and days since maintenance. Interrupted use and moving the BSF negatively impacted effluent quality. Households with children age 6–10 collecting BSF filtered drinking water, or with more members, had higher effluent FCs. BSFs fed only river water performed better, on average, than mixed-source filters. Implications for BSF implementation in developing countries are discussed, including aqueous chemistry aspects of performance.

Key words | aqueous chemistry, bacteria removal, fecal coliform, household water treatment, multivariate modeling, point-of-use, socio-economic status, turbidity, water hardness

INTRODUCTION

Household drinking water treatment is increasingly recognized as one component of public health interventions to reduce water- and sanitation-related diarrhea disease burdens in low-income communities in developing countries (WHO 2007). One low cost option is the Biosand filter (BSF), a slow sand filter adapted for intermittent batch-operated household use capable of reducing bacteria (1–2 log), viruses (0.5–1 log), and protozoa (4–5 log) as well as turbidity (Buzunis 1995; Palmateer et al. 1999; Stauber et al. 2006; Elliott et al. 2008; Jenkins et al. 2011).

Steady growth in BSF implementation in over 70 developing countries (CAWST 2012) has been accompanied by evidence of sustained use in the home, sometimes years later, but often also by lower than desired removal performance and high variability compared to lab ratings. There are many potential causes of poor performance of in-home household water treatment, particularly a biological system like the BSF. However, little attention has been directed at systematically investigating the observed high variability and very poor performance of some BSF units in field settings to identify practical remedies or design solutions to assure the highest possible quality of drinking water for the growing population of current and future BSF users.

This study examines in-home operation and performance of BSF units used to treat highly turbid river water and relatively cleaner rain water in 30 households in rural and peri-urban communities in the River Njoro watershed in the Rift Valley, Kenya, as part of a BSF health impact
study (Tiwari et al. 2009). Bacterial removal, turbidity removal and effluent quality are analyzed across the 50 BSF units, using fecal coliform (FC) as the bacterial indicator organism. A set of factors affecting in-home BSF performance is proposed and associations with observed BSF bacterial removal and effluent variability assessed. The analysis aims to elucidate biophysical mechanisms and other factors that may account for the high variability of in-home BSF performance observed in this setting and elsewhere, to support evidence-based improvements to BSF design, implementation, and guidelines to reduce occurrences of poor in-home performance.

METHODS AND MATERIALS

Study location, households and filter unit

Participating households had the following characteristics: resident of a diarrhea risk neighborhood, river water as their primary or secondary drinking water source, and having a child under 5 years of age, 8th grade or less maternal education, and low income. Household socio-economic, demographic, water, sanitation, and hygiene characteristics were collected during eligibility screening and baseline surveys.

The BSF in this study was the circular concrete design (height = 0.95 m, diameter = 36 cm) containing 50 cm of river sand ($d_{10} = 0.15$ mm, uniformity coefficient = 2.4) and a 5 cm static water level (Tiwari et al. 2009). Female heads were instructed on filter operation, including treated water use, waiting eight hours between feeding 20 L batches of water, and the wet harrowing method of filter maintenance to restore slow flow rates. The raw water applied to the BSF at sampling time is referred to as ‘influent’ or ‘flush’ water, while the treated water stored in the BSF pore space which exits the BSF drain is referred to as ‘effluent’ or ‘pore’ water.

Monitoring and data collection

For 6 months following installation in March 2007, trained local BSF technicians visited households monthly to collect BSF influent (1 L, representative) and effluent (250 mL, mid-batch) samples, measure flow rate, and record sample sources, days since maintenance, and filter problems.

Sample collection and lab methods are detailed in Tiwari et al. (2009) and summarized in the supplemental material, available online at http://www.iwaponline.com/washdev/005/050.pdf. A user questionnaire on BSF operation, maintenance, management, usage, perceived performance, and valuation was administered twice during the study, providing data for unit-level factor variables described later.

Data preparation

Samples yielding 0 observable colony forming units (CFU) in 100 mL were set to 0.5 CFU for log calculations and designated as having <1 CFU/100 mL. Influent and effluent turbidity and FC concentration and calculated instantaneous filter removals were screened for outliers. A water sample was excluded if it was an extreme outlier ($P_{75}$ or $P_{25} \pm 3.(P_{75}-P_{25})$; $P_x = x$th percentile value) among samples of the same water source (i.e., river or rain) and river location (i.e., upper or lower) along with all values for that sampling event. Ten FC and five turbidity sample event sets were eliminated, resulting in 168 and 173 valid paired influent-effluent sample sets, respectively.

BSF bacterial and turbidity performance

FC concentration values are reported and analyzed in $\log_{10}$ units of CFU per 100 mL, assuring normal distributions of residuals in statistical analyses (Weiss 2011). FC removal was measured in $\log_{10}$ units as the difference between the $\log_{10}$ influent and effluent CFU/100 mL quantities. Turbidity is reported in nephelometric turbidity units (NTU) and amount removed as percent of influent NTU. In-home BSF performance is reported overall and separately for rain and river water, the two drinking water sources treated by households during the study.

Factors affecting bacterial performance variability overall and between filters

In-home BSF bacterial performance was evaluated using a hierarchical approach in which explanatory factors in the study setting were proposed and categorized from proximal to distal (degrees of separation) in their influence on BSF performance, starting with biophysical mechanisms, household...
BSF usage, household BSF management, household environment, household socioeconomics, and community setting (Figure 1; see supplemental Table S-1 for factor variables, available online at http://www.iwaponline.com/washdev/003/050.pdf.). Data for biophysical mechanistic (BPM) factors (measurable and varying biological and/or physical parameters which affect BSF performance) was mostly collected at each monitoring visit so these factors could be evaluated to explore variability among sampling measurements. Thus, effluent FC variability was evaluated using all (river and rain) valid samples ($n = 168$) in bivariate analysis of individual BPM factors, followed by multivariate analysis of BPM factors having bivariate significance. FC removal variability was evaluated for the 155 river–river influent–effluent pairs in bivariate analysis of individual BPM factors only. Community context, household socioeconomic and environmental factors, and household BSF management and use factors were largely static and therefore more relevant to the analysis of unit-level performance variability among the 30 BSF households. Three unit-level metrics were derived for this purpose: a unit’s minimum, average, and maximum performance, and evaluated against household and community-level factors in bivariate analyses of unit FC removal and effluent quality. Bivariate analyses consisted of one-way analysis of variance or linear regression, and associations at the $p = 0.10$ level are described as being significant in this exploratory study.

Multivariate analysis of effluent quality used generalized estimating equations (GEE), accounting for correlation of samples taken from the same unit. Independent BPM factor variables with a bivariate $p$-value $\leq 0.3$ were included in the initial GEE model and retained if their $p$-value $< 0.05$ in the GEE analysis. Various models were tested and the corrected quasi-likelihood under independence criterion (QICC) used to select the best multivariate model of observed BSF bacterial effluent quality. Analyses were conducted using SPSS (IBM, Armonk, NY).

## RESULTS AND DISCUSSION

### BSF bacterial performance

Households used river and rain water with their BSF. A total of five or six monthly influent–effluent sample pairs were collected from each household. FC results are reported in Table 1. On average, compared to rain, river water had significantly higher influent ($1.55 \log$ more FC; 2-tailed $p < 0.001$) and effluent bacteria (0.83 log more FC; 2-tailed $p = 0.002$). Rain influent was comparable to river effluent for FC (2-tailed $p = 0.894$). Only 2.3% of untreated influent samples were no or low risk ($0$ or $< 10 \text{CFU/100 mL}; \text{WHO 2006}$) for drinking compared to 28.5% of BSF treated effluent samples ($8.9\% < 1 \text{CFU/100 mL}$ and $19.6\% 1–10 \text{CFU/mL}$). Just 3.6% of BSF effluent samples were very high risk ($> 1,000 \text{CFU/100 mL}$) compared to nearly half of influent samples (all river).

A challenge for evaluating BSF removal of in-home placements is the impracticality of sampling the same batch of water before and after treatment, referred to as ‘representative sampling’ hereafter. This and other in-home BSF performance studies have not employed representative sampling, limiting determination of true removal efficiencies. Under non-representative sampling, cumulative probability distributions are useful to visualize the breadth of filter performance. Figure 2(a) displays cumulative distribution curves by water source of influent and effluent log FC. The river curves do not cross, demonstrating unambiguous improvement to river FC quality by BSF treatment. The
Table 1 | BSF influent and effluent concentration and removal during 6 months of monitoring of 30 household BSF placements in rural Kenya for FC (upper half) and turbidity (lower half)

<table>
<thead>
<tr>
<th>Sources</th>
<th>Influent (CFU/100 mL)</th>
<th>Effluent (CFU/100 mL)</th>
<th>Log Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent</td>
<td>Effluent</td>
<td>n</td>
</tr>
<tr>
<td>River</td>
<td>River</td>
<td>151</td>
<td>850.35</td>
</tr>
<tr>
<td>River</td>
<td>Rain</td>
<td>3</td>
<td>1037.26</td>
</tr>
<tr>
<td>Rain</td>
<td>River</td>
<td>3</td>
<td>11.08</td>
</tr>
<tr>
<td>Rain</td>
<td>Rain</td>
<td>11</td>
<td>29.57</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>168</td>
<td>634.16</td>
</tr>
</tbody>
</table>

$^a$Geometric mean.

$^b$Geometric standard deviation.

$^c$Corrected mean: sample pairs with different sources, the influent value is replaced with the mean of the matching source’s influent samples; e.g., river–rain samples have the influent value replaced with mean rain values.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Influent (NTU)</th>
<th>Effluent (NTU)</th>
<th>Percent removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent</td>
<td>Effluent</td>
<td>n</td>
</tr>
<tr>
<td>River</td>
<td>River</td>
<td>155</td>
<td>40.69</td>
</tr>
<tr>
<td>River</td>
<td>Rain</td>
<td>3</td>
<td>56.67</td>
</tr>
<tr>
<td>Rain</td>
<td>River</td>
<td>3</td>
<td>14.17</td>
</tr>
<tr>
<td>Rain</td>
<td>Rain</td>
<td>12</td>
<td>10.58</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>173</td>
<td>38.42</td>
</tr>
</tbody>
</table>

$^a$Corrected mean: sample pairs with different sources, the influent value is replaced with the mean of the matching source’s influent samples; e.g., river–rain samples have the influent value replaced with mean rain values.

Figure 2 | Bacterial concentration cumulative distribution plots of (a) BSF influent and effluent water by source (unpaired), and (b) BSF instantaneous removal for river–river influent-effluent pairs plotted with each removal value’s associated influent and effluent bacterial concentration.
Far greater variability was observed for removal and efficiency (Table 1, Figure 2(b)). Across the 155 river–river sample pairs, FC reductions were observed in 94.6% of cases and $1 \log$ removed 64.1% of the time. On average river–river instantaneous sample pairs (90% of observations) produced substantial FC removal ($1.4 \log \sim 96\%$) near the higher end of reported average values (e.g., Stauber et al. 2006; Jenkins et al. 2011) but with a large standard deviation. Rain–rain instantaneous sample pairs (6.5% of observations) produced FC removals averaging $0.9 \log$ (87%). Low rain removals may arise from comparatively low rain influent FC (Stauber et al. 2006).

Removal was recalculated for mixed-source sample pairs by replacing the influent value with the geometric mean influent concentration of the correct source water. ‘Corrected’ removals (Table 1) produce positive mixed-source averages in-line with same-source pairs. However, as these suggest and statistical analysis confirms, quality of flush water (sampled influent) used to push out pore water affected effluent quality, indicating mixing occurred in the BSF unit, and explains the difference in average instantaneous removal for a given water source, between same- and corrected mixed-source values. Mixing (referred to as breakthrough or imperfect plug flow) associated with a ratio of batch to pore volume greater than 1 was observed by Elliott et al. (2008).

Figure 2(b) displays the cumulative distribution of river–river instantaneous FC removal with each value’s influent and effluent FC measurement plotted at the same position. Far greater variability was observed for removal and effluent FC than influent FC. Nine sample pairs (5.4%; all sources) had negative FC removal. These were characterized by comparatively low influent FC, on average $1.7 \log$ lower than average influent of the 159 positive removal pairs (2-tailed $p < 0.001$). Negative values, expected for rain flush paired with river pore water, occurred for one of the three rain–river pairs, 3/11 rain–rain and 5/151 river–river pairs. Possible reasons for negative (uncorrected) instantaneous removals include mis-matched flush-pore water qualities, breakthrough, a contaminated exit pipe, and shedding or poor attachment. The latter involve mechanisms that are influenced by changes in aqueous chemistry discussed later.

Among the 15 < 1 CFU/100 mL effluent samples, nine came from the 10 filter units that only had river water applied (15.8% of all samples from river only filters), demonstrating BSF ability to treat heavily contaminated, highly turbid surface water. Among households that applied river and rain water to their BSF unit, six of 111 effluent samples (5.4%) contained <1 CFU/100 mL.

Variability within a filter unit was high for influent, effluent, and removal as previously observed (Murphy et al. 2010). Influent FC was most consistent, with an average household relative standard deviation (RSD) of 25%, but greater for those switching sources. Household effluent FC variability was high (RSD ~ 70%) regardless of switching. Household removal RSD ranged from 23 to 186%, averaging 60%.

**BSF turbidity performance**

BSFs in this study were fed average influent of 38.4 NTU, far above influent turbidity reported in published BSF field and lab performance evaluations thus far (typically $<10$ NTU). BSF influent and effluent turbidity and instantaneous turbidity removals and variability are reported in Table 1 (lower half). Corrected removals for mixed-source pairs used the arithmetic mean influent turbidity of the appropriate source. On average, river water had significantly more turbidity in influent (29 NTU more; 2-tailed $p < 0.001$) and effluent (13 NTU more; 2-tailed $p = 0.001$) than rain. Treated river water had significantly more turbidity than untreated rain water (13 NTU more; 2-tailed $p = 0.001$). Cumulative distributions of influent and effluent turbidity (not shown) follow similar patterns as FC (Figure 2(a)); BSF treatment unambiguously improved river water turbidity but frequently increased rain water turbidity.

Instantaneous turbidity removals demonstrated patterns similar to FC, with extreme positive and negative uncorrected removals observed for mixed-source pairs. River–river pairs averaged 32.5% turbidity removal (16.8 NTU removed), a considerably lower percentage than reported...
elsewhere (Duke et al. 2006; Earwaker 2006; Stauber et al. 2006; Jenkins et al. 2011), but consistent with controlled laboratory testing of this BSF unit with River Njoro water prior to in-home placement. Lowest instantaneous turbidity removals (all pairs), including many negative values, occurred in the first month of monitoring. Turbidity removal improved thereafter. Filter age (youth) may have played a role in these results. Additionally, River Njoro water contains minimal hardness (6 mg L$^{-1}$ as CaCO$_3$), contributing to decreased removal of organic matter and particles as discussed further.

**Factors associated with BSF bacterial performance variability**

BPM factors associated with BSF effluent FC and instantaneous FC removal variability are reported in Table 2. BPM and other factor categories (Figure 1) associated with variations in unit level metrics for FC effluent and removal performance across households are discussed below (detailed unit-level factor associations and $p$-value results found in Table S-2 of the supplementary material, available online at http://www.iwaponline.com/washdev/003/050.pdf). Bivariate analyses with at least one association with a $p$-value $\leq 0.10$ have been reported in Table 2 (and Table S-2) and are referred to as 'significant' associations.

**Associations with removal overall and unit removal metrics**

Instantaneous FC removal for river–river pairs (last three columns, Table 2) was most significantly associated with influent FC concentration and cumulative to-date applied FC (summed FC in influent samples to-date, indicative of treating more river than rain water). Both factors displayed a positive relationship with log removal. The filter unit – a categorical variable representing the collective household practices, environment, and filter construction/installation – was significantly associated with bacterial removal performance, indicating household-level and filter configuration/set-up effects on performance.

At the unit level, maternal education was significant for a unit’s average and maximum removal, and secondary education (highest level observed) was associated with the greatest removal for both. Higher paternal education was significantly associated with higher unit minimum removal. Community (representing environmental, societal, and BSF training/technician effects) was significant for average, Table 2 | Significance of bivariate associations between individual factors and study-wide BSF effluent FC using all pairs ($n = 168$) and BSF instantaneous FC removal using river–river pairs ($n = 155$)

<table>
<thead>
<tr>
<th>Factor Category – Variable</th>
<th>Log([fecal coliform]$_{\text{effluent}}$) Trend (nominal):</th>
<th>Log fecal coliform removal Trend (nominal):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$-value</td>
<td>slope (scale)</td>
</tr>
<tr>
<td>Community context factor – community</td>
<td>0.043</td>
<td>n</td>
</tr>
<tr>
<td>Biophysical mechanistic factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pore water source</td>
<td>0.002</td>
<td>River worse</td>
</tr>
<tr>
<td>Flush water source</td>
<td>0.002</td>
<td>River worse</td>
</tr>
<tr>
<td>Pore/flush water source pairs</td>
<td>0.012</td>
<td>River–river worst; rain–rain best</td>
</tr>
<tr>
<td>Influent flush water fecal coliform concentration (log)</td>
<td>0.000</td>
<td>0.483</td>
</tr>
<tr>
<td>Effluent pore water turbidity concentration</td>
<td>0.016</td>
<td>0.013</td>
</tr>
<tr>
<td>Cumulative to-date applied turbidity</td>
<td>0.000</td>
<td>–0.003</td>
</tr>
<tr>
<td>Cumulative to-date applied fecal coliform (log)</td>
<td>0.418</td>
<td>–0.175</td>
</tr>
<tr>
<td>Days since cleaned</td>
<td>0.001</td>
<td>–0.006</td>
</tr>
<tr>
<td>Filter unit/household</td>
<td>0.083</td>
<td>n</td>
</tr>
</tbody>
</table>

* = differences among individual communities and households;
NA = not applicable; removal analysis restricted to river–river sample pairs.

$p$-value $> 0.1$: time to filter 1 L, sand type, installation filter time, tribe, location in basin, influent turbidity, turbidity removal (%), turbidity removal ($\Delta$ NTU).
maximum, and minimum removal. Total removed turbidity (all six samples summed, proxy for BSF lifetime applied turbidity) was significant and positively associated with a unit’s average and maximum removal. Number of rooms, a socio-economic and BSF placement hygiene indicator, was associated with better removal for all three unit indicators, and significant for average removal. Reported use of treated BSF water for drinking was positively associated with all three indicators, and significant for maximum removal. Similarly, large-volume households (treating $\geq 50$ L d$^{-1}$; range 30–60 L d$^{-1}$) were better performers on all three indicators, and the association was significant for maximum removal. Large volume users in this setting passed more river water through their filters, which may have provided more regular doses of nutrients, oxygen, and suspended fine particles to enhance the filter’s mechanical and biological removal processes.

**Associations with overall effluent bacterial performance**

Among BPM factors associated with effluent FC (Table 2), effluent (pore) and influent (flush) source were each highly significant. River pore and flush water produced higher effluent FC concentrations compared with rain water. Flush FC was highly significant and positively associated with effluent FC (slope = 0.5). Both influent and effluent turbidity were positively associated with effluent FC but effluent turbidity showed a much stronger and significant association. Higher flush water turbidity resulted in increased effluent bacteria, suggesting breakthrough. However, cumulative to-date applied (influent) turbidity was highly significant, and negatively associated with effluent FC concentration. As more turbidity was applied over the operating life of the filter, effluent bacterial concentrations decreased. In this setting, more turbidity likely correlated with more river water (and less rain water) being fed to the filter, and thus also with high levels of fecal contamination (e.g., nutrients) and particles. These may have contributed to biofilm growth or development of an inorganic filter cake (i.e., accumulation of fines on the sand surface), both of which can improve removal.

Time since maintenance was highly significant and resulted in improved effluent bacterial quality; however, the effect was small ($-0.006 \log$ CFU/100 mL per day). Buildup of fines with time increases mechanical screening and surface area for biofilm establishment, improving bacterial removal and decreasing BSF flow rates.

Study participants were instructed to maintain the filter (wet harrowing method) when they needed to restore an adequate flow rate. While the longest reported time since maintenance was 161 d, the median was 14 d. During technician training, translation of ‘maintenance’ into the local term ‘cleaning’ resulted in significant misunderstandings of when to do wet harrowing. At least one technician transmitted maintenance as a ‘cleaning’ activity, resulting in some users regularly ‘cleaning’ the first 3–5 inches of filter sand initially. Corrective instructions were issued during month two. Finally, as before, filter unit/household, representing differences in household practices, environment, and filter installation, was significantly associated with effluent FC. Evidence of systematic effects on performance from household-level and unit-specific differences are described next.

**Associations with unit effluent bacterial quality**

Flow rate at installation, an indicator of initial sand packing geometry and tested to ensure no ‘short-circuiting’, was significantly associated with a unit’s maximum (worst) effluent concentration. Lower initial flow rate (increased time to filter 1 L) resulted in lower unit maximum bacterial effluent concentration (improved performance).

Two households reported interruptions in BSF use (1 and 21 d). BSF units used without interruption performed better for all three effluent FC metrics, with the findings significant for a unit’s average and minimum (best) effluent. Household member involvement in BSF drinking water collection was significantly associated with effluent bacterial quality. No households reported extraction by children age <6, but two households reported extraction by children age 6–10 and their units performed significantly worse for all three effluent quality metrics. BSF performance may be compromised by the involvement of children (e.g., exit pipe contamination). Potential for poor exit pipe hygiene through hand contact as a contributor to poor effluent bacterial quality was further explored in relation to the household population. Number of children age <6 was not significantly associated with any metric, but the number of members in...
other age groups and larger household size were significantly associated with higher effluent FC concentrations (i.e., more members resulted in lower quality effluent). Indicators of higher socioeconomic status were generally associated with better effluent, in particular for a unit’s maximum FC concentration. Significant factors for better effluent included: vehicle/motorcycle ownership ($n = 1$) and greater number of rooms (range 1–7). Greater number of rooms in this setting resulted in filter placement in more hygienic locations relative to animals, children, and other contaminating activities. Households that rented ($n = 5$) had significantly higher (worse) unit maximum effluent FC concentration compared to owners or living in a house owned by an employer/relative.

Among other factors examined, some consistent but non-significant (i.e., $p \geq 0.10$) trends were observed which may represent potential areas to investigate more rigorously in future in-home BSF performance evaluations. Upper watershed households were mostly subsistence farmer-pastoralists, relied almost exclusively on river water, yet consistently produced effluent with fewer FCs. Households that used only river water ($n = 10$) had lower (better) effluent FC concentrations for all three metrics. Among them, eight were in the upper watershed. Un-moved BSF units performed better than moved ones, high incidence of ‘cleaning’ (4/mo) was associated with the worst (highest) FC levels, and BSFs with no reported problems (flow, clarity, taste) produced higher quality effluent. One household was observed to block the BSF outlet and was among the worst performers. Following re-education on use/management, no household reported or was observed to block the BSF outlet. Households with a housewife mother had units that performed better than units in households where the mother was also engaged outside the home. Large volume users (treat $\geq 50$ L d$^{-1}$) had better unit effluent FC for all three metrics, with this factor significant for the minimum (best). Households that reported greater use of BSF for drinking had better effluent quality (lower FC) on all three metrics (none significant). Finally, concrete floors ($n = 4$) were associated with higher effluent FC concentrations (not significant) but these households were more likely to be in the mid-watershed where source switching was widespread and misinformation about maintenance was greatest.

**Multivariate model of BSF effluent bacterial quality**

The minimized QICC multivariate GEE model of overall effluent bacterial quality as a function of biophysical factors is:

$$\log \left( \frac{\text{CFU}}{100 \text{ mL}} \right)_{\text{eff}} = 0.706 + \beta_{\text{source}} + 0.189 \cdot \log \left( \frac{\text{CFU}}{100 \text{ mL}} \right)_{\text{in}} + 0.003 \cdot D + 0.007 \cdot T_{\text{in}} - 0.003 \cdot T_{\text{in-TD}}$$

where eff and in are effluent and influent, respectively, $\beta_{\text{source}}$ represents the pore water source and equals 0.529 and 0.000 for river and rain water, respectively, $D$ is days since maintenance, $T_{\text{in}}$ is influent (flush) turbidity, and $T_{\text{in-TD}}$ is the summation of applied turbidity to-date. Each factor is significant at $\alpha = 0.05$ except days since maintenance ($p = 0.156$). Influuent and effluent source and quality were important (i.e., $\beta_{\text{source}}$, log (CFU/100 mL)$_{\text{in}}$, and $T_{\text{in}}$) as was past BSF use (cumulative applied turbidity) and management (maintenance frequency). One household had not cleaned their filter the entire study duration (161 d), equating to 0.5 log reduction (improvement) in effluent FC from allowing the schmutzedecke to grow undisturbed for $+5$ months. One NTU more of cumulative to-date applied turbidity, in this setting, shows potential for a similar positive impact on BSF effluent quality as another day of schmutzedecke growth. Maximum to-date applied turbidity was 515.5 NTU, equating to 1.5 log improvement in effluent FC.

**Aqueous chemistry implications**

As previously noted, turbidity removal from River Njoro water was lower than observed in other BSF studies, despite FC removals consistent with other BSF studies. These disparities may be explained by aqueous chemistry and interparticle forces (i.e., van der Waals attractive and electrostatic repulsive forces). Lake Nakuru basin geology, including the River Njoro watershed, is principally volcanic and typically dominated by silica. Both volcanic rock and the bacteria likely have negative zeta potentials (a measure of particle charge; electrostatic repulsion) at neutral pH values. River Njoro water is nutrient rich from heavy fecal
pollution and erosion but very soft. The biological layer in the filters likely thrived with the plentiful nutrients in the influent and successfully removed FC (likely through a combination of predation and adsorption). However, the low hardness of the water hindered adsorption of larger and non-biological particles (WeberShirk & Dick 1997a, b).

In lab testing, FC shedding was observed for an extended time after the BSF feed water source was changed from River Njoro water to groundwater and comparatively poor FC removal was observed among rain–rain samples in the household placements. These observations may also be explained via aqueous chemistry and interparticle forces, depending on solution pH and ionic strength. Lake Nakuru basin is alkaline (high pH far from particles’ isoelectric point) which results in increased negative zeta potential (~particle charge) and corresponding increases in electrostatic repulsion between bacteria and the filter media which could lead to bacterial shedding upon a change of feed to local groundwater. Rainwater is very low ionic strength and typically slightly acidic. Low ionic strength results in longer range electrostatic repulsive forces which could lead to shedding; substantial negative average turbidity removals were also observed for rain–rain samples, suggesting increased repulsive forces.

CONCLUSION

Many studies have demonstrated that BSFs improve water quality; however, the improvement and effluent quality are variable, often falling short of the WHO <10 CFU/100 mL low risk drinking water level (WHO 2006). In this study, water quality was generally improved; overall mean FC removal was 1.36 log (95.6%), and overall mean effluent concentration was 27.9 CFU FC/100 mL. Turbidity removal (18%) was lower than reported elsewhere, likely a result of extremely soft River Njoro water causing high interparticle repulsion.

Analyses of factors affecting BSF performance reveal that more educated households, and those with more rooms, fewer members, a stay-at-home mother, and where no children age 6–10 collected BSF drinking water, as well as other indicators of greater socioeconomic status, have better performing filters. These findings suggest a particular need for attention to in-home BSF usage, management and potential contamination sources and practices, particularly among households of lower socioeconomic status and with children to assure high BSF performance.

Components of BSF setup, use, and management were also found to impact effluent quality. High initial flow rate was correlated with the worst effluent water. Higher applied daily volumes and more applied turbidity associated with river water resulted in cleaner effluent over the long term. Frequent filter maintenance was associated with decreased effluent quality. Moving the BSF or interrupting daily use of the BSF both negatively impacted the filter's effluent quality. Finally, filters operated exclusively with highly turbid, nutrient rich, yet soft, River Njoro water performed better overall than filters operated with river and rainwater. Aqueous chemistry provided useful insight on bacterial shedding and poor turbidity removal associated with source water quality characteristics and switching in this study.

These study findings have implications for (a) source water analysis and filter testing with attention to aqueous chemistry prior to in-home placement for any water BSF households might use; (b) quality control over filter installation and set-up, and (c) fool-proof instructions and even accessory tools, to assure minimal frequency and proper technique for filter maintenance. Incorporating post-filtration disinfection into the BSF design, for example via an attachment to the exit pipe, could be an avenue to overcome lower than rated BSF performance observed in household settings.

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REFERENCES


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