Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28900

275 (2022) 207–220
November

Optimization of removal thermotolerant coliform (TTC) from drinking water using bio-sand filter (BSF) Masafer Yatta/Hebron West Bank – occupied Palestinian territories

Ahmed Al-Sayara[a], Amer Marei[b,*], Saed Khaya[c], Ben Sonneveld[d]

[a]*Al-Quds University-Jerusalem, West Bank, email: ahmedsayareh@gmail.com*
[b]*Al-Quds University-Jerusalem, West Bank, email: marei@staff.alquds.edu*
[c]*Palestinian Technical University-Tulkarem, West Bank, email: saed.khayat@gmail.com*
[d]*Vrije Universiteit Amesterdam, Neatherland, email: b.g.j.s.sonneveld@vu.nl*

Received 7 April 2022; Accepted 29 August 2022

ABSTRACT

In Massafer Yatta–Hebron Governorate, around 1,400 Palestinian people are herding sheep and goats and live in caves and movable tents without a water network or sewer system. In the winter season rainwater is harvested for drinking purposes and stored in underground cisterns. Yet, sporadic water quality tests indicated a contamination level of micro-organisms ranging from 20 to 100 Colony Forming Unit (CFU/100 mL). In this area, rife with political conflicts, connection to a piped network seems unsure, at best, and calls for using natural and available resources to filter clean and potable water are justified. This study addresses these social requests by testing the efficiency of Thermo Tolerant Coliform removal (TTC) using bio-sand filters (BSFs) under real conditions in a full factorial design of experiment. The dependent variables are charge volume, age of BSF, the outside temperature, residential time, turbidity, water sources, and free chlorine contents. The independent variables are volume of BSF and sand grain size. The result shows that the 5 h residence time of water and the media age of more than one month is significant to remove the TTC from drinking water with *P*-values of 0.0439 and 0.0089, respectively. Water with 500 CFU/100 mL, TTC needs more than 5 h residence time to reduce the TTC below the 10 CFU/100 mL. Turbidity and sources of drinking water did not affect the removal of TCC, yet, using 0.18 mm effective sand grain size was significant in removing TTC. The adoption of a 23 h water residency period was the most important of all operating parameters including the 0.18 mm effective sand size to remove about 99.8% of TTC. This study recommends a BSF that generates more than 20 L in 23 h, and the BSF Schmutzdeke should be replaced every 4 y.

Keywords: Bio-sand filter; Drinking water; Factorial design; Thermotolerant coliform

1. Introduction

There are approximately 1.1 billion people worldwide who are deprived from safe drinking water. This lack of access, combined with insufficient water supplies, is to blame globally for a stunning 4 billion cases of diarrheal diseases [1]. Sadly, every year, more than 500,000 children die because of diarrhea [2]. The occupied Palestinian territories are no exception. Approximately 12.3% of its population lacks access to public water supply [3] and diarrhea is a leading cause of outpatient visits and hospitalizations. According to the Vulnerability Profile Project (VPP) [4], approximately 297,900 Palestinians live in 532 residential sites in Area C (under Israely military control) without a

* Corresponding author.

Presented at the 1st Palestinian-Dutch Conference on Water, Sanitation and Hygiene (WASH), and Climate Smart Agriculture (CSA), 5–6 September 2022, Nablus, Palestinian Authority

1944-3994/1944-3986

regular and safe supply of drinking water through the public water grid [5]. Given the current political situation there is little hope that permission will be granted to connect these families to a piped water network, in the short term.

A marginalized group of Palestinians living in Masafer Yata – Hebron Governorate, a C-area, unconnected to a formal water grid and chlorination system, will be the focus of our study. The main prevailing economic activities of the Masafer Yata people consists of herding and rainfed agriculture. Most of their water needs are covered by rainfall water harvesting techniques during the winter season. Yet, collected water from house yards is in most cases contaminated with debris and residual animal manures. According to the Comet-Me (Community Energy Technology-Middle East) database, TTC levels in cisterns ranges from 20–1,000 colony forming unit CFU/100 mL exceeding by far the tolerable levels of <10 CFU/100 mL. Hence, there is a dire need for the Masafer Yata households to assure a safe water supply with available natural filtering methods that can replace conventional and proven contamination removal techniques. Additionally, the performance of natural filtering techniques has to be tested under various biophysical conditions to assess their applicability at sites in Masafer Yata with different conditions. In this study, we aim to address these research gaps by testing the efficiency Bio-sand filters (BSFs) for Thermo Tolerant Coliform removal (TTC) under real conditions using a full factorial experimental design.

The BSF is a widely used technology for water treatment in developing-country at the household level. It has been introduced in at least 36 countries around the world, with over 500,000 people using it [7]. BSF appears to be an appropriate technology for biological water treatment in the marginal area of the Palestinian territories. It is simple to operate, low maintains cost, affordable, durable, made from local materials, has zero energy consumption, and is sustainable [8]. Moreover, under the prevailing living conditions of the people in Masafer Yata, BSF out performs other multi-stage water treatment methods. Compared to Rapid and Slow Sand Filter techniques because BSF is easy to transport, easy to operate, and has low maintenance cost [6].

Physical parameters such as sand effective size, residence time, and charge volume have been found to influence BSF performance [9]. Janjaroen [10] stated that the high removal rate of various influent contaminants in BSF is due to interception, sedimentation, diffusion, and adsorption to sand and the biological layer. Napotnik et al. [11] reported that filter ripening (medium age), higher influent bacterial concentration, finer sands, lower heads, and shorter supernatant of 3–5 cm all resulted in improved bacterial removal. Stevik et al. [12] reported that the most important physical parameters influencing *E. coli* immobilization infiltration columns were reduced grain size and increased specific surface area.

The Center for Affordable Water and Sanitation Technology (CAWST) [13], and Ngai et al. [14] investigated the effect of temperature on BSF performance and reported that warm filters removed 17.8% more *E. coli*. Arnold et al. [15] reported that colder temperatures reduced the BSF efficiency removal of tested indicator species on average. The bio-layer, or Schmutzdecke, within the top few centimeters of the BSF, is important for pathogen removal and is regarded as critical and highly effective for filter performance due to physical and biological mechanisms involving enhanced sieving, adsorption, deposition, and predation. Janjaroen [10] reported that several microbiologically mediated filtration mechanisms, including predation, scavenging, adsorption, and bio-oxidation. Haig et al. [16] reported also that a large microbial diversity of 36 phyla and 239 families in slow sand filters, with Proteobacteria as the dominant phylum. According to Napotnik et al. [11] the BSF performance is highly dependent on filter ripening with microbial communities over several weeks of operation, these communities require sufficient nitrogen, phosphorus, and carbon.

The interaction of pathogens and sand particles was found to be positively influenced by divalent cations found in hard water. The well-known cation exchange capacity (CEC), particularly Ca^{+2}, was proposed as a mechanism for high pathogen aggregation and attachment to the sand surface via cation bridge formation. In the presence of natural organic matter (NOM), the cation bridge was also improved [10]. CEC, on the other hand, was described by Stevik et al. [12] as a limiting factor in using the BSF in water purification because fluid shear forces in the filter system may be stronger than chemisorptions due to high flow velocity. Furthermore, dissolved oxygen (DO) is regarded as a more important chemical parameter, with high DO concentrations being important for increased microbial activity.

The difference between a slow sand filter (SSF) and BSF is the operation of the BSF with the elevation of the outlet locates above the sand layer which keeps the sand column saturated with water and allows the development of the biofilm (schmutzdeke) at the top of the sand filter. The biofilm consists mostly of organic material, very fine sedimentary particles, fungi, protozoa, algae, aquatic insects larvae, and bacteria. The removable micro-organisms in treated water depend on the biological action of the schmutzdeke [6].

Rapid sand filter (RSF) is also considered a multi-stage water treatment used by water service providers such as municipalities, that need to treat large volumes of water, this system needs land area for operation, where coarse sand and other granular media to remove particles as well as flocculated particle. The two types of rapid sand filters are the gravity type, and pressure type [6]. In the study area where residents live in small families over a large area, and in many cases, they move to other places, the BSF-technology is the best choice for water treatment because it was easy to transport, easy to operate, and low maintenance cost.

In this research, BSF operation conditions are characterized and optimized using the design of the experiment software (DoE) [17], a set of applied statistics under controlled condition to evaluate the factors that control the value of a parameter or group of parameters. The effect of ten operating parameters on BSF efficiency for Thermotolerant Coliform (TTC) removal is investigated; these are residence time, charging volume, media age, turbidity, water source, temperature, sand grain size, count of TTC in the input water, chlorine contents, and inflow rate.

2. Material and methods

Applying the Design of the Experiments (DoE) has the advantage that with fewer experiments needed information could be gained to estimate the interactions between the parameters, as well as to develop an empirical model. A few steps are required; first define the signal Delta y (Δy), which is the minimum change you wish to detect in your response. In this research TTC is the measurement tool (response) for the BSF treatment efficiency, and, second, to determine the noise (σ) inherent in the investigated process. Noise is determined through a review of historical data or similar processes. In the present study, we pooled all BSF-TTC results available between 2015 and 2019 from the Comet-Me database, where the standard deviation; σ was 29. The third is to calculate the signal/noise ratio ($\Delta y/\sigma$), this value determines the power of the chosen design. The power is the probability of detecting the desired signal in the given noise.

Factorial designs are primarily used to determine which factors are critical to the process. This can take the form of screening for a few critical factors among a large number of possibilities or characterizing how known factors interact and affect the process individually. The Regular Two-Level Factorial Design-Builder allows you to create designs with two levels of the full factorial and regular fractional factorial. This led to investigating the relationship between two and twenty-one factors using four to 512 runs. This collection of designs demonstrates an efficient method for sorting through a large number of variables to identify the critical few ones [18]. When numeric factors are present, center points can be added to determine curvature. Adding center points enables a statistical check of the planar two-level factorial model's goodness-of-fit. The average response value obtained from the actual center points is compared to the center point's estimated value obtained by averaging all the factorial points. If there is curvature, the actual value of the center point will be either greater or less than the value predicted by the factorial design points. The curvature of the surface may indicate that the design is approaching an optimal region. The following section describes the DoE for each factor included in each experiment:

2.1. First DoE

In this experiment, a two-level factorial design 2^{5-1} with 4 center points was used to characterize the influence of the following physical factors: residence time, charge volume, media age, water source, and turbidity are three numeric factors, center points were added for additional statistical checks and the search of optimal regions within factor levels if curvature was discovered (Table 1). Twenty-four runs were designed for this experiment.

2.2. Second DoE

In this experiment, a replicated regular two-level factorial design 2^{5-1} was used to characterize the influence of the following physical factors: temperature, residence time, charge volume, effective size, and inflow rate. While maintaining a constant middle-temperature level throughout the experiment was not possible, center points were excluded (Table 2). Thirty-two runs were designed for this experiment.

2.3. Third DoE

In this experiment, the influence of chlorine content in tap water on BSF efficiency was investigated. Unlike rain harvest water, tap water used by the residence in the study area contains trace amounts of free chlorine. An optimal design was used for this experiment (Table 3). This option generates a custom fractional factorial design with difficult-to-change factors that require randomization restrictions. Customization options include defining a model specifically for your application and giving you more control over the number of groups and runs. Seventeen runs were designed for this experiment [19].

2.4. Fourth DoE

Response Surface Method (RSM) and Behnken Box Design (BBD) [20] were used in this experiment similar to those who used it in their studies conducted on BSF [21]. Seventeen runs were designed to mathematically model the interaction of influent TTC count, media age, and residence time on BSF efficiency (Table 4). RSM methodology is based on statistical and mathematical methods that can be used for modeling and analyzing engineering problems. For any process, there is a yield or response. This response is reliable on the changes and interactions of certain parameters [22]. If parameters can be measured the RSM can be expressed as follows:

$$Y = f\left(x_1, x_2, x_3 \ldots . x_k;\ \beta_0, \beta_1, \beta_2, \ldots \beta_n\right) \tag{1}$$

Table 1
Characterization of experiment No 1

Factor name	Units	Type	Low	Medium	High
Residence time	h	Numeric	1	3	5
Charge volume	L	Numeric	4	6	8
Media age	month	Numeric	1	37	73
Water source	Type	Category	Harvest 1		Harvest 2
Turbidity	NTU	Numeric	1	10	20

Table 2
Characterization of experiment No 2

Factor name	Units	Type	Low	High
Temperature	°C	Category	25	33
Residence time	h	Numeric	2	4
Charge volume	L	Numeric	6	8
Effective size	mm	Category	0.18	0.23
Inflow rate	h	Category	Flow meter	Manual charge

Table 3
Tap water influence characterization No 3

Factor name	Units	Type	Low	Medium	High
Charge volume	L	Discrete	6	7	8
Water source	Type	Nominal	Tap water	Mixed	Harvest

Table 4
BSF optimization experiment

Factor name	Units	Low	Middle	High
Residence time	h	1	12	24
Media age	month	4	40	77
Influent TTC count	CFU/100 mL	10	500	1,000

where Y is the response of the process and X are variables and β stands for parameter and β_0 is a constant.

Assuming all the independent parameters are continuous and controllable with a negligible error, there is a chance to approximate and mathematically model the relationship between independent variables and response.

BBD is a second-order rotatable design with three levels of each parameter. BBD is depicted as a cube with a central point and the middle points of the edges [20]. The number of experiments (N) needed to develop BBD is defined as:

$$N = 2k(k-1) + C_o \tag{2}$$

where k is the number of factors and C_o is the number of central points.

2.5. Analytical methods

Table 5 summarizes the analytical methods for testing parameters in this paper.

2.6. BSF design

The BSF design is shown in Fig. 1 according to the specifications of the Center for Affordable Water and Sanitation Technology (CAWST) [23]. The filter is a 90 cm long and 25 cm diameter cylinder pipe. A 10 cm layer of small gravel is installed at the bottom, followed by another 10 cm layer of larger gravel and a 40 cm layer of sieved and treated sand. The filter has approximately 19 L of sand and is capable of receiving 8 L maximum.

3. Results and discussion

3.1. First DoE

Harvest water 1 and 2 were used to feed water into the filters in this experiment (Annexes Table A1). The

Table 5
Analytical methods

Parameter	Analytical methods
TTC	Delagua Microbiological Kit
PH	HI-98129 pH-meter
Electrical conductivity (EC)	WWT
Free chlorine	The Eutech Colorimeter C 201
Turbidity	Nephelometric tube method
Porosity	CAWST bio-sand filter guidelines
Effective size and uniformity coefficient	CAWST bio-sand filter guidelines

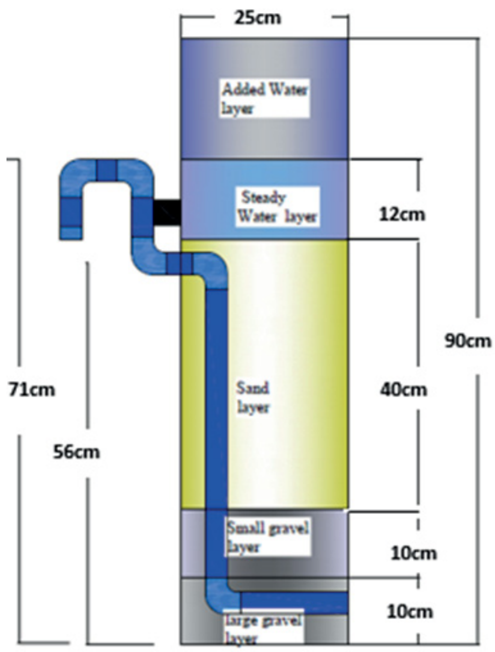

Fig. 1. Biosand filter design.

TCC counts in the charged waters were 414 ± 67 and 497 ± 57 CFU/100 mL, respectively. Only residence time and media age were significant in the analysis of results using Design-Expert software (Analysis of Variance ANOVA), with P-values of 0.0439 and 0.0089, respectively. Charge volume, turbidity, or changing the water source had no effect (Fig. 2). The residence time was compared to levels of 1, 3, and 5 h in this experiment. TTC was reduced by 50 CFU after increasing the residence time from 1 to 5. Pathogens are eliminated by the BSF based on their time spent in contact with sand particles. The ability to absorb or trap more pathogens increases as water retention in sand media increases. These findings are consistent with CAWST recommendations of a minimum of 6 h between each dosing cycle [24]. Despite this, the 5 h residence time operation format was not completely effective when the water source had a TTC concentration of around 500 CFU/100 mL. The TTC after BSF results in this experiment were higher than the acceptable water quality limits of 0–10 CFU/100 mL. The average TTC was 22.62 CFU/100 mL in effluent samples. Although there was no significant difference in TTC removal when charge volume was increased, this was not in contradiction to its important role in the filtration process as has been described by Baumgartner et al. [25]. Based on the current BSF design in the methods, the total sand volume in BSF can be around 19.6 L with the porosity of each filter being measured at the end of all experiments. In this experiment, the average filter porosity was 0.43, which equates to about 8 L of water retained in 19.6 L of sand. This explains why charge volume is unimportant in this study. The entire charged volume was, roughly speaking, contained in the BSF sand layer when the filter was filled 4, 6, or 8 L.

Most previous studies focused on filter age ranging from 1 to a few months, but in this experiment, we involved filters with ages ranging from 1 to 6 y. The results of the present study showed an increase in BSF efficiency after a month of operation. BSF is thought to be effective for many years at a time. In the current study, we found that BSF is most effective at reducing TTC to acceptable water quality (less than 10 CFU/100 mL) in the range of 28 to 46 months of age. With a factorial model, the current experiment design had center points. The points were used to determine whether the data had a curvature. The significance of curvature was determined by the P-value of 0.0018. To define the source of curvature, the software suggested augmenting the generated model to the response surface method (RSM). This augmentation revealed that BSF TTC removal may decline after a media age of more than 55 months when residence time is 5 h (Fig. 3).

Finally, the turbidity in the range of 1–20 NTU had no significant effect on BSF removal efficiency. However, BSF must reduce turbidity to acceptable levels (less than 5 NTU) to ensure that water is safe to drink.

3.1.1. First DoE fit statistical analysis

The DoE is used to estimate the reliability of experiment results. The hypothesis was whether changing the levels of the assigned parameters for this DoE will induce a significant change on the efficiency of the BSF for TTC removal or not. The assigned parameters and their levels appear in Table 1. The model itself was significant in this experiment, with a P-value of 0.009; however, this significance requires validation. A variety of fit statistic values are provided

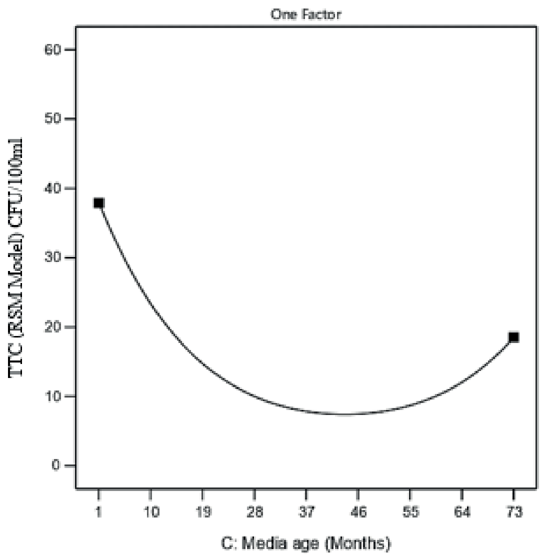

Fig. 3. Influence of media age on TTC removal when residence time is 5 h.

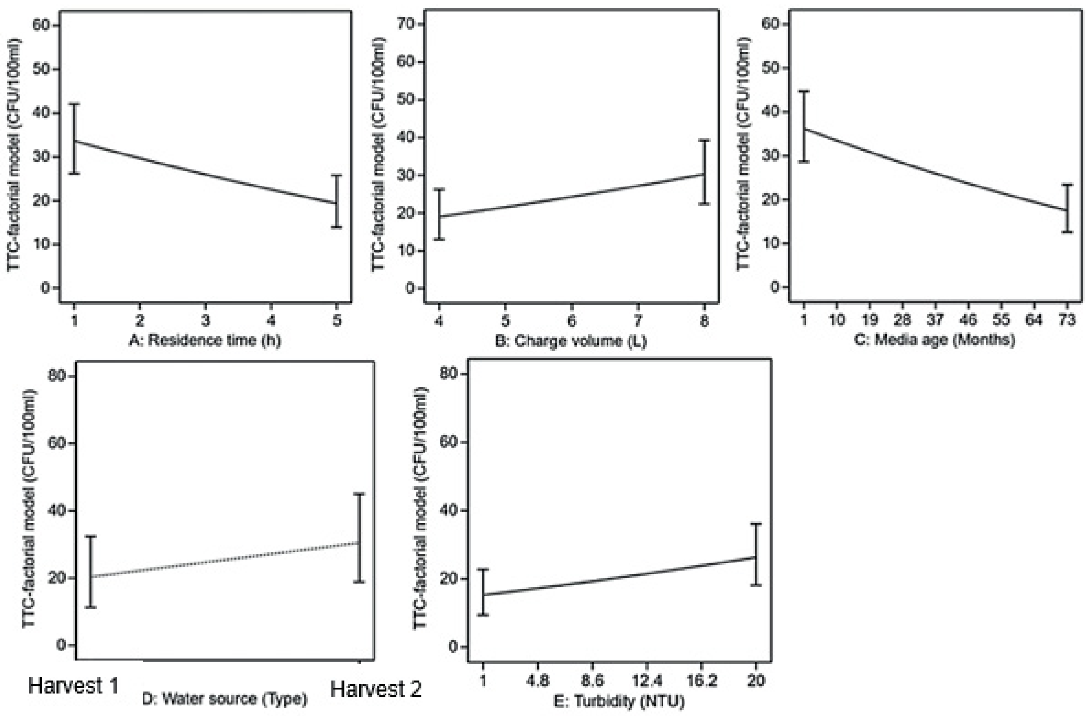

Fig. 2. First DoE (A) residence time, (B) charge volume, (C) media age, (D) water source, and (E) turbidity.

by DoE. The R^2 value indicates how much of the data the model can explain. It was 0.37 in this experiment, which is less than the desired value of >0.8. This was expected given that charge volume, turbidity, and water source were minor factors without influence on the TCC. The combined predicted and adjusted R^2 informs how much variation in the data is explained by our chosen model. Adjusted R^2 is a version of R^2 that considers insignificant factors. It is a popular way to compare the goodness of fit of regression models with different numbers of independent variables. Predicted R^2 is a variant of R^2 that is used to assess the accuracy of a regression model's predictions. The adjusted R^2 and predicted R^2 values should not differ significantly from one another. Calculating the difference between the two values is a good rule of thumb; it should not be more than 0.2. The Predicted and Adjusted R^2 in this experiment were 0.12 and 0.30, respectively. This indicates that both models were in reasonable agreement, implying that the regression model used in this experiment can be used to draw some conclusions.

3.1.2. First DoE statistical modeling

The provided diagnostic construct to understand whether experiments have been successful. The standard plot of residuals confirms the normal distribution of residuals. Residual products should fit a line approximately and should not form a certain shape that indicates non-linearity (Fig. 4). The fundamental concept underlying any normal probability plot is that if the data follow a normal distribution with mean and variance, then a plot of the normal distribution's theoretical percentiles vs. observed sample percentiles should be approximately linear. We create a normal probability plot of the residuals because we are concerned with the normality of the error terms. If the resulting plot is nearly linear, we proceed under the assumption that the error terms are normally distributed.

In any experiment, there are attempts to find out whether outliers have a heavy impact on the generated model. The residual vs. predicted plot was created by the DoE software to aid in the identification of outliers. If no results fall within or above the reference redlines, this indicates the absence of outliers. Fig. 5 plots the predicted values of this experiment's model against the residuals. The random scattering around the zero line (highlighted in black) is easily visible, indicating a good-distributed set of results. The two redlines at the top and bottom of the graph are set to indicate whether any results are outliers. There are no results on the graph that fall over or below the redlines, indicating that there were no outliers in this experiment.

The experiment lasted a few days due to a 5 h residence time in some runs. During the experiment, the residuals vs. run plot is useful for detecting timeline-based trends in the residuals. On the plot, residuals should appear random; if there is a pattern, something went wrong during the experiment. Outliers, which indicate a problem with the model, a required transformation, or a reason to verify or repeat a specific run, are also addressed by the plot. There were no runs outside of the redlines, and the results are randomly scattered below and above the zero-black line, as shown in Fig. 6. A specific error in the experiment, such as a cluster of results above the reference zero line while the rest are below, is usually the cause of patterns. There were no sources of errors during the experiment because no patterns were observed.

In this first DoE, fit statistics and diagnostics revealed that the experiment went well and that no outliers had an impact on the model. Based on the regression model generated from the results analysis, the DoE assists in predicting optimal factor values. The most optimal solution was found to be 5 h of residence time, 7.77 L of charge volume, and 53.3 months of media age (if this result agrees with the other result).

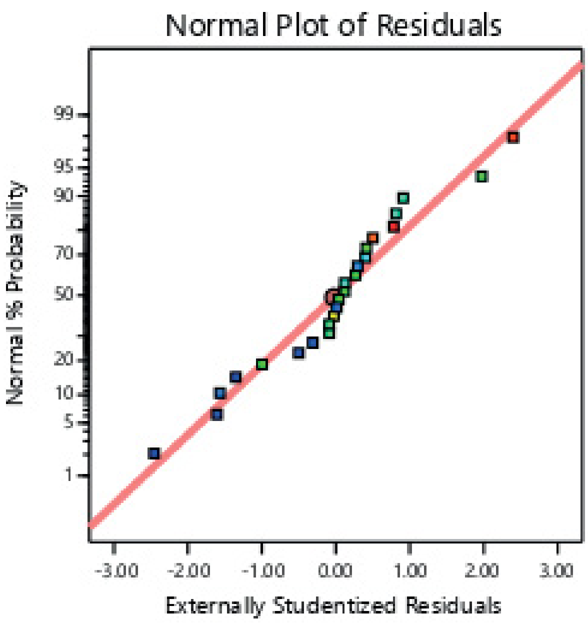

Fig. 4. First DoE normal plot of residuals.

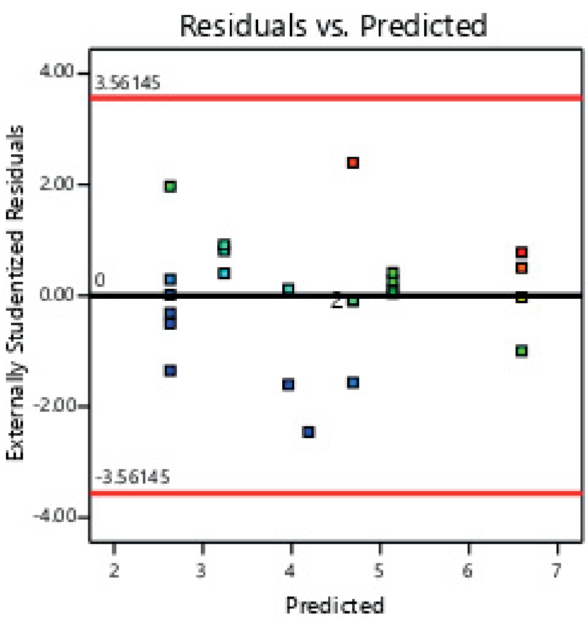

Fig. 5. First DoE residuals vs. predicted.

3.2. Second DoE

3.2.1. Statistical modeling

This DoE aimed for modeling the influence of the parameters temperature, residence time, charge volume, effective size, and inflow rate on BSF efficiency for TTC removal (Annexes Tables A2a and b). The average concentration of TTC in the influent was 477 ± 29 CFU/100 mL, and the average room temperature inside the cave was 25°C ± 0.5°C. The average temperature outside the cave was 33.4°C ± 2°C.

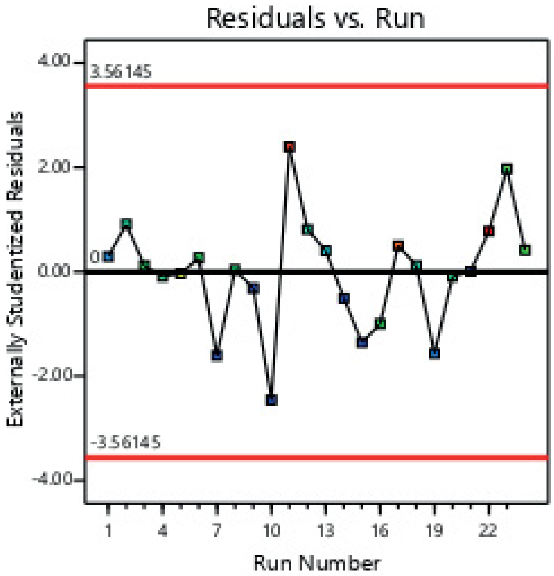

Fig. 6. First DoE residuals vs. run distribution.

The automatic inflow rate was set to 650 mL/min using a water meter. For specified measurement and corresponding run, the meter was allowed to operate for 12 min to fill 8 L and 9 min to fill 6 L. For manual charging, 6 or 8 L are measured using a scaled bucket and then poured all at once into the filter. The effective grain size range between 0.18 and 0.23 mm. Fig. 7 presents the relation between TTC and different parameters. With *P*-values of 0.0016 and 0.0238, respectively, the analysis of variance ANOVA revealed that effective size and residence time had a significant influence on BSF TTC removal. Temperature, inflow rate, and charge volume are not significant.

The effect of temperature on BSF was investigated as both constant and fluctuating. There was no difference in BSF TTC removal when filters were operated at a constant temperature of 25°C or a fluctuating average temperature of 33°C. Fig. 8 presents the effect on TTC removal at 25°C and 33°C, combined with the grain size parameter, where the 0.18 mm was more effective in removing TTC.

The ability of bacteria to be transported through porous media was tested by Webster and N. Fierer [26]. They reported that at room temperature (25°C), permeability impairment was significantly lower than at 4°C. Higher bacterial effluent concentrations were detected at 25°C, which is consistent with this result. A decrease in the Brownian energy of the bacteria at low temperatures should increase coagulation, resulting in both more extensive aggregation and the formation of larger cell clusters, if the residence time increased from 2 to 4, a significant rise in TTC removal was observed. 1–5 h is considered long for a non-linear factor without a middle point, these two levels were used in this experiment. The lack of charge volume is significant due to the sufficient sand pore space, which can hold volumes between 6 and 8 L.

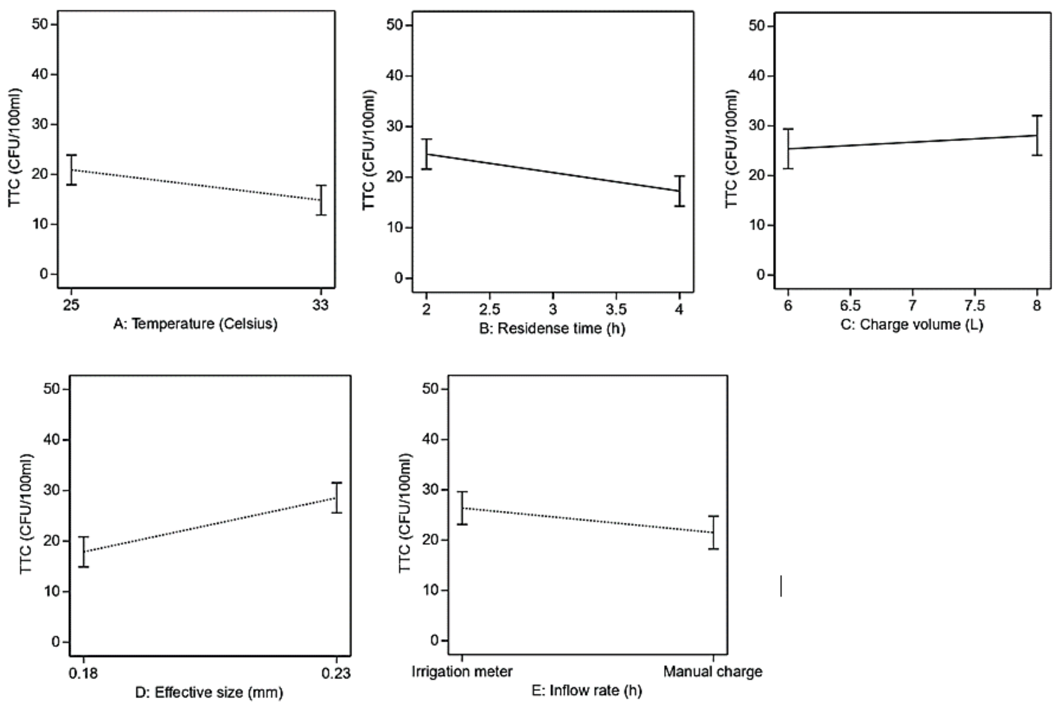

Fig. 7. Second DoE (A) temperature, (B) residence time, (C) charge volume, (D) effective size, and (E) inflow rate.

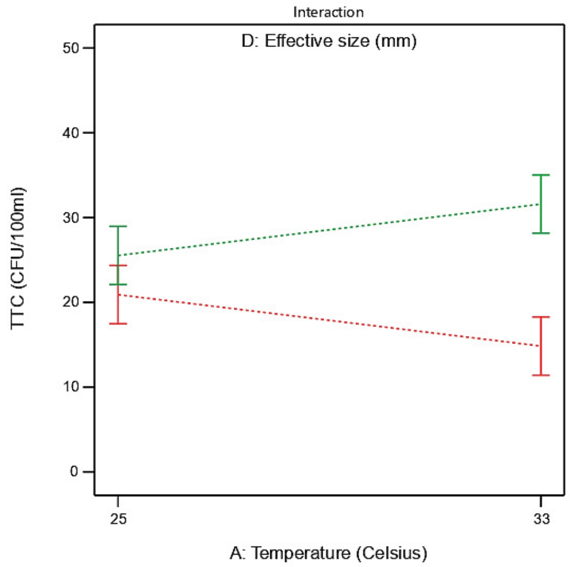

Fig. 8. Temperature-effective size interaction on BSF TTC removal.

The effect of sand grain size of 0.18 had the greatest impact on TTC removal because adsorption and straining, which are responsible for bacterial immobilization in porous media, are mainly controlled by the grain size. The capillary forces in the fine sand can promote a stable water flow through the entire filter volume, so the smallest grain size was found to be the most important physical factor influencing bacterial immobilization. TTC removal can also be linked to the uniformity coefficient. When BSF was tested for grain size, the 0.18 mm, it had an acceptable uniformity coefficient of 1.62, while BSF with a grain size of 0.23 mm had a uniformity coefficient of 2.26. In Fig. 8 the red dots show the interaction of temperature and 0.18 mm effective size; while the green dots show the interaction of temperature and 0.23 mm effective size. When the temperature was 25°C both 0.18 and 0.23 mm had similar efficiency for TTC removal in BSF. However; when the temperature increased to 33°C; the 0.18 mm filter removed more TTC (TTC was lower in effluent water). These findings of sand effective size and uniformity coefficient are consistent with CAWST guidelines. Method of inflow between manual and automatic did not affect the removal of TTC, which is likely due to the mechanical action of the diffuser at the top of the sand filter, regardless of the water inflow method, because the diffusion of water within the sand filter controlled by sand grain size [27].

3.2.2. Fit statistics

The review of fit statistics in this experiment showed a 0.46 R^2 value. Adjusted and Predicted R^2 were in reasonable agreement with values of 0.4071 and 0.3005.

3.2.3. Diagnostic statistics

The residuals' normal plot revealed a normal distribution, most of residuals fit on a straight line, and do not form a specific shape (Fig. 9).

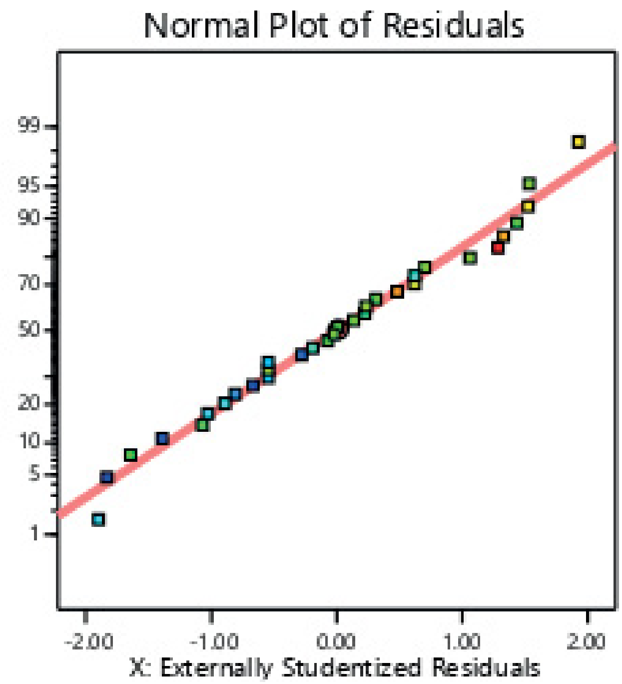

Fig. 9. Second DoE residuals plot.

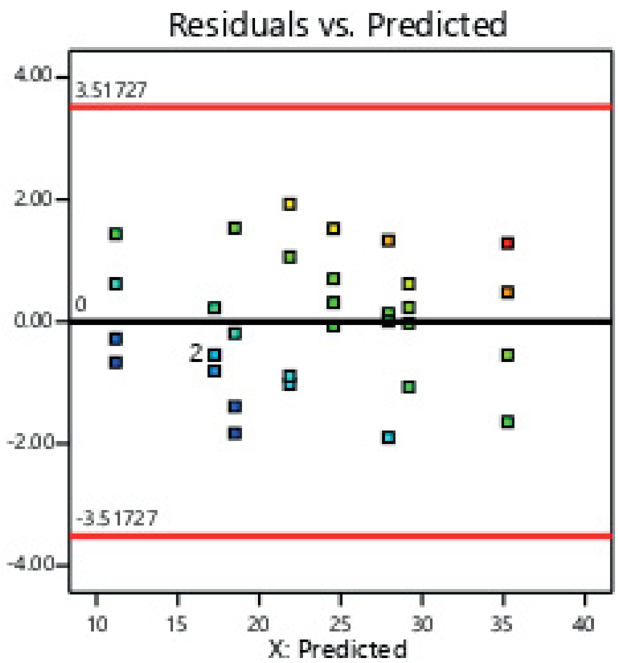

Fig. 10. Second DoE residuals vs. predicted.

Fig. 10 presents the residual vs. predicted, where no outliers had a significant impact on the model. Even though the experiment lasted only a few days, the residuals vs. run plot revealed no pattern, indicating that no time trends had an impact on the experiment (Fig. 11).

The fit statistics and diagnostic constructs revealed that the model can be applied to make predictions, according to the DoE, the most appropriate format for producing a minimum TTC of 11 CFU/100 mL is to run BSF for 4 h, with 0.18 mm effective size, charge volume of 7 L, and temperature of 33°C.

3.3. Third DoE

The effect of chlorination on the removal of TCC, where three different types of water namely tap chlorinated water, harvested water, and 1:1 mixed water (harvested with tap water) was tested (Annexes Table A3). Results are present in Fig. 12. Tap water was used, collected from the distributing public grid point at Twania village.

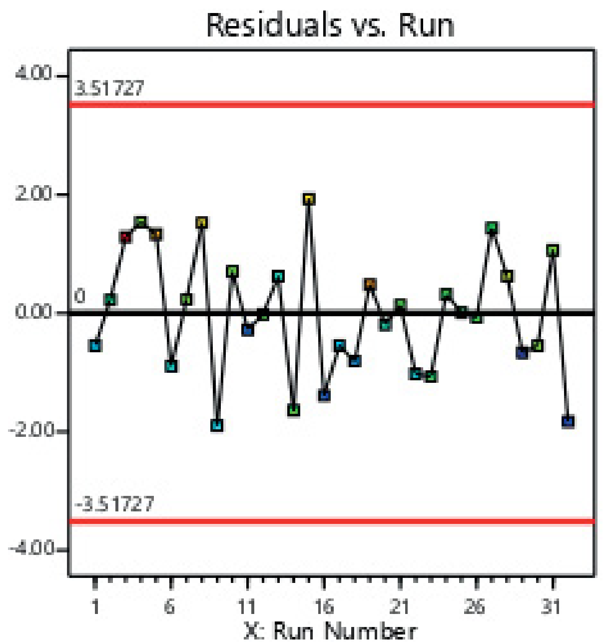

Fig. 11. Second DoE residuals vs. run.

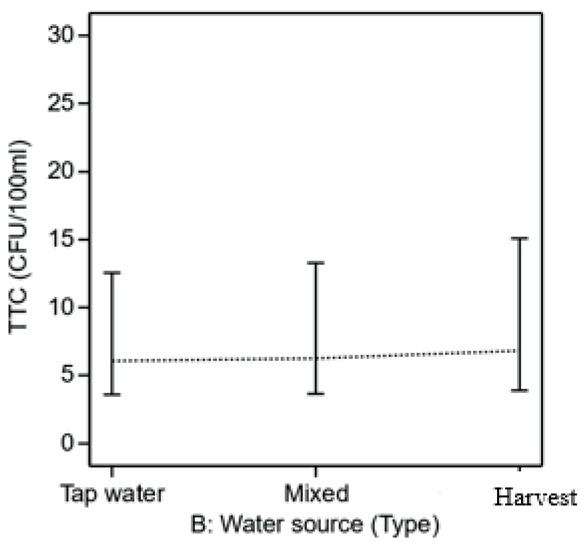

Fig. 12. Tap water, rain harvest, and 1:1 mixed water on BSF TTC removal.

Chlorinated water with average free chlorine contents of 0.19 ± 0.03 ppm, with 0 CFU/100 mL; while the harvested water contained 490 ± 28 CFU/100 mL. A mixture of 1:1 ratio from the two sources was tested with an average TTC of 400 ± 10 CFU/100 mL. ANOVA analysis revealed a *P*-value of 0.8461, which indicates that the low free chlorine content of tap water did not affect the removal of TTC when the total influent batch increased from 6 to 8 L, and the mixing ratio is 1 to 1, we did not find any significance of low free chlorine below 0.2 ppm on the TTC removal. Previous studies show the influence of disinfection processes using chlorine-mono-chloramine on biofilm re-growth in the ground- and surface water. The low chlorine content does not affect attached viable cells susceptibility when it is below 0.35 and 0.2 ppm in surface and groundwater respectively [28].

3.4. BSF optimization experiment

In the first experiment, it was approved that a 5-h residence time and a media age of one month have a significant impact on improving BSF TTC removal (minimized TTC by 50 Δy). In the second experiment, it was approved that finer sand with an effective size of 0.18 mm improves the TTC removal. The significant models of the first and second experiments proposed a volume of 7 L as the desired charge volume. These findings were considered in the current optimization experiment. The charge volume was set to 7 L, and the effective sand size of 0.18 mm was chosen. The BSF's ages were upgraded to 4, 40, and 77 months at this point. The residence time, influent water TTC, and media age were compared to find the optimal residence time needed for complete water treatment (Annexes Table A4). The ANOVA showed that the residence time, and influent count of TTC, as well as their interaction, were all significant *P*-values of 0.0006, 0.0004, and 0.0006, respectively.

The influence of media age has a *P*-value of 0.4295, which is vanished in this experiment, making it insignificant. This is likely due to the use of media age ranging from four to 77 months. Fig. 13 shows the interaction of residence time and influent count. The surface slice of the graphical presentation demonstrates that increasing the residence time to 24 h was required to keep BSF efficiency at 1,000 CFU/100 mL, at that point, the color of the surface slice changed from blue to green to show the difference in TTC response.

3.4.1. Fit statistics

This experiment's fit statistics and diagnostics revealed an R^2 value of 0.92, the data are well explained by the significant RSM model. The adjusted and predicted R^2 were 0.87 and 0.76 respectively, which was a reasonable agreement. The difference between them was less than 0.2.

3.4.2. Diagnostic statistics

The normal plot of residuals has shown that they are normally distributed; they are roughly on a straight line (Fig. 14).

The residuals vs. predicted in Fig. 15 illustrate that there were no significant outliers in this experiment. There were

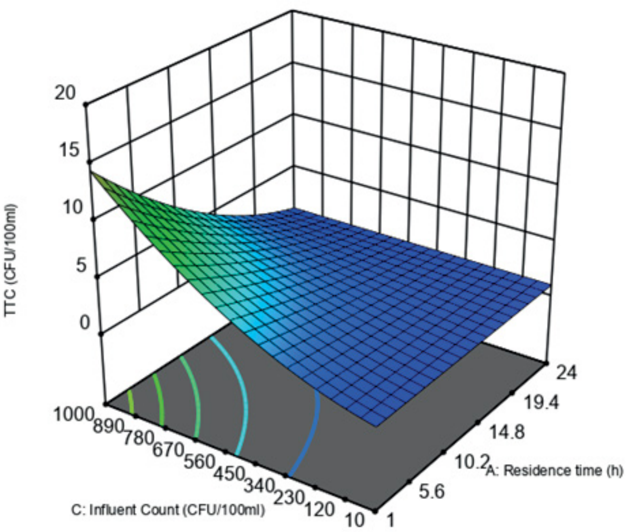

Fig. 13. RSM graphical presentation of influent count and residence time interaction.

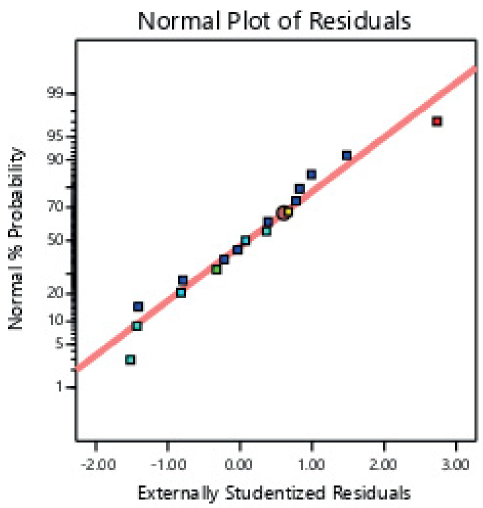

Fig. 14. Residuals of BSF optimization experiment.

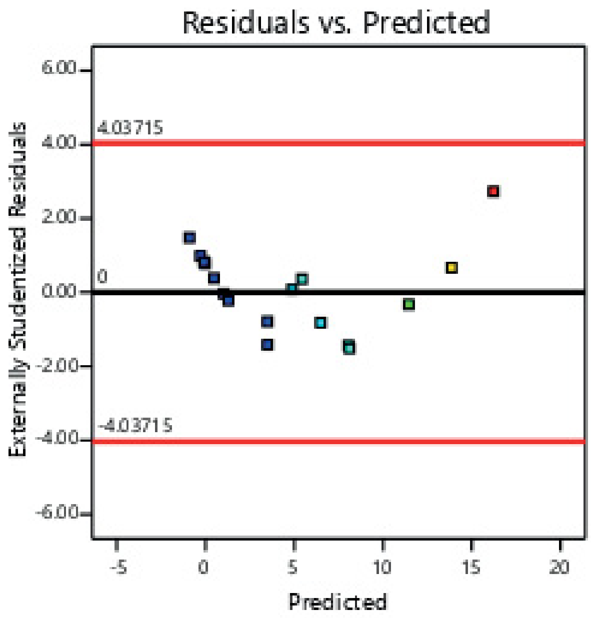

Fig. 15. Residuals vs. predicted residence in BSF optimization experiment.

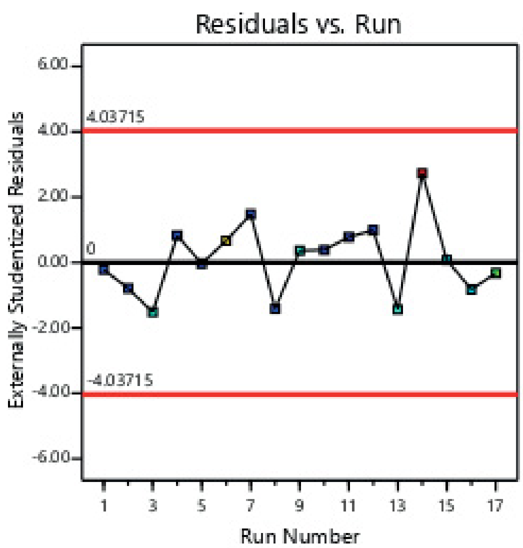

Fig. 16. Residuals vs. run distribution BSF optimization experiment.

no residuals that are either above or below the reference redlines.

The residuals are plotted against the run order in the residuals vs. rRun plot. In this experiment, the distribution of residuals appears random, indicating that no time trends or interruptions occurred during the experiment days (Fig. 16).

The model can be used to make predictions in this experiment, based on the current fit statistics and diagnostic constructs, following are the ideal conditions for maximum TTC removal by BSF. According to the DoE: the influent count was 475.9 CFU with a residence time of 23 h and a media age of 29.9 months. The result is 99.8% TTC removal because the response TTC result under these conditions is 0.953 CFU/100 mL. This optimal residence time value of nearly 24 h was reported by Rajesh Tundia [21] and Nair et al. [29]. The mathematical model developed by RSM can be used to predict response for different levels of each factor, especially when TTC at the water source is high, up to 1,000 CFU/100 mL. TTC must be measured at the water source in this case, and media age is given as the BSF installation date can be documented. The following equation can be used to calculate predicted residence time and tell farmers how many times they can use the BSF to achieve the lowest TTC possible.

$$\begin{aligned}\text{TTC}\left(\text{sqrt}\right) &= 1.63 - 0.6927A - 0.0748B + 0.7313C \\ &\quad + 0.1517AB - 0.7392AC - 0.0981BC \end{aligned} \tag{3}$$

where *A* is residence time per hour (1–24 h); *B* is media age in months (4–77 months); *C* is influent TTC in CFU/100 mL (10–1,000).

4. Conclusions

5 h of residence time is the optimum time to achieve sufficient removal of CFU to be less than 10 CFU/100 mL, but this time was not effective when the TTC concentration was above the limit of 500 CFU/100 mL in this case the best BSF operation residence time is 23 h The BSF media age reach the optimum removal efficiency after one month of operation, Filter age could be reduced to less than 4–6 y using the BSF operation format of once every 1–5 h residence time. The BSF operation format of 12–24 h, on the other hand, extends the filter age to over 6 y. This is due to the BSF operating less frequently (1–2 times per day. Filling the BSF with water from a different source does not affect TTC removal if the TTC concentrations are relatively equal. The TTC removal from BSF is influenced by a smaller effective sand size. To improve BSF efficiency, effective size should be considered alongside the uniformity coefficient.

The BSF is a potential solution to minimize the impact of water-borne diseases especially in the Massafer Yatta area, where harvested water is the main source for domestic purposes, the size of the BSF should be designed according to the family need, a larger filter capable of producing more than 20 L per charge is preferable. Due to the high temperature during the summer season, it is recommended that the BSF should be installed with 0.18 mm effective sand.

Acknowledgments

The authors acknowledge the financial support by the Netherlands Ministry of Foreign Affairs through OKP-ICP-PAA-103455-project. Thanks to Comet-ME staff and team for hosting this research and providing technical assistance. To Stat-Ease for providing design expert software student copy; to Mark J. Anderson for his assistance as a stat-help team member. To Dr. Andre Gohler from National Reference Laboratory for Escherichia coli; for his provided consultation on Thermotolerant Coliform (TTC) preparation and analysis. To Dr. M Mansoor Ahammed from S V National Institute of Technology for his consultation on the optimization experiment design. To CAWST, the Center for Affordable Water and Sanitation Technology for their feedback on filter design and operation.

References

[1] M.D. Sobsey, C.E. Stauber, L.M. Casanova, J.M. Brown, M.A. Elliott, Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world, Environ. Sci. Technol., 42 (2008) 4261–4267.

[2] S. Kumar, A. Haikerwal, S.K. Saxena, Epidemiology of Water-Associated Infectious Diseases, S.K. Saxena, Ed., Water-Associated Infectious Diseases, Springer, Singapore, 2020, pp. 19–25.

[3] N. Mahmoud, W. Hogland, M. Sokolov, V. Rud, N. Myazin, Assessment of rainwater harvesting for domestic water supply in Palestinian rural areas, MATEC Web Conf., 245 (2018) 06012, doi: 10.1051/matecconf/201824506012.

[4] N. Monitor, NGO, 2015, Retrieved January.

[5] S. Jarrar, No Justice, No Adaptation: The Politics of Climate Change Adaptation in Palestine, La balsa de piedra: revista de teoría y geoestrategia iberoamericana y mediterránea, 2015, pp. 1–26.

[6] D.A. Duran Romero, M.C. de Almeida Silva, B.J.M. Chaúque, A.D. Benetti, Biosand filter as a point-of-use water treatment technology: influence of turbidity on microorganism removal efficiency, Water, 12 (2020) 2302, doi: 10.3390/w12082302.

[7] M.A. Elliott, C.E. Stauber, F. Koksal, F.A. DiGiano, M.D. Sobsey, Reductions of *E. coli*, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter, Water Res., 42 (2008) 2662–2670.

[8] M. Kubare, J. Haarhoff, Rational design of domestic biosand filters, J. Water Supply Res. Technol. AQUA, 59 (2010) 1–15.

[9] D.G. Jenkins, L.A. McCauley, GIS, SINKS, FILL, and Disappearing Wetlands: Unintended Consequences in Algorithm Development and Use, Proceedings of the 2006 ACM Symposium on Applied Computing (SAC), Dijon, France, April 23–27, 2006.

[10] D. Janjaroen, Biosand filter (BSF): types and mechanisms behind its efficiency, Appl. Environ. Res., 38 (2016) 87–102.

[11] J.A. Napotnik, D. Baker, K.L. Jellison, Effect of sand bed depth and medium age on *Escherichia coli* and turbidity removal in biosand filters, Environ. Sci. Technol., 51 (2017) 3402–3409.

[12] T.K. Stevik, G. Ausland, J.F. Hanssen, P.D. Jenssen, The influence of physical and chemical factors on the transport of *E. coli* through biological filters for wastewater purification, Water Res., 33 (1999) 3701–3706.

[13] H.G. Hwang, M.S. Kim, S.M. Shin, C.W. Hwang, Risk assessment of the schmutzdecke of biosand filters: identification of an opportunistic pathogen in schmutzdecke developed by an unsafe water source, Int. J. Environ. Res. Public Health, 11 (2014) 2033–2048.

[14] T.K.K. Ngai, B. Coff, D. Baker, R. Lentz, Chapter 42 – Global Review of the Adoption, Use and Performance of the Biosand Filter, N. Nakamoto, N. Graham, M. Robin Collins, R. Gimbel, Eds., Progress in Slow Sand and Alternative Biofiltration Processes: Further Developments and Applications, International Water Association, 2014, pp. 309–317.

[15] N. Arnold, A. Archer, B. Barkdoll, Bacterial adaptation and performance of household biosand water filters in differing temperatures, Water Sci. Technol. Water Supply, 16 (2016) 794–801.

[16] S.-J. Haig, C. Quince, R.L. Davies, C.C. Dorea, G. Collins, Replicating the microbial community and water quality performance of full-scale slow sand filters in laboratory-scale filters, Water Res., 61 (2014) 141–151.

[17] B. Durakovic, Design of experiments application, concepts, examples: state of the art, Periodicals Eng. Nat. Sci. (PEN), 5 (2017) 421–439.

[18] F.H. Abu Elamreen, A.A. Abed, F.A. Sharif, Detection and identification of bacterial enteropathogens by polymerase chain reaction and conventional techniques in childhood acute gastroenteritis in Gaza, Palestine, Int. J. Infect. Dis., 11 (2007) 501–507.

[19] R. Leardi, Design-Expert 6.0, Stat-Ease, Inc., E. Hennepin Avenue, Ste 480, Minneapolis, MN 55413-2726, USA, 2021. Available at: http://www.statease.com/swprice.html

[20] S.L.C. Ferreira, R.E. Bruns, H.S. Ferreira, G.D. Matos, J.M. David, G.C. Brandão, E.G.P. da Silva, L.A. Portugal, P.S. dos Reis, A.S. Souza, W.N.L. dos Santos, Box-Behnken design: an alternative for the optimization of analytical methods, Anal. Chim. Acta, 597 (2007) 179–186.

[21] K. Rajesh Tundia, M.M. Ahammed, D. George, The effect of operating parameters on the performance of a biosand filter: a statistical experiment design approach, Water Sci. Technol. Water Supply, 16 (2016) 775–782.

[22] N. Aslan, Y. Cebeci, Application of Box–Behnken design and response surface methodology for modeling of some Turkish coals, Fuel, 86 (2007) 90–97.

[23] T.K.K. Ngai, R.R. Shrestha, B. Dangol, M. Maharjan, S.E. Murcott, Design for sustainable development—household drinking water filter for arsenic and pathogen treatment

in Nepal, J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng., 42 (2007) 1879–1888.
[24] C.C.V. Chan, K. Neufeld, D. Cusworth, S. Gavrilovic, T.K.K. Ngai, Investigation of the effect of grain size, flow rate and diffuser design on the CAWST biosand filter performance, Int. J. Service Learning Eng., Humanitarian Eng. Social Entrepreneurship, 10 (2015) 1–23.
[25] J. Baumgartner, S. Murcott, M. Ezzati, Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems, Environ. Res. Lett., 2 (2007) 024003.
[26] T.M. Webster, N. Fierer, Microbial dynamics of biosand filters and contributions of the microbial food web to effective treatment of wastewater-impacted water sources, Appl. Environ. Microbiol., 85 (2019) e01142–19.
[27] T.K.K. Ngai, D. Baker, Chapter 43 – Recent Advances in Household Biosand Filter Design, N. Nakamoto, N. Graham, M. Robin Collins, R. Gimbel, Eds., Progress in Slow Sand and Alternative Biofiltration Processes: Further Developments and Applications, International Water Association, 2014, pp. 319–330.
[28] M.N.B. Momba, S. Ndaliso, M.A. Binda, Effect of a combined chlorine-monochloramine process on the inhibition of biofilm regrowth in potable water systems, Water Sci. Technol. Water Supply, 3 (2003) 215–221.
[29] A.T. Nair, M. Mansoor Ahammed, K. Davra, Influence of operating parameters on the performance of a household slow sand filter, Water Sci. Technol. Water Supply, 14 (2014) 643–649.

Annexes

Table A1
TTC results of residence time, charge volume, media age, water source, and turbidity characterization experiment

Run	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response
	A: Residence time	B: Charge volume	C: Media age	D: Water source	E: Turbidity	TTC-factorial model
	h	L	Months	Type	NTU	CFU/100 mL
1	3	6	37	Harvest 1	10	9
2	5	8	73	Harvest 1	20	19
3	5	4	1	Harvest 1	20	28
4	1	4	73	Harvest 2	1	21
5	1	8	1	Harvest 2	1	43
6	5	4	1	Harvest 2	1	30
7	3	6	73	Harvest 2	10	4
8	5	8	1	Harvest 1	1	27
9	3	6	37	Harvest 1	10	5
10	5	4	37	Harvest 1	1	2
11	1	8	73	Harvest 2	20	54
12	5	4	73	Harvest 2	20	18
13	5	8	73	Harvest 2	1	14
14	3	6	37	Harvest 2	10	4
15	3	6	37	Harvest 2	10	1
16	1	4	1	Harvest 2	20	29
17	1	4	1	Harvest 1	1	52
18	3	6	73	Harvest 1	10	17
19	1	8	73	Harvest 1	1	8
20	1	4	73	Harvest 1	20	21
21	3	6	37	Harvest 2	10	7
22	1	8	1	Harvest 1	20	57
23	3	6	37	Harvest 1	10	24
24	5	8	1	Harvest 2	20	32

Table A2a
TTC results of temperature, residence time, charge volume, effective size and inflow rate characterization experiment

Run	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response 1
	A: Temperature	B: Residence time	C: Charge volume	D: Effective size	E: Inflow rate	TTC
	Celsius	h	L	mm	h	CFU/100 mL
1	25	4	8	0.18	Manual charge	13
2	25	4	6	0.18	Irrigation meter	19
3	33	2	6	0.23	Manual charge	45
4	33	2	6	0.18	Irrigation meter	30
5	33	4	8	0.23	Manual charge	38
6	25	4	6	0.23	Manual charge	15
7	25	2	6	0.23	Irrigation meter	31
8	25	2	8	0.18	Irrigation meter	36
9	33	4	6	0.23	Irrigation meter	14
10	25	2	6	0.18	Manual charge	30
11	33	4	8	0.18	Irrigation meter	9
12	25	2	8	0.23	Manual charge	29
13	33	4	6	0.18	Manual charge	16
14	33	2	8	0.23	Irrigation meter	23
15	25	4	8	0.23	Irrigation meter	36
16	33	2	8	0.18	Manual charge	8
17	25	4	8	0.18	Manual charge	13
18	25	4	6	0.18	Irrigation meter	11

Table A2b
TTC results of temperature, residence time, charge volume, effective size and inflow rate characterization experiment

Run	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response 1
	A: Temperature	B: Residence time	C: Charge volume	D: Effective size	E: Inflow rate	TTC
	Celsius	h	L	mm		CFU/100 mL
19	33	2	6	0.23	Manual charge	39
20	33	2	6	0.18	Irrigation meter	17
21	33	4	8	0.23	Manual charge	29
22	25	4	6	0.23	Manual charge	14
23	25	2	6	0.23	Irrigation meter	21
24	25	2	8	0.18	Irrigation meter	27
25	33	4	6	0.23	Irrigation meter	28
26	25	2	6	0.18	Manual charge	24
27	33	4	8	0.18	Irrigation meter	22
28	25	2	8	0.23	Manual charge	34
29	33	4	6	0.18	Manual charge	6
30	33	2	8	0.23	Irrigation meter	31
31	25	4	8	0.23	Irrigation meter	30
32	33	2	8	0.18	Manual charge	5

Table A3
TTC results of tap water influence characterization experiment

Run	Factor 1	Factor 2	Response 1
	A: Charge volume	B: Water source	TTC
	L	Type	CFU/100 mL
1	6	Tap water	3
2	8	Tap water	4
3	7	Mixed	15
4	6	Tap water	8
5	7	Harvest	3
6	6	Mixed	2
7	8	Harvest	4
8	7	Tap water	3
9	8	Mixed	2
10	6	Harvest	3
11	7	Harvest	7
12	7	Mixed	6
13	6	Tap water	12
14	6	Tap water	4
15	8	Harvest	11
16	6	Mixed	7
17	7	Tap water	3

Table A4
TTC results of residence time optimization with influent count and media age experiment

Run	Factor 1	Factor 2	Factor 3	Response 1
	A: Residence time	B: Media age	C: Influent count	TTC
	h	Months	CFU/100 mL	CFU/100 mL
1	24	40	10	1
2	12	40	500	2
3	12	4	1,000	6
4	12	4	10	1
5	24	77	500	1
6	1	40	1,000	15
7	1	40	10	1
8	12	40	500	1
9	12	77	1,000	6
10	12	77	10	1
11	24	4	500	1
12	24	40	1,000	1
13	1	4	500	6
14	1	4	1,000	19
15	1	77	500	5
16	1	40	500	5
17	1	77	1,000	11