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Optimisation of biochar filter for handwashing wastewater treatment and potential treated water reuse for handwashing

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A B S T R A C T

Portable handwashing facilities help fight the transmission of water-borne diseases. However, in places lacking piped drainage systems, handwashing wastewater (HW) is commonly discarded into the ground. This harms the environment and public health and wastes reusable water. This study optimised the biochar filtration parameters such as particle size (0.5–2 mm), filter depth (15–30 cm) and flow rate (1–2.5 L/h) to remove colour, turbidity, phosphates and *E. coli* from HW using Response Surface Methodology. Fifteen configurations studied the impact of filtration parameters on pollutant removal. Quadratic models provided the best fit for pollution removal data. Optimal conditions were 1.25 mm particle size, 30 cm filter depth and 1 L/h flow rate, with predicted removals of 97.06, 97.50, 82.67 and 73.06 % for colour, turbidity, phosphates and *E. coli*, respectively. Biochar filter performance under optimal conditions validated the models. Actual removal efficiencies of 97.63, 99.85, 85.94 and 76.08 % for colour, turbidity, phosphates and *E. coli*, respectively, aligned closely with predicted values. Treated HW quality complied with several international water quality standards. Optimising biochar filtration is crucial for integrating this technology into portable handwashing facilities with potential water reuse, benefiting communities in developing countries with limited handwashing infrastructure and access to water.

1. Introduction

Portable handwashing facilities play a critical role in fighting the transmission of water-borne diseases [1]. During the recent COVID-19 pandemic, several handwashing facilities for individual and group use were deployed across the globe to reduce the transmission of COVID-19 infection among people [2]. From basic structures (e.g., tippy taps) to more advanced constructions (e.g., smart handwashing facilities) [2,3], designs provided hand hygiene in community settings from low- and middle-income countries lacking handwashing infrastructure [4]. Although portable handwashing facilities have been successful in mitigating COVID-19, certain aspects concerning the unsustainable management of the resulting handwashing wastewater have been raised [5].

Handwashing wastewater generated from handwashing practices in portable handwashing facilities without connection to a piped drainage system is commonly discarded into the ground without treatment [6]. Direct release of untreated handwashing wastewater into the soil, freshwater and underground water bodies causes severe environmental and public health consequences. It can result in eutrophication [7], damage to soil properties, plant germination [8] and the breeding of disease-carrying mosquitoes [9]. Beyond the risks of environmental and human health damage, the untreated discharge of handwashing wastewater represents a waste of low-polluted water sources that may be treated and reused on-site [10,11]. Therefore, developing sustainable handwashing facilities with on-site wastewater treatment and treated water reuse is critical to ensure hand hygiene in poor settings lacking handwashing infrastructure, continuous water supply and high-quality water sources [12].

In recent years, various handwashing facilities with on-site wastewater treatment and treated water reuse for handwashing purposes have been developed worldwide. These facilities incorporated strategies for water reuse in handwashing applications in line with the circular economy context and the Sustainable Development Goals (SDG) 6 “Clean Water and Sanitation” [13]. Handwashing facilities such as Gravit'eau (French), Autarky (Swiss) and WOTA (Japanese) rely on a wide range of wastewater treatment systems. These include a sediment/

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grease trap, aerated membrane bioreactor, reverse osmosis, filtration (e.g., using granular activated carbon, silica sand and zeolite), and disinfection (e.g., chlorination or ultraviolet rays) to ultimately achieve high-quality treated water for further reuse in handwashing [11,14–17]. Nonetheless, these systems are usually expensive, high-energy demanding and need high-maintenance [18]. These characteristics limit their applicability to high-income countries. Therefore, the development of affordable and technically feasible cleaning technologies for handwashing wastewater treatment and treated water reuse is still needed for low-and middle-income countries.

The excellent physicochemical properties of biochar have made this adsorbent, formed from the thermal decomposition of organic wastes, a pollutant-removing agent widely employed for greywater treatment [19,20]. As a waste-based adsorbent material, the use of biochar for wastewater is a major synergistic strategy to promote the circular economy in both the water and waste sectors [21]. Recently, Bautista et al. [22] reported the high efficiency of biochar filtration systems in removing physical, chemical, nutrient and microbial pollutants from greywater to enable water reuse in restricted activities (e.g., irrigation, toilet flushing, car/cloth washing). Different ranges of main biochar filtration parameters (e.g., particle size, filter depth and flow rate) have been studied for their influence on greywater treatment [22]. However, there is still no consensus on what are the optimal biochar filtration parameters to improve greywater quality. Furthermore, the optimisation of biochar filtration systems using empirical models to estimate the combined impact of filtration parameters on the removal of pollutants in greywater is still not fully studied. To date, optimisation studies of biochar filtration parameters have been limited to evaluating the removal of physical pollutants (e.g., turbidity and total suspended solids) [23], but water quality parameters associated with appearance, nutrients, and pathogen contamination have not been adequately studied yet.

To address this knowledge gap, this study aimed to optimise the main biochar filtration parameters (particle size, filter depth and flow rate) to remove water quality parameters such as colour, turbidity, phosphates and *Escherichia coli* (*E. coli*) from synthetic handwashing wastewater (a type of greywater) for possible water reuse for handwashing applications. Colour and turbidity measured appearance. *E. coli* monitored hygiene quality (microbial safety). Phosphates indicated the nutrient chemical composition. The optimisation of biochar filtration parameters to remove colour, turbidity, phosphates, and *E. coli* from handwashing wastewater is crucial for developing and integrating this wastewater treatment technology into portable handwashing facilities with potential water reuse. This could benefit communities in low-and middle-income countries and water-scarce regions with limited handwashing infrastructure, to continue water service and to provide access to good-quality water.

2. Materials and methods

2.1. Filtration media

The filter media was composed of gravel, silica sand, glass wool and biochar. Biochar was the main component of the filtration media. The selection of biochar was due to its proven physicochemical properties to remove pollutants from greywater [22]. In this study, the physicochemical properties of biochar were not enhanced through chemical processes such as activation. This was made to maintain cost-effectiveness and ensure the applicability of biochar filters in low- and middle-income countries. By avoiding additional chemical treatments, the production and implementation of biochar filters can be kept affordable, making them more accessible for communities in low and middle-income countries. The rest of the materials were selected because of their abundant availability and use in water filtration technologies [24]. Commercially available 3–8 mm particle size gravel was purchased from Sakana, UK. White silica sand of 0.25–0.5 mm was acquired from Trustleaf, UK. Glass wool made of nitrile rubber and 15–25 μm fibre diameter was purchased from Merck, UK. Standard wheat straw biochar with a surface area of 26.40 m^2/g was produced on a pilot-scale pyrolysis unit at 550 °C temperature, 80 °C/min heating rate and 15 min residence time [25].

Biochar production took place at the UK Biochar Research Centre (University of Edinburgh, UK). The selection of wheat straw as the feedstock material for biochar production was the abundant production of this agricultural waste during the harvesting season in several low- and middle-income countries. The choice of biochar production parameter (e.g., temperature, heating rate and residence time) was its influence on desirable biochar physical and chemical properties for wastewater treatment (e.g., surface area and functional groups). Using an adjustable grinder, the biochar was ground and sieved using laboratory soil sieves with different mesh sizes to achieve the desired particle sizes (0.5, 1.25 and 2 mm). The filtration materials (except for glass wool) were washed with deionised water to remove finer material or impurities. After washing, they were oven-dried at 60 °C for 24 h and cooled in a desiccator for 1 h at room temperature (20 °C) before use.

The Brunauer-Emmett-Teller (BET) analyser (Nova 4000 analyser, Quantachrome Instruments, USA) was used to determine the total surface area of biochar. A thermogravimetric analyser (Mettler-Toledo TGA/DSC1, Mettler Toledo, USA) was used to estimate the moisture content and total ash. The C and H contents were analysed using an elemental analyser (Flash 2000, CE Elantech Inc., New Jersey, USA), while the O content was determined by difference. A solution composed of 1 g of biochar and 20 mL of deionised water was prepared to measure the pH and electrical conductivity of biochar using benchtop probes (Mettler-Toledo, USA). The biochar characterisation was performed at the UK Biochar Research Centre (University of Edinburgh, UK). Table 1 displays the basic characteristics of the standard wheat straw biochar. Mašek et al. [25] provided a complete characterisation of the biochar material.

2.2. Preparation of synthetic handwashing wastewater

Chemical substances, commercial products and living cultures were used to prepare synthetic handwashing wastewater to simulate the properties of real handwashing wastewater from sinks. Synthetic handwashing wastewater was used to guarantee the repeatability of the quality of the tested wastewater. Ingredients were selected based on research conducted on synthetic greywater formulations from previous literature (Table S1). Ingredients were selected based on their functionality to mimic common components in real handwashing wastewater. The full ingredients used in handwashing wastewater simulation are listed in Table S1, along with their mimic function and their contribution to water quality parameters. The final concentrations of each ingredient per litre of tap water were determined in the laboratory. This was done until the water quality of the resulting synthetic handwashing wastewater was within the reported characteristics for real handwashing wastewater. Ingredients were weighed on a precision electronic balance (PX224, Ohaus, USA) and mixed in tap water until powder-based ingredients dissolved completely. Synthetic handwashing

Table 1
Characteristics of the standard wheat straw biochar.

Parameter	Units	Value
BET surface area	m^2/g	26.40
Moisture	wt%	1.88
Total ash	wt%	21.25
pH		9.94
Electrical conductivity	dS/m	1.70
C_{tot}	wt%	68.26
H	wt%	2.10
O	wt%	6.92

C_{tot}: total carbon; H: hydrogen; O: oxygen.

wastewater was prepared on the same day as the biochar filters were fed. This was to avoid alterations in wastewater physicochemical and microbial characteristics reported after long storage periods [26].

2.3. Optimisation of the biochar filter configuration

2.3.1. Experiment design using response surface methodology

Response Surface Methodology (RSM) investigated the relationship between the removal efficiency of water quality parameters in synthetic handwashing wastewater and optimal biochar filtration conditions. A Box-Behnken design (BBD) in the Design-Expert Software (version 13, Stat-Ease) evaluated the effect of three biochar filtration parameters (independent variables) on the removal of colour, turbidity, phosphates and *E. coli* (dependent variables) from synthetic handwashing wastewater [27]. The BBD model used three factors with three levels each. The three factors or operating parameters were: (i) particle size, (ii) filter depth and (iii) flow rate. The three levels for each parameter were low (referred to as - 1), medium (referred to as 0) and high (referred to as +1) levels. Particle size varied from 0.5 to 2.0 mm, filter depth was in the range of 15–30 cm and the flow rate ranged from 1 to 2.5 L/h. For particle size, the low, medium and high levels were 0.5, 1.25 and 2 mm, respectively. For filter depth, the low, medium and high levels were 15 cm, 22.5 cm and 30 cm, respectively. For flow rate, the low, medium and high levels were 1, 1.75 and 2.5 L/h, respectively. The operating parameters and their ranges were selected according to Bautista Quispe et al. [22]. Based on the number of independent variables (particle size, filter depth and flow rate), the Design-Expert Software suggested fifteen configurations (experimental runs) in a randomised order. Three replications at the centre points evaluated the experimental error and reproducibility. The different configurations and their operating parameters can be seen in Table S2.

2.3.2. Development of empirical models

A polynomial equation (Eq. (1)) modelled the relationship between the independent variables and the target responses (removal of colour, turbidity, phosphates and *E. coli*). *Y* is the predicted response or relative removal efficiency (colour, turbidity, phosphates and *E. coli*). The model coefficients (b_x) are the intercept or regression coefficient (b_o), linear (b_i), quadratic (b_{ii}) and interaction coefficients (b_{iii}). X_i and X_j are the coded values of the independent variables (particle size, filter depth and flow rate) and ε is the experimental or residual error of the model [28,29]. By using the model reduction function from the Design-Expert Software, insignificant model terms were eliminated with a backward selection method at a significance level (α value) of 0.1.

$$\mathrm{Y} = b_0 + \sum_{i=1}^{n} b_i X_i + \sum b_{ii} X_1^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} X_i X_j + \varepsilon \quad (1)$$

Statistical and practical significance tests evaluated the goodness of data fitting to regression models. Statistical significance test was assessed using an analysis of variance (ANOVA) with α value of 0.05 for the developed models, the model coefficients and the model lack of fit. The practical significance test was assessed using statistical parameters from the model goodness of fit such as standard deviation, mean, coefficient of variation, coefficient of determination (R^2), adjusted R^2, predicted R^2 and adequate precision. Model reproducibility was determined by the coefficient of variation, while adequate precision determined the signal-to-noise ratio [30]. Lastly, the adequacy of the fitted models was graphically checked through the (i) normal probability plot of residuals, (ii) predicted values versus actual values plot, (iii) residuals versus predicted values plot and (iv) residuals versus run plot.

2.4. Experimental set-up and operation of biochar filters

Based on the design matrix of configurations suggested by the Design-Expert Software (Table S2), fifteen downward biochar filters were constructed in this study. Biochar filters were made of a 50 cm height and 4.5 cm diameter acrylic tube. Biochar filters were supported on metal laboratory stands and labelled as F1 - F15 (Fig. 1). In the filtration column, the filtration media (e.g., gravel, silica sand and biochar) was packed from bottom to top in decreasing particle size order [31]. The bottom part of all filters was packed with a 2.5 cm layer of gravel, followed by a 2 cm layer of glass wool and a 4 cm layer of silica sand. The medium part of the filters was filled with a layer of biochar media. According to the design matrix of configurations, the biochar layer depth and particle size ranged from 15 to 30 cm and 0.5–2 mm, respectively. The top part of the biochar filter was again packed with a 2.5 cm layer of gravel. Gravel on top ensured uniform distribution of influent and prevented flotation of biochar particles and water evaporation, while gravel at the bottom eased effluent flow [32,33]. A stainless-steel wire mesh of 4.5 cm diameter between layers acted as a separator and prevented small particle-size media from washing away [34]. Biochar filters were wrapped with aluminium foil to impede light transmission and algae growth [35,36]. Synthetic handwashing wastewater was prepared at room temperature (20 °C) in a 20 L plastic container with periodic stirring. Peristaltic pumps were used to feed the biochar filters with the synthetic handwashing wastewater through a 4 mm silicone tube at a fixed flow rate of 1, 1.75 and 2.5 L/h according to the type of configuration (Table S2). Biochar filters were continuously fed under non-saturated conditions with 2.5 L of synthetic handwashing wastewater three times per week for five weeks. After an hour and a half of feeding the filters, both influent and effluent samples were collected into 0.5 L sterile sample bottles for immediate analysis or within 24 h after collection. Whenever refrigeration was required, samples were stored at 4 °C. Fig. 1 provides a schematic representation of the experimental configuration and set-up. A real photo of the configuration and set-up of the biochar filters can be seen in Fig. S1.

2.5. Characterisation of untreated and treated handwashing wastewater

The effectiveness of the biochar filters for the treatment of synthetic handwashing wastewater was assessed based on water quality analysis of the influent (untreated handwashing wastewater) and effluent (treated handwashing water) samples. The water samples analysis took place at the High-performance Analytical Hub at the Centre for Agroecology, Water and Resilience (Coventry University, UK).

Water sample analysis was done in triplicates. Physical, chemical and microbial parameters were analysed in both the untreated and treated handwashing wastewater. Temperature, pH and electrical conductivity were measured using a multimeter laboratory pH meter (Hanna Instruments, USA). Turbidity and colour were determined photoelectrically using the Palintest Photometer (Palintest Water Technologies, UK). Total suspended solids (TSS) were analysed gravimetrically. Chemical oxygen demand (COD), phosphates (PO_4^{3-}), nitrates (NO_3^-), hardness ($CaCO_3$) and sulphates (SO_4^{2-}) were determined based on the photometry method using the Palinstest water test kits (Palintest Water Technologies, UK) based on the standard methods for the examination of water and wastewater [37]. Inactivated *E. coli* DH5α was used as a microbial indicator of faecal pollution. Colonies in water samples were inoculated in 3 M Petrifilm plates incubated at 42 °C ± 1 °C for 24 h ± 2 h (3 M, USA). For optimal growth conditions, the pH of the sample suspensions was adjusted to 6.5–7.5 with drops of either 0.1 M of hydrochloric acid (HCl) or 0.1 M of sodium hydroxide (NaOH).

The characterisation of the influent addressed the analysis of all these parameters. Meanwhile, the characterisation of the effluent focused on the water quality parameters of interest in this study such as colour, turbidity, phosphates, and *E. coli*. As mentioned earlier, the parameters colour and turbidity measured appearance; *E. coli* indicated hygiene quality and phosphates assessed nutrient content. The measurements of pH, temperature and electrical conductivity of the influent and effluent samples monitored the stability of the biochar filtration processes. The effectiveness of the pollution removal was estimated

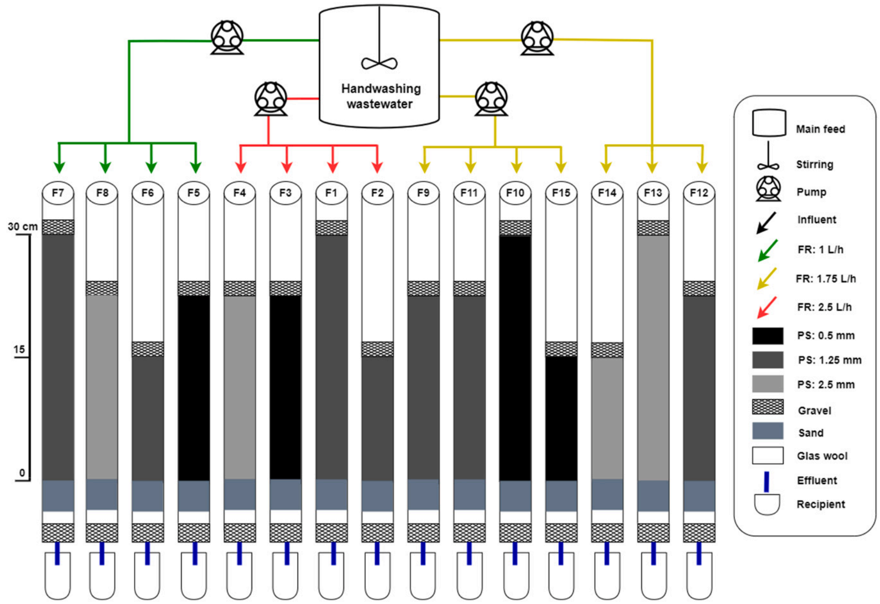

Fig. 1. Schematic representation of the fifteen biochar filters configuration and set-up.

using Eq. (2).

$$Removal\ (\%) = \left[\left(C_i - C_f\right)/C_i\right] \times 100 \tag{2}$$

2.6. Filter optimisation, model validation and further performance analysis

The optimisation function of the Design-Expert Software was used to determine the optimal biochar filtration parameters to maximise the removal of colour (Y_1), turbidity (Y_2), phosphates (Y_3) and *E. coli* (Y_4) within the ranges of operating parameters under study (see Section 2.3.1.). The Design-Expert Software explored a combination of factors (particle size, filter depth and flow rate) and suggested the optimal levels that simultaneously satisfied the maximum removal for colour, turbidity, phosphates and *E. coli*. A Design-Expert's ramp function graph of desirability was created to represent the optimal operating parameters and their corresponding predicted removal efficiency of colour, turbidity, phosphates and *E. coli*. Using the desirability function from the Design-Expert Software, the desirability value was calculated as an indicator that all the predicted responses are within the acceptable limits. The Desirability value ranges from 0 to 1, where values closer to 0 or 1 represent responses outside or within the limits, respectively.

The effectiveness of the developed models for predicting the removal of colour, turbidity, phosphates, and *E.coli* was validated by testing three biochar filters under optimal operating conditions suggested by the Design-Expert Software. The experimental set-up and operation for all three filters were the same as in Section 2.4. The performance of the biochar filters under optimised conditions lasted for 10 days. The analysis of water quality for colour, turbidity, phosphates, and *E.coli* was performed in triplicates following the same methods described in Section 2.5. The validation was determined by comparing the predicted values of the regression models with the experimental values. The models were considered valid when the mean experimental values of the responses were within the range of 95 % prediction interval (PI) low and 95 % prediction interval high [38]. Additionally, the performance of the biochar filter with optimised operating parameters was also evaluated for the removal of COD, TSS, nitrates, ammonium, hardness, sulphates and chloride. The purpose of this was to provide insights into the potential of the optimised biochar filter to remove a wide range of water quality parameters to levels in compliance with international water quality guidelines. To date, water quality standards for the reuse of treated handwashing wastewater in handwashing applications are yet unavailable [17]. Therefore, guidelines for high-quality water (e.g., drinking water) and improved-quality water (e.g., water reuse for restricted activities) were used as reference guidelines to evaluate the quality of the treated handwashing wastewater and its potential for reuse in handwashing practices (Table 9).

2.7. FTIR analysis of biochar filter media before and after handwashing wastewater treatment

FTIR analysis was performed on the biochar material from the optimised biochar filter before and after the filtration of synthetic handwashing wastewater. The purpose was to determine changes in surface functional groups of biochar to gain insight into the possible mechanisms affecting the removal of pollutants from synthetic handwashing wastewater. Five grams of biochar samples before and after use as a filter media in the optimised biochar filter were collected and oven-dried at 60 °C for 24 h. Both biochar samples were analysed by the Fourier-transform infrared spectroscopy (FTIR) using a Nicolet™ iN10 Infrared Microscope (Thermo Scientific, UK). The experimental set-up parameters were as follows: reflection as collection mode, cooled detector, collection time of 12 s and normal spectral resolution. The scanning range was 675–4000 cm^{-1}. The FTIR spectra of 10 different points across the biochar samples were obtained.

3. Results and discussion

3.1. Characteristics of untreated synthetic handwashing wastewater

Handwashing wastewater is low-pollution greywater generated in handwashing basins [39]. The physical, chemical and microbial characteristics of the synthetic handwashing wastewater prepared using the proposed recipe in Table S1 are displayed in Table 2. As expected, the concentration of water quality parameters in the synthetic handwashing wastewater was low compared to other types of greywater, such as the bathroom, washing machine, shower, kitchen sink and dishwasher wastewater [20,40,41]. Synthetic handwashing wastewater used in this study contained levels of water quality parameters within the range reported in the literature for real handwashing wastewater (Table 3). For instance, the pH (7.1), turbidity (201 FTU), COD (499.8 mg/L O_2) and TSS (251.2 mg/L) of the synthetic untreated handwashing

Table 2
Characteristics of untreated handwashing wastewater.

Parameter	Units	N	Value
Temperature	°C	16	16.0 ± 2.0
Electrical conductivity	μS/cm	16	494.8 ± 66.6
pH		16	7.1 ± 0.2
Turbidity	FTU	12	201 ± 14.4
Colour	mg/L Pt	12	966.3 ± 48.9
COD	mg/L O_2	9	499.8 ± 40.0
TSS	mg/L	14	251.2 ± 57.2
Phosphates	mg/L PO_4^{3-}	16	100.4 ± 16.0
Nitrates	mg/L NO_3^-	12	15.5 ± 2.6
Hardness	mg/L $CaCO_3$	14	311.5 ± 16.1
Sulphates	mg/L SO_4^{2-}	16	117.7 ± 9.0
E. coli	CFU/mL	10	21,350 ± 8372

COD: chemical oxygen demand; TSS: total suspended solids.

wastewater was found in between the range of pH (5.55–8.1), turbidity (84.3–348.33), COD (110–587 mg/L O_2) and TSS (40–471 mg/L) previously reported (Table 3). The influent values for phosphates, nitrates, hardness and *E. coli* were higher than the real values in the literature (Tables 2 and 3) [42,43]. Nonetheless, these high concentrations of water quality parameters in handwashing wastewater were used as proxies for worst-case pollution scenarios. In real-world conditions, handwashing wastewater composition varies depending on the water quality, handwashing habits, water consumption style and geographical location [39]. The low standard deviation in most of the influent characteristics of the untreated synthetic handwashing wastewater suggested that the quality of the produced synthetic handwashing wastewater was repeatable during the study period (Table 2).

3.2. Characteristics of treated synthetic handwashing wastewater

The effluent samples from each of the fifteen biochar filters were analysed for colour, turbidity, phosphates and *E. coli*. The temperature and pH of the effluent samples were also tested to monitor the stability of biochar filtration. The complete characterisation of the effluent samples can be found in Table S3. Among the tested fifteen filters, three of them (F9, F11 and F12) operated with the same conditions at the centre point such as particle size 1.25 mm, filter depth 22.5 cm and flow rate 1.75 L/h. As expected, their effluent characteristics were similar in contrast to the rest of the filters, in which effluent characteristics fluctuated with changing operating conditions. Colour, turbidity, phosphates and *E. coli* removal ranged from 78.1 to 98.8, 83.6–96.4, 67–86.4 and 47.9–97.7 %, respectively (Table 4). Temperature and pH showed lower range fluctuations of 15.8–17.1 °C and 7.0–7.8, respectively (Table S3). This suggested that conditions inside the filters were stable to facilitate common removal mechanisms in biochar filtration. These mechanisms included agglomeration [19,33], sedimentation/precipitation, surface filtration, straining, adsorption, hydrolysis [32,44], biofilm adsorption and biofilm straining [31,33]. Experimental percentage removal data of colour, turbidity, phosphates and *E. coli* were further input in the Design-Expert Software to optimise the biochar filter operating conditions that achieve the highest removal of colour, turbidity, phosphates, and *E. coli* from the synthetic handwashing wastewater (see Section 3.3).

3.3. Optimisation of the biochar filter configuration

3.3.1. Development of regression model equations

The BBD in the Design-Expert Software established the relationship between the independent variables (particle size, filter depth and flow rate) and the dependent variables or responses (removal of colour, turbidity, phosphates and *E. coli*). Table 4 presents the biochar filtration configurations and their corresponding experimental and predicted values for each of the responses. According to the sequential model sum of squares, the empirical regression model for each response was chosen

Table 3
Characteristics of real handwashing wastewater in the literature.

Reference	pH	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	Ammonium (mg/L NH_4^+)	Nitrates (mg/L NO_3^-)	Phosphates (mg/L PO_4^{3-})	TC (CFU/100 mL)	FC (CFU/100 mL)	*E. coli* (CFU/100 mL)	Chloride (mg/L Cl^-)	Hardness (mg/L $CaCO_3$)	Surfactants (mg/L)	Colour (mg/L Pt)
[45]				383	1.15	0.28								
[46]	8.1	102	40	433	0.53	0.34	45.5	50,000	32					
[47]			181	298	0.3	6	13.3							
[48]				263										
[49]	7.32	164	153	587			0.4	9420		10				
[50]	7		259	386	0.39		15		3500		237		3.3[a]	
[42]	7.2	211	318	110		10.2		>200.5[b]	>200.5[b]			14.4	41.9	
[23]	6.62	775	288.8					13,935		2543				8508.6
[51]	8.1	289	204	562						1030				550
[10]	5.55	348.33	471.67											2614.67
[52]	7.6	180.1	90.3	225.3						8				
[53]	7.2	84.3	89.2	340.5		0.06	14					47.2		

TSS: total suspended solids; COD: chemical oxygen demand; TC: total coliforms, FC: faecal coliforms.
[a] Surfactants as Methylene Blue Active Substance (MBAS).
[b] As Most Probably Number per 100 mL (MPN/100 mL).

Table 4
Box-Behnken matrix design with experimental and predicted data.

Conf.	A: PS (mm)	B: FD (cm)	C: FR (L/h)	Colour removal (%)		Turbidity removal (%)		Phosphates removal (%)		*E. coli* removal (%)	
				Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
1	1.25	30	2.5	95.6	97.0	95.5	96.2	85.8	85.9	61.1	60.5
2	1.25	15	2.5	93.3	91.9	93.1	92.3	85.9	85.9	48.9	47.5
3	0.5	22.5	2.5	95.0	95.4	95.2	94.3	86.4	85.9	64.0	64.6
4	2	22.5	2.5	93.8	93.5	93.2	94.3	85.4	85.9	47.9	49.3
5	0.5	22.5	1	95.8	95.5	95.0	95.5	83.3	82.7	78.7	77.1
6	1.25	15	1	92.8	91.9	95.2	93.6	83.1	82.7	58.3	60.1
7	1.25	30	1	95.8	97.1	96.4	97.5	81.8	82.7	73.0	73.1
8	2	22.5	1	93.6	93.5	95.5	95.5	82.5	82.7	62.1	61.9
9	1.25	22.5	1.75	82.7	83.2	88.1	87.8	75.9	74.1	88.9	88.5
10	0.5	30	1.75	87.9	86.7	91.8	89.8	77.7	74.1	97.7	99.7
11	1.25	22.5	1.75	84.8	83.2	88.6	87.8	75.6	74.1	87.1	88.5
12	1.25	22.5	1.75	83.6	83.2	87.1	87.8	74.9	74.1	89.7	88.5
13	2	30	1.75	85.2	84.7	89.7	89.8	73	74.1	85.9	84.4
14	2	15	1.75	78.1	79.6	83.6	85.8	71.4	74.07	71.0	71.4
15	0.5	15	1.75	79.8	81.6	85.7	85.8	70.0	74.1	87.5	86.7

Conf.: configuration of the biochar filter; Exp.: experimental value; Pred.: predicted value; PS: particle size, FD: filter depth, FR: flow rate.

based on a high-order polynomial with significant ($p < 0.05$) additional terms and no aliasing (see Table S4). The Design-Expert Software proposed the quadratic models for the four responses. Using the backward selection method with α value of 0.1, insignificant model terms were eliminated before the Design-Expert Software generated the quadratic regression equation for each response. The final quadratic model corresponding to colour (Y_1), turbidity (Y_2), phosphates (Y_3) and *E. coli* (Y_4) is given in Eqs. (3)–(6) where A, B and C are particle size (mm), filter depth (cm) and flow rate (L/h), respectively. Positive (+) and negative (−) signs indicated synergistic and antagonist influence of the independent variables on the response, respectively. For instance, the filter depth had a synergistic effect on the colour (Y_1) and *E. coli* (Y_4) removal [53,54].

$$Y_1 = 138.73 - 1.30A + 0.34B - 70.39C + 20.10C^2 \quad (3)$$

$$Y_2 = 121.95 + 0.26B - 44.95C + 12.60C^2 \quad (4)$$

$$Y_3 = 125.89 - 61.36C + 18.14C^2 \quad (5)$$

$$Y_4 = -67.77 - 10.17A + 3.22B + 148.98C - 0.05B^2 - 44.96C^2 \quad (6)$$

3.3.2. Statistical significance: ANOVA

ANOVA with α value of 0.05 evaluated the statistical significance for the regression models, model terms and the lack of fit of each model. According to the F-values for colour (79.35), turbidity (45.95), phosphates (53.06) and *E. coli* (303.12) removal quadratic models, the models were significant ($p < 0.05$) (Table 5). In all models, noise has only a 0.01 % chance of causing an F-value as large as this one. The p-values for the overall model of each response were <0.0001, which suggested that the developed models were highly significant (Table 5). Therefore, the null hypothesis of no relationship between the dependent and independent variables was rejected. Thus, the quadratic model of the independent variables (particle size, filter depth and flow rate) significantly affected the removal of colour, turbidity, phosphates and *E. coli* (dependent variables).

Model terms were also significant ($p < 0.05$). For the reduced quadratic model corresponding to colour, turbidity, phosphates and *E coli* removal, the significant terms were B and C^2; B and C^2; C and C^2; and A, B, C, B^2 and C^2, respectively (Table 5). Based on the F-values of the significant model terms, the weight of influence of the independent variables (particle size, filter depth and flow rate) on the dependent variables (colour, turbidity, phosphates and *E. coli* removal) can be described. Colour and turbidity removals were mainly influenced by the quadratic effect of filter depth (F-value of 281.87 and 116.47, respectively), followed by the main effect of filter depth (F-value of 31.03 and

Table 5
ANOVA of the reduced quadratic models for the responses.

Source	F-value	p-value	Remarks
(a) ANOVA for the reduced quadratic model for colour removal			
Model	79.35	<0.0001	Significant
A-Particle size	4.49	0.0601	
B-Filter depth	31.03	0.0002	
C-Flow rate	0.0066	0.9366	
C^2	281.87	<0.0001	
Lack of Fit	1.66	0.4301	Not significant
(b) ANOVA for the reduced quadratic model for turbidity removal			
Model	45.95	<0.0001	Significant
B-Filter depth	19.38	0.0011	
C-Flow rate	2.02	0.1831	
C^2	116.47	<0.0001	
Lack of Fit	3.15	0.2641	Not significant
(c) ANOVA for the reduced quadratic model for phosphates removal			
Model	53.06	<0.0001	Significant
C-Flow rate	5.31	0.0399	
C^2	100.81	<0.0001	
Lack of Fit	17.37	0.0556	Not significant
(d) ANOVA for the reduced quadratic model for *E. coli* removal			
Model	303.12	<0.0001	Significant
A-Particle size	201.52	<0.0001	
B-Filter depth	146.44	<0.0001	
C-Flow rate	136.48	<0.0001	
B^2	13.89	0.0047	
C^2	1029.11	<0.0001	
Lack of Fit	1.39	0.4807	Not significant

ANOVA: analysis of variance.

19.38, respectively). Phosphates removal was mainly influenced by the quadratic (F-value of 100.81) and main (F-value of 5.31) effect of flow rate. In terms of *E. coli* removal, the most significant influencing factor was the quadratic effect of flow rate (F-value of 1029.11), followed by the main factor of particle size (F-value of 201.52), filter depth (F-value of 146.44), flow rate (F-value of 136.48) and the quadratic effect of filter depth (F-value of 13.89) (Table 5). *E. coli* removal was the only dependent variable affected by all independent variables.

The lack of fit compares the variation between the experimental and predicted data with the variation between replicates [55]. The lack of fit F-values were 1.66, 3.15, 17.37 and 1.39 for the quadratic model of colour, turbidity, phosphates and *E. coli*, respectively. This implied the lack of fit was not significant to the pure error for all models. There was

43.01 % (p-value of 0.4301), 26.41 % (p-value of 0.2641), 5.56 % (p-value of 0.0556) and 48.07 % (p-value of 0.4807) chance that a lack of fit F-value this large could occur due to noise for the quadratic colour, turbidity, phosphates and *E. coli* removal models, respectively (Table 5). The lack of fit was not significant for all models, suggesting the models fitted the experimental data and may be useful for making removal predictions in the future.

3.3.3. Practical significance: model summary output table

The results from the model summary output table from the analysis of the Design-Expert Software assessed the practical significance of the developed models. The standard deviation of the quadratic models for colour, turbidity, phosphates and *E coli* removal was 1.30, 1.27, 1.96 and 1.52, respectively (Table 6). This means that the amount of random variation left in the process was little suggesting that the developed models were accurate. The coefficient of variation was 1.46, 1.39, 2.47 and 2.07 % for the colour, turbidity, phosphates and *E coli* removal models, respectively (Table 6). The values of the coefficients of variations were lower than 10 %, which indicated high model reproducibility, as there was less variability around the mean values [56].

The R^2 was used for the validation of the proposed models. All models showed values relatively closer to 1 suggesting that the data satisfactorily fitted the proposed models. Models for colour, turbidity, phosphates and *E coli* removal depicted R^2 values of 0.970, 0.926, 0.898 and 0.994, respectively (Table 6). This indicated that 97.0, 92.6, 89.8 and 99.4 % variations of the colour, turbidity, phosphates and *E coli* removal, respectively, were explicable across the independent parameters (particle size, filter depth and flow rate) ranges. The adjusted R^2 is the amount of variation in the experimental data (runs) explained by the model (higher is better). Adjusted R^2 values of 0.957, 0.906, 0.882 and 0.991 were reported for colour, turbidity, phosphates and *E coli* removal model, respectively. This implied that the developed models, respectively, explained 95.7, 90.6, 88.2 and 99.1 % of variations in the experimental data (Table 6). The predicted R^2 is the amount of variation in predictions explained by the model (higher is better). The predicted R^2 values of 0.923, 0.851, 0.860 and 0.983 for colour, turbidity, phosphates and *E coli* removal models, respectively, were in reasonable agreement with their respective adjusted R^2 values (Table 6) as their difference was <0.2 indicating no presence of abundant insignificant terms in the models.

Lastly, the adequate precision which measures the signal-to-noise ratio (a ratio >4 is desirable) was reported to be 23.22, 17.82, 13.44 and 54.31 for colour, turbidity, phosphates and *E coli* removal models, respectively (Table 6). Considering all models showed ratios >4, the developed models were useful for navigating the design space. Overall, the fit statistical analysis demonstrated that the developed regression models provided an adequate fit for the existing data and were accurate at making predictions.

3.3.4. Model diagnostics and adequacy checks

The adequacy of the fitted models was graphically checked using the (i) normal probability plot of residuals, (ii) predicted values versus actual values plot, (iii) residuals versus predicted values plot and (iv) residuals versus run plot (Fig. 2). In general, the residual plots for each model showed that the experimental results followed approximately a straight line, which indicated that the data were normally distributed (Fig. 2a–d) [23]. The predicted values versus actual values plots for the developed models are shown in Fig. 2e–h showed a significant correlation between the actual and predicted values ($p < 0.05$). Minimal divergence of the experimental data from the straight line indicated adequate representation of the relationship between independent (biochar filtration operating parameters) and dependent variables (colour, turbidity, phosphates and *E. coli* removal) [30,56]. The residual versus predicted plots showed constant variance across the design space for all models, which means the up-and-down scatter of the residuals from small predictions was similar to the up-and-down scatter of large predictions (Fig. 3a–d) [57]. The residual versus run plots are illustrated in (Fig. 3e–h) and showed no obvious pattern (random scatter) for any of the response models. This suggested both accurate data distribution within the acceptable limits (red lines) and no detection of constant error [58]. Overall, the inspected diagnostic plots exhibited trends associated with adequate models [59].

Table 6
Statistical analysis summary of model goodness of fit.

Statistical parameter	Colour removal (%)	Turbidity removal (%)	Phosphates removal (%)	*E. coli* removal (%)
Std. Dev.	1.30	1.27	1.96	1.52
Mean	89.19	91.58	79.51	73.45
C.V. %	1.46	1.39	2.47	2.07
R^2	0.970	0.926	0.898	0.994
Adjusted R^2	0.957	0.906	0.882	0.991
Predicted R^2	0.923	0.851	0.860	0.983
AP	23.22	17.82	13.44	54.31

Std. Dev.: standard deviation; C.V.: coefficient of variation; R^2: coefficient of determination; AP: adequate precision.

3.4. Response surfaces

3.4.1. Colour removal

Suspended and dissolved matters are the main cause of colour contamination in the influent handwashing wastewater [60]. Colour removal is critical to comply with quality appearance parameters to facilitate the reusing of treated handwashing wastewater in handwashing applications [11,17]. The interactive effects between filtration parameters on the removal of colour are shown in 2D contour plots (Fig. 4). It can be seen that colour removal increased with an increased filter depth (Fig. 4a) and decreased flow rate (Fig. 4b). Colour removal in the biochar filters occurred due to the agglomeration of coarse particles and successive precipitation over the filter surface [19,33]. However, as the biochar filter configuration increased in depth, it is believed removal conditions were enhanced by the straining and adsorption of finer particles on the upper and along the deeper zones of the filter, respectively [61]. In the literature, larger depth configurations of biochar filtration systems favoured physical removal processes (e.g., agglomeration, straining) to remove impurities from greywater responsible for colour contamination [32]. For instance, Olupot et al. [23] reported 56 % of colour removal (effluent concentration of 3644 mg/L Pt/Co) in effluent handwashing wastewater after silica sand filtration.

Low flow rates favoured a longer interaction time between the handwashing wastewater and the biochar filter media resulting in better colour removal efficiencies [62]. This tendency was also observed by Lawan & Surendran [63] who reported a reduction of suspended solids above 90 % for biochar filters operating at a low flow rate of 0.53 L/h. Overall, it did not appear that particle size was a significant factor in colour removal when it interacted with either the filter depth or the flow rate. Colour removal was observed beyond 96 % for the different particle sizes under testing (Fig. 4b). This agreed with the ANOVA test where particle size was not a significant factor ($p > 0.05$) in colour removal (Table 5). Contrary to this finding, Olupot et al. [23] suggested that the lower porosity in smaller particle sizes of silica sand caused high solid matter retention that resulted in high water colour quality. The lack of significance of particle size ($p > 0.05$) on colour removal in the present study could be explained by the larger filter depth range in the current study (15–30 cm) than the filter depth range in Olupot et al. [23] of 6–12 cm. It is suggested that the biochar filter depth out dominated the particle size operating parameter in removing colour probably due to the presence of a larger area within the biochar filter for the occurrence of straining and adsorption processes.

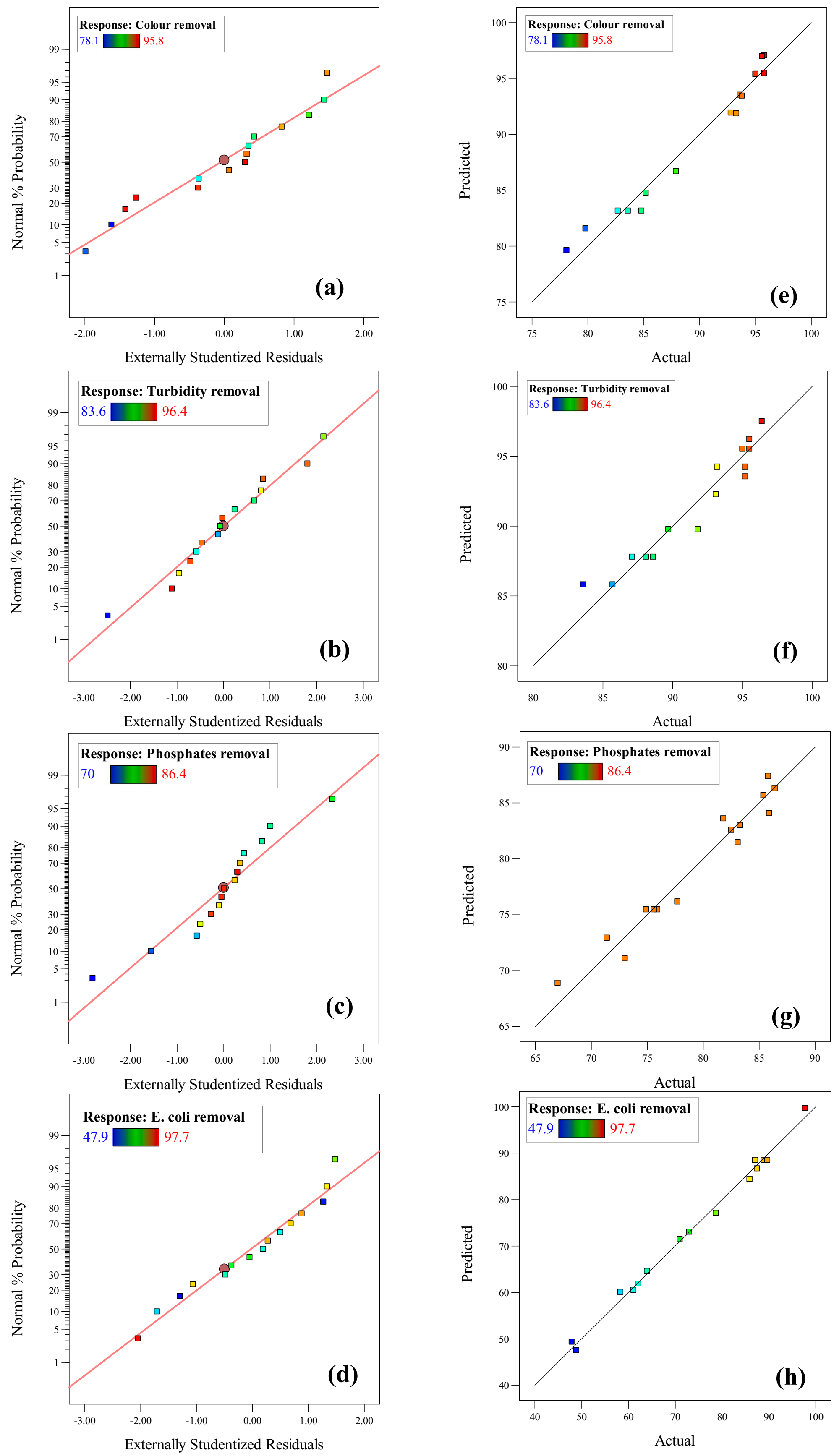

Fig. 2. Normal probability plot of residues for colour (a), turbidity (b), phosphates (c) and *E. coli* (d) removal. Predicted values versus experimental values for colour (e), turbidity (f), phosphates (g) and *E. coli* (h) removal.

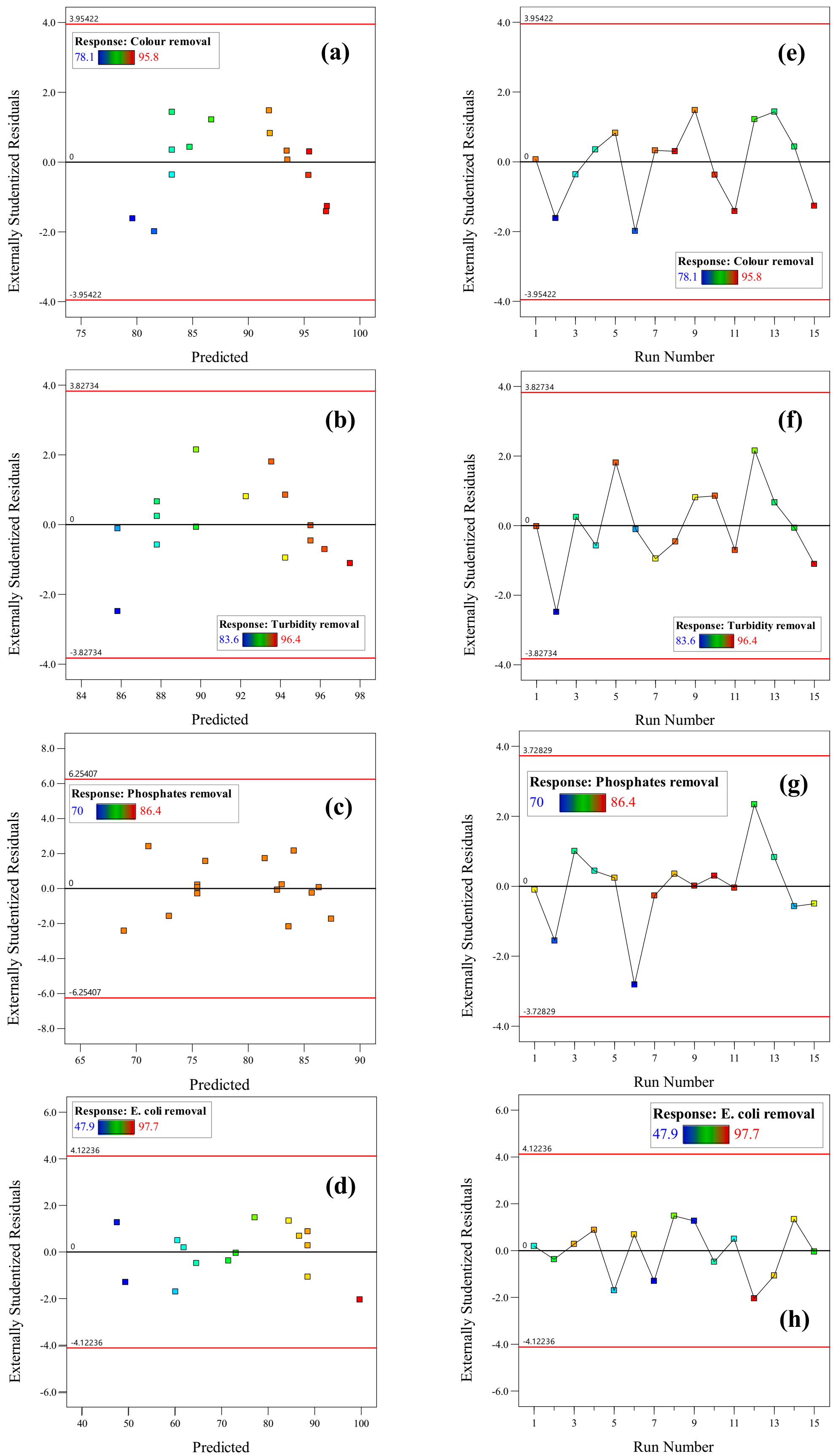

Fig. 3. Residuals versus predicted plot of residues for colour (a), turbidity (b), phosphates (c) and *E. coli* (d) removal. Residuals versus run number for colour (e), turbidity (f), phosphates (g) and *E. coli* (h) removal.

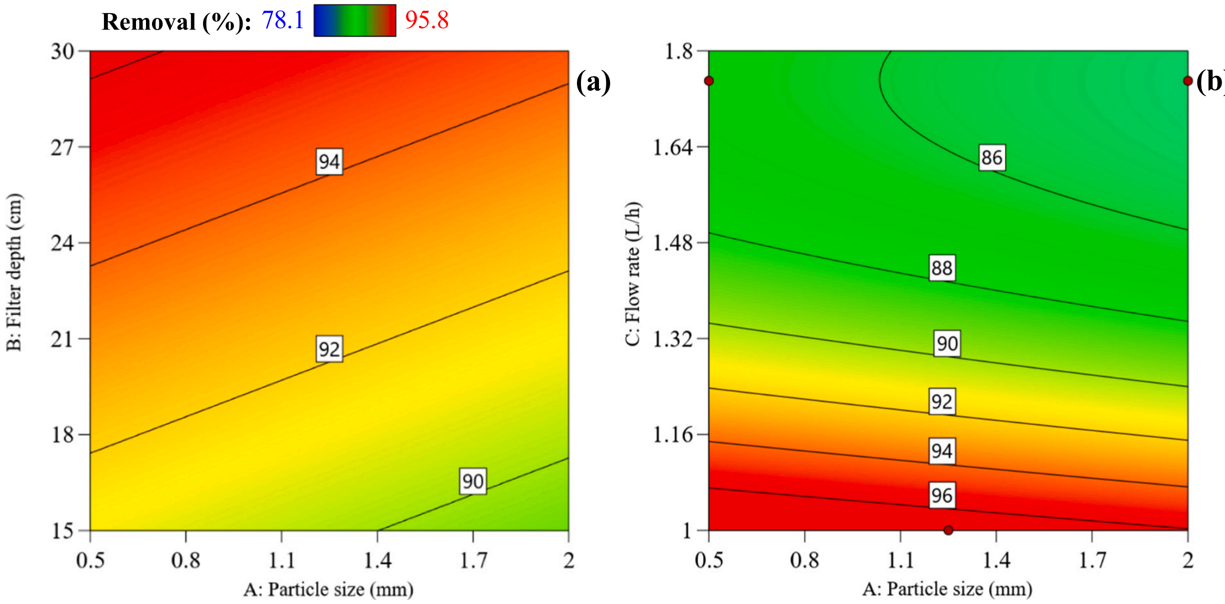

Fig. 4. 2D contour plots of colour removal. (a) Interaction of particle size and filter depth at a flow rate fixed at 1.06 L/h. (b) Interaction of particle size and flow rate at filter depth fixed at 30 cm.

3.4.2. Turbidity removal

In the present study, the main source of turbidity in synthetic handwashing wastewater was the anionic surfactant sodium dodecyl sulphate (SDS). As reported in the literature, SDS comprises 69.8 % of the soap composition in handwashing wastewater [64]. The second source of turbidity was kaolin clay, which mimicked real suspended matter, organic, and inorganic matter and food residues generated during handwashing practices [65]. Both components were responsible for the cloudy and soapy appearance of the influent synthetic handwashing wastewater. Influent water samples revealed turbidity levels (201 FTU, Table 3) above international drinking water and water reuse regulations (<5 and <20 NTU, respectively, Table 9). Hence the need for turbidity removal. The results of the interactive impact of the operating parameters on the turbidity reduction are presented in Fig. 5.

Turbidity removal increased as the filter depth increased in length (Fig. 5a) and it decreased as the flow rate increased (Fig. 5b). Likewise, particle size was not influential in turbidity removal either when it interacted with the filter depth (Fig. 5a) or the flow rate (Fig. 5b). For instance, removals beyond 96 % and 94 % were observed when the particle size range (0.5–2.0 mm) interacted with either the filter depth (Fig. 5a) or flow rate (Fig. 5b), respectively. These findings agreed with the ANOVA results (Table 5) where particle size was not a significant factor in turbidity reduction ($p > 0.05$). Similar removal mechanisms for colour removal such as agglomeration, precipitation, straining and adsorption are believed to be responsible for turbidity elimination [22]. To date, several studies have investigated the use of biochar filtration for turbidity removal from greywater under the influence of filter depth and flow rate. For instance, Biruktawit [36] found that a 36 cm layer of

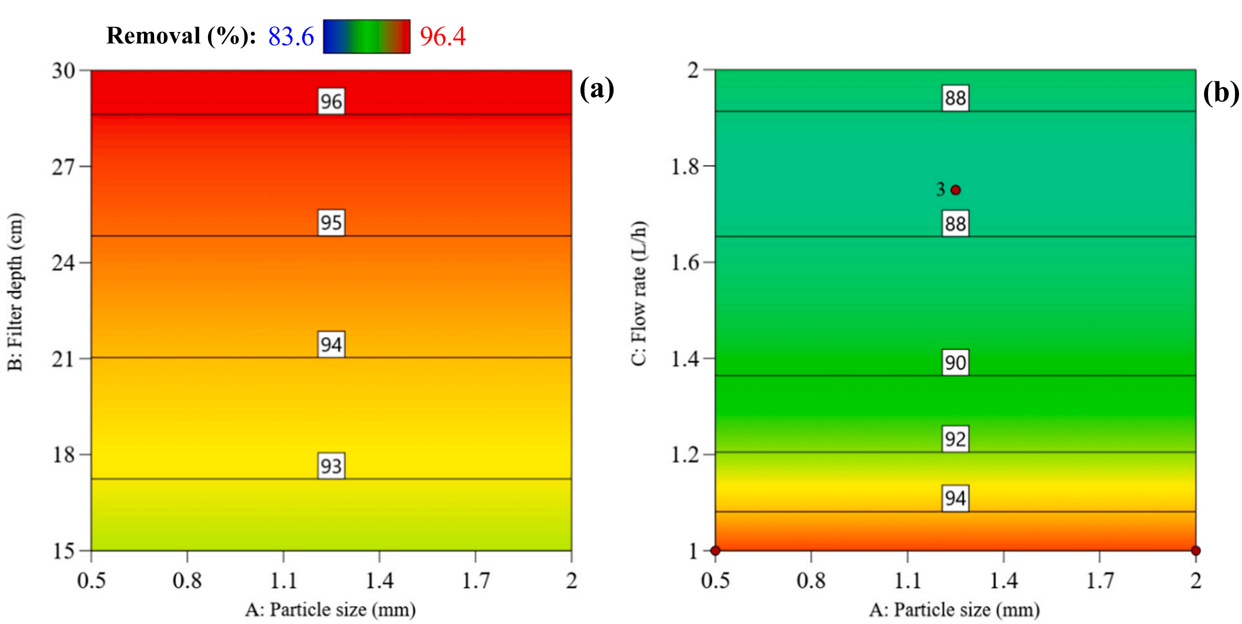

Fig. 5. 2D contour plots of turbidity removal. (a) Interaction of particle size and filter depth at a flow rate fixed at 1.06 L/h. (b) Interaction of particle size and flow rate at filter depth fixed at 30 cm.

banana peel biochar as filtration media was effective in removing up to 92 % of the turbidity in greywater (9.17 NTU in the effluent). On the other hand, Lawan & Surendran [63] reported 71.2 % of turbidity removal for a biochar filter operated at 0.53 L/h.

As a type of greywater, the study of handwashing wastewater treatment in several treatment technologies has been recently studied. Reynaert et al. [17] achieved almost complete turbidity removal in water effluent (0.44 NTU) from a treatment system using an aerated bioreactor, ultrafiltration membrane, granular activated carbon and electrolysis for chlorine disinfection. Olupot et al. [10] reduced turbidity levels up to 5 NTU (98.5 % removal) in handwashing wastewater treated in an in-series filtration system composed of silica sand, zeolite and granular activated carbon filters. Later on, Olupot et al. [23] reported a concentration of 337 NTU (55.02 % removal) in water effluent samples from a silica sand filter with optimised operating parameters of particle size, filter depth and flow rate. In comparison to the literature findings, the turbidity levels in the biochar filters under study ranged from 7.2 to 32.9 FTU (83.6–96.4 % removal), suggesting similar turbidity removal performance between biochar filtration and the treatment systems previously described (see Table 4 and Table S3).

In the current study, the anionic surfactant SDS was one of the main sources of turbidity contamination in the proposed synthetic handwashing wastewater. Thus, it is suggested that biochar SDS adsorption was the main removal mechanism for turbidity reduction. This is based on a recent study by Bautista et al. [66] who reported the potential of agricultural waste-based biochars to remove SDS from aqueous solutions. This suggests that biochar filtration holds the potential to remove soap components (e.g., SDS) and therefore eliminate the soapy appearance of handwashing wastewater previously reported in the literature [16]. Moreover, the effective performance of biochar filtration in removing turbidity highlights the possibility of using biochar as a sustainable and low-cost adsorbent to improve the appearance of handwashing wastewater as an alternative to chemically-activated adsorbents (e.g., granular activated carbon).

3.4.3. Phosphates removal

Handwashing wastewater contains a low level of phosphorus (P) in comparison to domestic wastewater [67]. Despite this, current portable handwashing facilities lacking piped drainage systems usually discard wastewater directly into the ground [6]. In countries where P-containing cleaning products have not been banned, P in greywater types such as handwashing wastewater represents an environmental and public risk [6]. The discharge of untreated P-containing wastewater triggers the eutrophication process, affecting the health of animals and humans [68]. Therefore, a treatment system for handwashing wastewater should target P removal. Fig. 6 shows the combined influence of the operating parameters on phosphates removal. High phosphates removal above 80 % was observed for low and medium values of flow rate. Operating parameters such as particle size and filter depth did not significantly affect the removal of the phosphates. This corroborates the findings in the ANOVA test ($p > 0.05$) and the suggested model terms for the reduced quadratic model for phosphates removal (Table 5 and Eq. (5)). The flow rate was the only significant factor ($p < 0.05$) and thus part of the model terms conforming the regression equation for phosphates removal predictability.

In the literature, several studies have targeted phosphates removal from greywater using biochar filtration systems. For instance, Deepa et al. [69] and Chithra & Dandapani [70] reduced phosphates up to 0.23 mg/L PO_4^{3-} (82.5 % removal) and 0.93 mg/L PO_4^{3-} (74 % removal) using biochar filter operated at 24.3 and 12.24 L/h, respectively. Similar to the findings in the present study, Salihu Wandeo [71] found high phosphates removal of 98.3 % (5.03 mg/L PO_4^{3-}) and 98.7 % (3.71 mg/L PO_4^{3-}) for filters with fig tree biochar particles of <2 mm and 2–4.7 mm particle size, respectively. The uptake of phosphates from handwashing wastewater has been limitedly explored. Reynaert et al. [17] reduced the phosphates concentration from handwashing wastewater

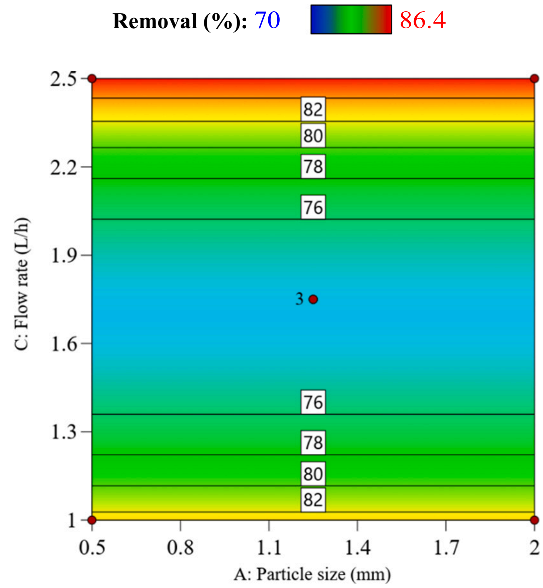

Fig. 6. 2D contour plots of phosphates removal. (a) Effect of particle size, flow rate and filter depth fixed at 30 cm.

(8.4 mg/L PO_4^{3-}) in half after treatment in the Autarky handwashing facility through successive treatment steps previously described. In the present study, the biochar filters effectively decreased the phosphates levels up to 13.6 mg/L PO_4^{3-} (86.4 % removal) in the synthetic handwashing wastewater (see Table 4 and Table S3). Phosphates concentrations in the treated effluent were still above the accepted levels of 0.4 mg/L PO_4^{3-} according to international guidelines for high-quality water such as drinking water (e.g., Peru, European Union) (Table 9). However, to comply with the existing water quality normative, in-series biochar filtration can be further explored to achieve a higher level of phosphates uptake.

Biochar can adsorb phosphates due to its porous structure, large surface area, abundant surface functional groups and high mineral content [72]. The phosphates uptake occurs mainly through the chemical precipitation of Mg, Ca, Fe or/and Al phosphates on the biochar surface [73]. As previously reported, P-loaded biochar can be used as a soil improver while releasing phosphates during irrigation for further crop uptake [74]. In this line, the use of biochar filtration for handwashing wastewater treatment and treated water reuse holds the potential to provide dual benefits. These include removing phosphates from handwashing wastewater while simultaneously packing the biochar filter material with P for further reuse in soil enhancement applications and potentially as a fertiliser. Before reusing biochar filter media in soil applications, pre-treatment such as thermal processes may be necessary. This could help break down anionic surfactant compounds that can damage soil properties and plant germination [8]. Thus, incorporating a biochar filtration system for the treatment of handwashing wastewater can be considered an alternative to boost the circular economy in several industrial sectors. These include the water (wastewater treatment), waste (waste material for biochar production) and soil (reuse of filter media as soil improver) sectors [21].

3.4.4. *E. coli* removal

Removal of pathogens is of great relevance to ensure microbial safety of treated handwashing wastewater [75]. Chlorination, ozonation and UV are the most widely used disinfection methods in handwashing facilities with on-site wastewater treatment [10,17,76]. Nevertheless, the main disadvantages of these methods are their high-energy demand, high-cost material and the generation of toxic by-products that are harmful to humans [75]. In this study, the impact of biochar filtration parameters on the reduction of *E. coli* concentration as an indicator of faecal contamination has been depicted in Fig. 7. The removal of *E. coli* was affected by the three operating parameters under testing. These findings agreed with the ANOVA results (Table 5) where particle size, filter depth and flow rate were significant factors in *E. coli* reduction ($p < 0.05$). Overall, the range of *E. coli* reduction in the fifteen biochar filtration configurations was 47.9–97.7 % (up to 2-log reduction) (Table 4). *E. coli* removal increased as the filter depth increased in length and the biochar particle decreased in size (Fig. 7a). High *E. coli* removal above 90 % was also observed when the biochar particle size and flow rate were kept in the range of 0.5–1.5 mm and 1.2–2.1 L/h, respectively (Fig. 7b). Similar reduction levels were observed for biochar filters operated at a filter media depth and flow rate of 21–30 cm and 1.3–2 L/h, respectively (Fig. 7c).

These results corroborated the findings of *E. coli* reduction from greywater in the biochar filtration system previously reported. Perez-Mercado et al. [33] and Enaime et al. [19] reported that higher fractions of micropores in smaller biochar particles increased microbial contact with the surface, favouring microbial adsorption through electrostatic interactions. In the same way, Perez-Mercado et al. [33] demonstrated that a high flow rate caused less contact time between microbes and the biochar surface. This affected the formation of biofilm layers on the biochar surface decreasing the *E. coli* removal through the biofilm straining process. In the case of filter media depth, longer filter media depths facilitated microbial reduction via biofilm adsorption and biofilm straining along the biochar filter [22,31]. In the literature, the removal of *E. coli* from handwashing wastewater has been achieved using chlorination, ozonation and UV. For instance, Reynaert et al. [10] and Oloput et al. [17] achieved <1 and 0 CFU/100 mL in recycled handwashing wastewater treated with chlorination, respectively. In the present study, effluent samples from biochar filtration still showed *E. coli* colonies. This was expected because biochar filters were fed with synthetic handwashing wastewater having much higher *E. coli* concentrations than usual *E. coli* levels in real handwashing wastewater (Table 3).

Overall, the incorporation of biochar filtration along with portable handwashing facilities for handwashing wastewater treatment and treated water reuse for handwashing can improve the hygiene quality

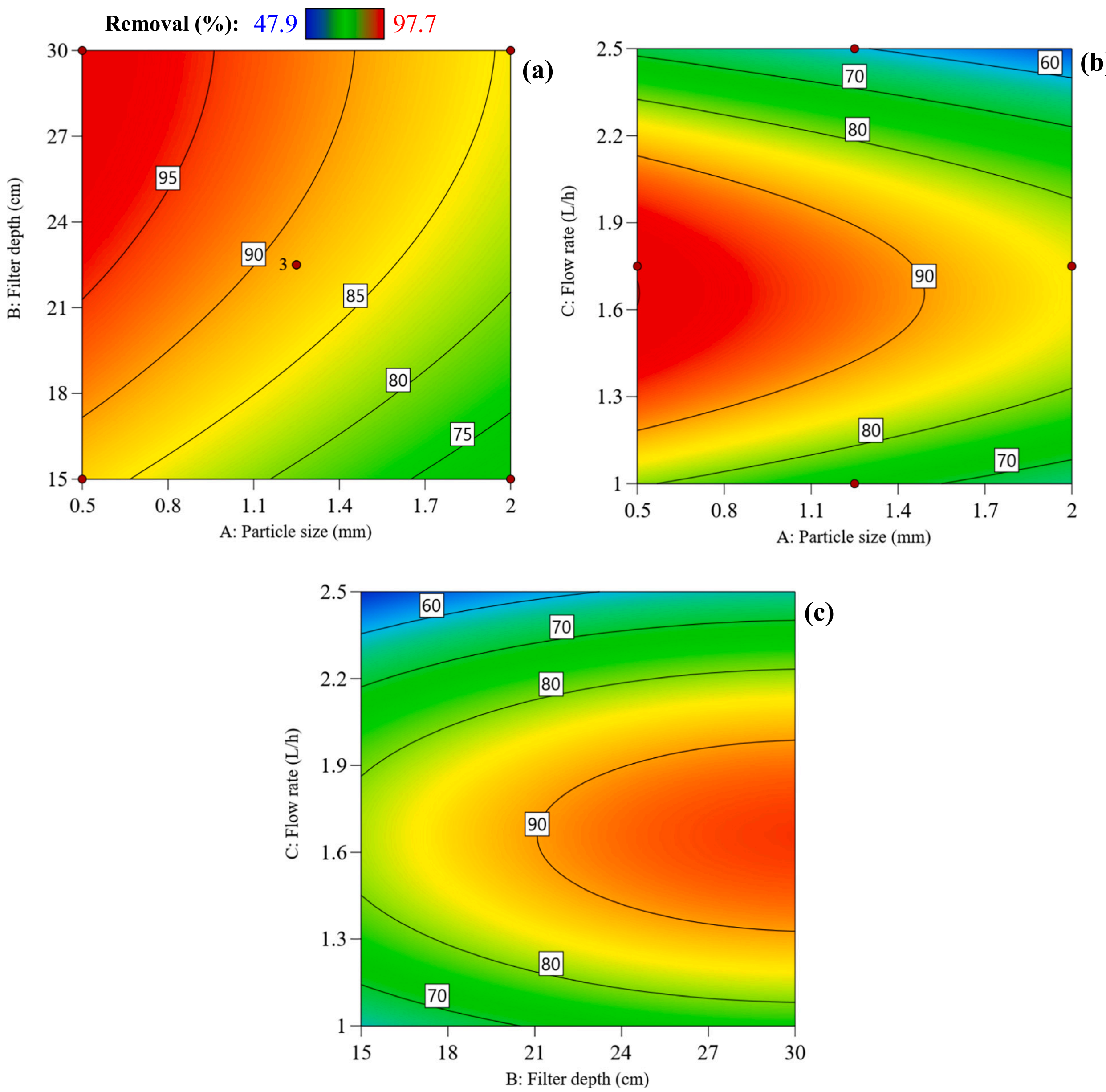

Fig. 7. 2D contour plots of *E. coli* removal. (a) Interaction of particle size and filter depth at a flow rate fixed at 1.75 L/h. (b) Interaction of particle size and flow rate at filter depth fixed at 30 cm. (c) Interaction of filter depth and flow rate at particle size fixed at 1 mm.

(microbial safety) of synthetic handwashing wastewater to a certain level. As this study used synthetic handwashing wastewater as a feeding influent, further research should study the performance of biochar filtration to remove *E. coli* when fed with real handwashing wastewater. Additionally, the removal of microbes such as total coliforms and heterotrophic bacteria using biochar filtration can be further investigated. Exploring the removal of a wider range of microbial pollutants can help ensure microbial safety on treated handwashing wastewater [75] in compliance with international water quality guidelines (e.g., drinking water and water reuse regulations) (Table 9). Furthermore, evaluating the microbial removal performance of the filters in the long term is essential to estimate the life span of the system and suggest successive treatment steps if needed. For instance, chlorination disinfection can be studied as a secondary treatment after biochar filtration to facilitate the presence of free chlorine (0.2 mg/L) in treated handwashing wastewater to ensure total microbial safety [10].

3.5. Process optimisation and validation of the models

The optimisation of the biochar filtration parameters was determined by setting the desired targeting goals of the responses in the Design-Expert Software. The range of independent variables was kept the same for filter depth (15–30 cm) and flow rate (1–2.5 L/h). A particle size range of 1–2 mm was chosen instead of 0.5–2 mm. This was because the production of 0.5 mm particle size required long grinding and sieving processes, high amounts of rinsing water and high biochar dust volumes. Hence, a particle size range between 0.5 and 2 mm was selected for further process optimisation to make biochar production more technically feasible in real-life conditions. The desired targeting goal for the responses was to maximise the removal of colour, turbidity, phosphates and *E. coli* from the reported removal range (Table 4). The reported removal range of colour, turbidity, phosphates, and *E. coli* was 78.1–95.8, 83.6–96.4, 67–86.4 and 47.9–97.7 %, respectively. A summary of the factors for choosing the optimal parameters for biochar filtration can be found in Table S5.

The optimal conditions were identified at 1.25 mm particle size, 30 cm filter depth and 1 L/h flow rate. The ramp function graph of desirability as suggested by the Design-Expert Software showed both the predicted values of all the responses obtained at the optimal conditions and the composite desirability value. The removal of colour, turbidity, phosphates and *E. coli* at optimal conditions was predicted as 97.06, 97.5, 82.67 and 73.06 %, respectively. The optimisation process in achieving the maximising goal of each response had composite desirability of 0.79 which means that the BBD is effective in optimising the filtration parameters (particle size, filter depth and flow rate) to achieve high removal efficiencies of colour, turbidity, phosphates and *E. coli*. Fig. S2 shows the ramp graphs of predicted removals under optimised conditions and composite desirability provided by Design-Expert Software (see supplementary information).

The performance of three biochar filters with the same configuration, operation, and optimised parameters demonstrated that the experimental removal efficiencies for the four responses aligned closely with the model-predicted removal efficiencies. Experimental removal efficiency means of 97.63, 97.93, 80.93 and 75.33 % were reported for colour, turbidity, phosphates and *E. coli*, respectively. Meanwhile, the predicted means from the models for colour, turbidity, phosphates and *E. coli* were 97.06, 97.50, 82.67 and 73.06 %, respectively. As can be seen in Table 7, the mean experimental values for all the responses were within the range of 95 % PI low and 95 % PI high which validated the models and suggested their reliable predicted capability [38].

Table 7
Model validation experiments (α = 0.05).

Analysis	Predicted Mean	Std. Dev.	N	95 % PI low	Experimental Mean	95 % PI high
Colour removal (%)	97.06	1.30	3	94.62	97.63	99.50
Turbidity removal (%)	97.50	1.27	3	95.15	97.93	99.85
Phosphates removal (%)	82.67	1.96	3	79.41	80.93	85.94
E. coli removal (%)	73.06	1.52	3	70.03	75.33	76.08

Std. Dev.: standard deviation; PI: prediction interval.

3.6. Performance of the optimised filter in removing other water quality parameters

The set of three biochar filters tested for the validation of the regression models simultaneously reduced COD, TSS, nitrates, ammonium, hardness, sulphates, and chloride in the synthetic handwashing wastewater. The removal of COD, TSS, nitrates, ammonium, hardness, sulphates, and chloride was 56.3, 94.5, 6.1, 92.4, 61.3, 54.7 and 4.3 %, respectively (Table 8). In the literature, few recent technologies have been used for the treatment of handwashing wastewater and the reuse of treated water for handwashing. Olupot et al. [10] developed a two-step system composed of in-series filtration (silica sand, zeolite and granular activated carbon) and chlorine disinfection. Reynaert et al. [17] designed a four-step treatment system called Autarky composed of an aerated bioreactor, ultrafiltration, activated carbon filtration and chlorine disinfection via electrolysis. Olupot et al. [23] used a roughing silica sand filtration unit with optimised particle size, filter depth and flow rate conditions. A comparison between the biochar filtration system in the present study and the ones reported in the literature revealed different performances for the removal of physical, chemical and microbial pollutants from handwashing wastewater.

Regarding the physical parameters, effluent water analysis showed colour, turbidity and TSS concentrations of 5916 mg/L Pt (19.81 % removal), 337 FTU (55.02 % removal) and 151.6 mg/L (52.51 % removal) for the optimised silica sand filtration [23]. Additionally, colour, turbidity and TSS values of 10 mg/L Pt (98.1 % removal), 5 FTU (98.5 % removal) and 9 mg/L (96.9 % removal), respectively, were reported for the in-series filtration [10]. Meanwhile, the handwashing wastewater treatment system in the Autarky handwashing facility reached values of 0 mg/L Pt, 0.44 FTU and 1.7 mg/L, for colour, turbidity and TSS, respectively (Table 8). In terms of the chemical parameters removal, the removal of several chemical parameters such as COD, hardness, sulphates and chloride was achieved by the optimised biochar filtration system in this study. In the literature, chemical pollutant removal was only assessed through COD tests. For instance, Oloput et al. [23] and Reynaert et al. [17] found COD levels of 757.50 mg/L O_2 (5.19 % removal) and 9.1 mg/L O_2 (99.7 % removal) in treated handwashing wastewater. COD removal was much higher with the treatment system from the Autarky facility compared to optimised biochar filtration in this study. However, it is worth mentioning that this study assessed the removal of a wider range of chemical water pollutants (e.g., hardness, sulphates, chloride) in contrast to the reported literature (Table 8).

In terms of nutrient removal such as phosphates and nitrates, effluent samples from the optimised biochar filtration system contained 17.8 mg/L PO_4^{3-} (80.9 % removal) and 17.3 mg/L NO_3^- (6.1 % removal) while effluents from the Autarky facility reported 4.4 mg/L PO_4^{3-} (99.9 % removal) and 5.5 mg/L NO_3^-. Generally, phosphates levels in effluent samples were greatly removed by both systems. However, enhancement in the biochar filtration technology or successive treatment steps are still needed to overcome the relatively low nitrates removal efficiency (Table 8). Concerning microbial removal, the treatment systems proposed by Reynaert et al. [17] and Oloput et al. [10] removed almost

Table 8
Comparison of removal performance between the optimised biochar filtration system and other handwashing wastewater treatment technologies.

		This study			Oloput et al. [23]			Reynaert et al. [17][a]			Oloput et al. [10]		
Parameter	Units	Inf.	Eff.	Rem. (%)	Inf.	Eff.	Rem. (%)	Inf.	Eff.	Rem. (%)	Inf.	Eff.	Rem. (%)
Temperature	°C	18.0 ± 0.6	17.4 ± 0.2										
pH		6.9 ± 0.0	7.5 ± 0.3		6.76	6.87			8		5.55		
EC	μS/cm	693.6 ± 32.3	760.8 ± 9.7						2490				
Colour	mg/L Pt	902.2 ± 16.4	21.7 ± 10.1	97.6 ± 1.1	7378	5916	19.81		0		637.33	10	98.1
Turbidity	FTU	171.1 ± 4.2	3.6 ± 1.7	97.9 ± 1.0	775	337	55.02		0.44		348	5	98.5
BOD_5	mg/L				417	284.75	31.71						
COD	mg/L O_2	360 ± 36.1	157.8 ± 20.4	56.3 ± 1.3	799	757.5	5.19	510	9.1	99.7			
TSS	mg/L	170.4 ± 13.2	9.1 ± 3.8	94.5 ± 2.6	288.8	151.6	52.51		1.7		471.67	9	96.9
Phosphates	mg/L PO_4^{3-}	93.2 ± 2.8	17.8 ± 1.6	80.9 ± 1.3				10.7	4.4	99.9			
TN	mg/L N							73.8	9.1	98.5			
Nitrates	mg/L NO_3^-	18.5 ± 3.1	17.3 ± 2.0	6.1 ± 5.0					5.5				
Ammonium	mg/L NH_4^+	1.0 ± 0.1	0.1 ± 0.0	92.4 ± 3.3					0.16				
Hardness	mg/L $CaCO_3$	344.4 ± 9.6	133.3 ± 33.3	61.3 ± 9.6									
Sulphates	mg/L SO_4^{2-}	140.9 ± 3.9	64.0 ± 11.6	54.7 ± 7.0									
E. coli	CFU/mL	24,166.7 ± 3617.1	6016.7 ± 1976.3	75.3 ± 6.0					<1α				n.d.
TRC	mg/L								0.2				
Chloride	mg/L Cl^-	47.1 ± 1.0	45.1 ± 2.0	4.3 ± 2.5									

EC: electrical conductivity; BOD_5: biological oxygen demand after five days of incubation; COD: chemical oxygen demand; TSS: total suspended solids; TN: total nitrogen; TRC: total residual chlorine.
n.d.: not detected.
α: expressed as the Most Probable Number per 100 mL (MPN/100 mL).
[a] Values reported for the Handwashing facility Durban.

Table 9
Drinking water and water reuse regulations in different countries worldwide.

Parameter	Units	Drinking water regulations					Water reuse regulations						
		Peru	EU	WHO	EPA	Australia	Germany	China	Japan	USA	Malaysia	Jordan	Italy
BOD_5	mg/L						5	<20	<20	10	12		
COD	mg/L	10									100	100	100
Temperature	°C	15–35		12–25									
Detergents	mg/L	0.5	0.2		0.5			1				100	
EC	μmho/cm	1500	2500[a]	400[a]							6000	1500	
Colour	Pt/Co	15	α	15	15	15							
Turbidity	NTU	5	α	5	0.5–1	5		<20	<2	<2			
pH		6.5–8.5	5.5–9.0	6.5–8.5	6.5–8.5			6–9	5.8–8.6	6–9	5–9	6–9	6–9.5
Chloride	mg/L Cl^-	250	250	250	250	250							
Hardness	mg/L $CaCO_3$	500		500	500	200							
TDS	mg/L	1000		<1000	500	500		<1000			4000		
TSS	mg/L	25	25								300		
Ammonium	mg/L NH_4^+							<20		<5			
Ammonia	mg/L NH_3	1.5				0.5					2.7		
Nitrates	mg/L NO_3^-	50	50	10	10	50							
Phosphates	mg/L PO_4^{3-}	0.4	0.4										
Sulphates	mg/L SO_4^{2-}	250	250	250	250	250							
TC	CFU/100 mL	0	50β	0	0	0	<100		<1000		50,000		
FC	CFU/100 mL						<10	<3		0	5000		
E. coli	CFU/100 mL	0	0	0	0	0							
Purpose		P	P	P	P	P	TF	IR	TF	TF,I,CW	I	DR	IR,DR
Reference		[78]	[79]	[80]	[81]	[82]	[83]	[84]	[85]	[86]	[87]	[88]	[89]

EU: European Union; WHO: World Health Organisation; EPA: Environmental Protection Agency.
BOD_5: biological oxygen demand after five days of incubation; COD: chemical oxygen demand; EC: electrical conductivity; TDS: total dissolved solids; TSS: total suspended solids; TC: total coliforms; FC: faecal coliforms.
P: potable, TF: toilet flushing, IR: irrigation, CW: car washing, DR: domestic reuse.
α: acceptable to consumers and no abnormal change.
β: expressed as the Most Probable Number per 100 mL (MPN/100 mL).
[a] μS/cm.

completely *E. coli* concentrations. Meanwhile, this study's biochar filtrations reduced the *E. coli* concentration by 75.3 % (6016 CFU/mL). Although the *E. coli* removal with biochar filtration was lower than the findings in Reynaert et al. [17] and Oloput et al. [10], it is relevant to point out that these authors used chlorine disinfection to target microbial reduction. Optimised biochar filtration, on the other hand, was operated with a worst-case scenario of faecal contamination and without any successive chemically-based method to remove *E. coli*. Despite that, biochar filtration was able to reduce the *E. coli* contamination from the synthetic handwashing wastewater to a certain level (Table 8).

The existing international drinking water and water reuse regulations (Table 9) were used as reference guidelines for good/high-quality water in light of the lack of water quality regulations for reusing treated handwashing wastewater for handwashing purposes. These guidelines served to evaluate the overall quality of treated handwashing wastewater and determine its potential for reuse in handwashing activities. Biochar filtration with optimised operating conditions appeared to remove several water pollutants from handwashing wastewater to concentrations below the current guidelines for drinking water and water reuse in different countries. Physical parameters such as temperature, pH (7.5), electrical conductivity (760.8 μS/cm) and turbidity (3.6 FTU) were found in compliance with drinking water guidelines from the World Health Organisation (WHO), European Union (EU), Environmental Protection Agency (EPA), Australia and Peru (Table 9). In terms of colour, the effluent had 21.7 mg/L Pt, which was a little higher than the limit values for drinking water quality. Chemical contamination such as hardness (133.3 mg/L $CaCO_3$), sulphates (64.0 mg/L SO_4^{2-}) and chloride (45.1 mg/L Cl^-) was detected below the WHO, EU, EPA, Australian and Peruvian drinking water guidelines. On the other hand, the COD (157.8 mg/L O_2) level was above the drinking water and water guidelines listed in Table 9. Concerning nutrient removal, nitrogen-based compounds such as nitrates and ammonium were reported below the Peruvian, EU and Australian drinking water and the Chinese and American water reuse (e.g., irrigation, toilet flushing and car washing), respectively. Regarding microbial water quality, although the biochar filtration lacked a secondary treatment targeting microbial disinfection (e.g., chlorination), the system reduced 75.3 % (2-log removal) of *E.coli* concentration (21,350 CFU/mL) resembling a worst-case scenario of faecal contamination.

Overall, most of the water quality parameters were below or slightly higher than the acceptable level of international norms for drinking water and water reuse. This means that biochar filtration has the potential to be a low-cost and sustainable technology for on-site handwashing wastewater treatment and treated water reuse. Thus, biochar filtration can be an alternative to other available technologies listed in Table 10. Biochar filtration can improve the water quality of handwashing wastewater and thus enable its reuse in handwashing. However, hand-to-mouth contact should be strictly avoided to prevent any infection risk [77]. Even though the treated handwashing wastewater in this study met several water quality parameters for drinking water, its reuse should not be intended for that purpose. Water for drinking applications requires the compliance of a wider range of water quality parameters that can only be achieved with much more sophisticated water treatment technologies. Further studies should examine in-series biochar filtration and the addition of chlorination as a second-step process to enhance the microbial removal performance of biochar filtration to ensure microbial safety of the treated handwashing wastewater.

3.7. FTIR analysis of biochar filter media before and after handwashing wastewater treatment

The FTIR spectra of biochar samples taken from the filter media of the optimised biochar filter before and after the treatment of synthetic handwashing wastewater are shown in Fig. 8. The FTIR spectra of the raw wheat straw biochar showed peaks at 3645.4 cm^{-1} (-O-H alcohol group), 3051.7 cm^{-1} (C—H aromatic group), 1919.6 cm^{-1} (C═O carbonyl group), 1597.1 cm^{-1} (C═C aromatic group), 1436.1 cm^{-1} (-CH_3 alkene group), 1224.5 cm^{-1} (C-O-C aromatic ether group) and 757.5 cm^{-1} (=C-H aromatic group) [90]. After raw biochar was exposed to synthetic handwashing wastewater, a change in absorption intensity, a shift in the wavenumber of functional groups and the formation of new absorption bands were observed in the FTIR spectra [91]. In the used biochar sample, an increase in peak intensity suggested an increase in the amount of the functional groups attached to the molecular bond [92]. After interaction with handwashing wastewater, the absorption band of -O-H, C—H, C═O and C═C groups (grey boxes) shifted to 3651.5, 3054.9, 1896.6 and 1614.2 cm^{-1}, respectively (green boxes). Furthermore, the absorption band of -CH_3 and C-O-C disappeared. A shift in peak position was an indication of a change in electron distribution in the molecular bond [90]. New absorption bands were also identified in the FTIR spectra of biochar samples after handwashing wastewater treatment. For instance, peaks at 3621.6–3745.4, 2917.7, 2352.8, 1696.2, 1400.9–1419.5, 1109.2, 1020.5 and 817.0 cm^{-1} demonstrated the presence of -O-H, C-H_n (alkene), NH_2 (amine), C═O, NH_4^+ (ammonium) and CO_3^{2-} (carbonate), SO_4^{2-} (sulphates), SiO_4^{4-} (silicate) and NO_3^- (nitrates), respective, on the biochar surface [93]. Overall, the differences in the FTIR spectrum demonstrated the capacity of biochar filter media to eliminate organic pollutants from handwashing wastewater through the process of biochar filtration.

Table 10
Available handwashing technologies with an on-site wastewater treatment system for treated water reuse.

Name	Treatment chain	Origin	Application	Water quality parameters	Reference
Gravit'eau	Sand and grease trap + ultrafiltration membrane + chlorination (optional) + activated carbon filter (optional)	France and Switzerland	Nigeria, Burkina Faso, Mali. Palestine, Germany,	Viruses and bacteria	[16]
Autarky handwashing facility	Aerated bioreactor + ultrafiltration membrane + granular activated carbon + electrolysis (for chlorine disinfection)	Switzerland	South Africa	pH, COD, residual chlorine, *E. coli*, turbidity, TSS	[11,17]
Handwashing facility with wastewater filtration system	Filtration with silica sand, zeolite and granular activated carbon + disinfection with chlorine	Uganda	Uganda	Turbidity, true colour, apparent colour, TSS, TC and *E. coli*	[10]
Automatic handwashing facility	Reverse osmosis	Indonesia	Indonesia	Not mentioned	[100]
Handwashing facility with water recycling system	Filtration with silica sand	Uganda	Uganda	TSS, turbidity, apparent colour, true colour, BOD_5 and COD	[23]
WOSH	Sediment filtration + activated carbon filtration + reverse osmosis membrane + UV rays + chlorine disinfection	Japan	Japan	Viruses and bacteria	[76]

COD: chemical oxygen demand; TSS: total suspended solids; TC: total coliforms; BOD_5: biological oxygen demand after five days of incubation; UV: ultraviolet.

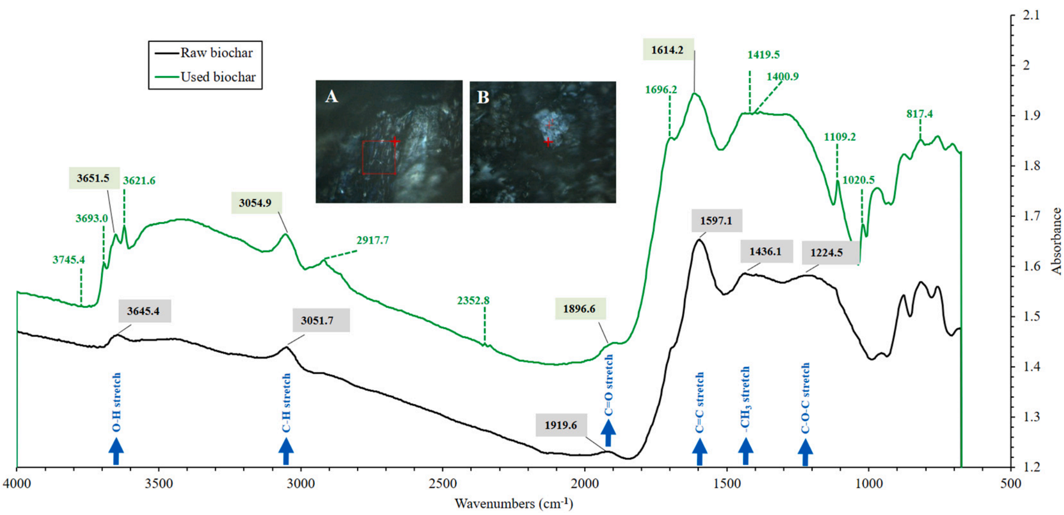

Fig. 8. FTIR spectra of biochar filter media before.

4. Potential use of biochar filtration in handwashing facilities with on-site wastewater treatment

Low contamination in handwashing wastewater makes this type of wastewater a potential source of water reuse because it does not require the same in-depth, expensive and centralised treatment process as domestic wastewater [94]. Treated handwashing wastewater may reduce water needs for handwashing activity in countries lacking continuous water frequency service, improved water sources and water quality to help mitigate the transmission of water-borne diseases [12]. Six handwashing facilities with on-site technologies for wastewater treatment and treated water reuse have been developed in the last decade to sustainably manage water in the circular economy context [13]. The majority of these technologies have incorporated a treatment chain mechanism composed of a sediment and grease trap, membrane filtration, reverse osmosis, filtration (granular activated carbon, silica sand and zeolite) and disinfection with chlorination or UV rays (Table 10). Most of these handwashing facilities were designed in high-income countries such as France, Switzerland and Japan and further field-tested in low- and middle-income countries located in Africa, South-east Asia and the Middle East. Although water quality regulation for the reuse of treated handwashing wastewater is not yet available [95], the effluents from these technologies have been reused for handwashing purposes. This is because they have been able to remove water quality parameters from handwashing wastewater to a certain extent in agreement with guidelines for high or improved quality water (e.g., drinking water and water reuse standards; Table 9).

The biochar filtration system with optimised operating conditions evaluated in the present study represents an advance in addressing the knowledge gap of modelling biochar filtration parameters to predict pollutants removal. Unlike the wastewater treatment technologies incorporated in handwashing facilities described in Table 10, the filtration system in this investigation used biochar as the main pollutant removal agent. Compared to adsorbents such as silica sand and zeolite, biochar is an adsorbent produced by the thermal decomposition of organic waste materials such as agricultural and forestry wastes [96]. Therefore, the use of biochar as an adsorbent waste-based material for handwashing wastewater treatment and treated water reuse for handwashing activity can be considered a synergetic strategy to promote the circular economy in both the water and waste sectors [21]. Technically, the configuration and set-up of biochar filtration are simpler, less costly, less energy-demanding, less time-consuming for maintenance and less dependent on foreign pieces of equipment [18]. These characteristics make the implementation of biochar filtration systems for handwashing wastewater treatment and treated water reuse more feasible for low and middle-income countries than the rest of the technologies listed in Table 10 [97].

In regards to water quality, the present study evaluated the performance of the optimised biochar filtration system for the removal of a wide range of pollutants in handwashing wastewater compared to the technologies previously described. Most water quality parameter values in the effluent samples were found below the limit concentrations for drinking water and water reuse in different countries worldwide (Table 9). Although guidelines for reusing handwashing wastewater are lacking, the similar effluent quality between biochar filtration and Graviteau, Autarky, and WOSH technologies suggests that biochar filtration can also be used in handwashing wastewater cleaning for further treated water reuse in handwashing applications in the field.

4.1. Practical implementation and development prospects

Biochar filtration can be utilised to treat wastewater generated by portable handwashing facilities (e.g., buckets with taps and tippy-taps) commonly used in community settings of developing countries [2,3]. The application of biochar filtration holds the potential to enhance the quality of handwashing wastewater, enabling its reuse in public places that have limited access to water supply and lack piped wastewater drainage systems. Such public places include remote rural schools, healthcare buildings and spaces of religious worship.

However, the widespread application of biochar filtration for handwashing wastewater treatment and treated water reuse is currently hindered by the absence of an established framework regarding water quality standards. In this study, international water quality regulations for drinking water and restricted water reuse were used as reference guidelines to assess the quality of treated handwashing wastewater within permissible parameters for water reuse in handwashing. Nevertheless, to further promote the adoption of biochar filtration, it is imperative to develop specific water quality standards for the reuse of treated handwashing wastewater in emerging small-scale wastewater cleaning technologies implemented in resource-poor countries [95].

The successful implementation and continued functionality of biochar filtration would depend on the availability of local or nearby agricultural and forestry residues for biochar production. However, within the current context of the circular economy, the concept of industrial symbiosis between the agricultural and water/wastewater treatment sectors could facilitate the supply of waste residues for biochar production in settings where excess biomass is not readily available [21]. For instance, local or regional agricultural companies could contribute their agricultural biomass wastes as raw materials for community-level biochar production.

Furthermore, the utilisation of biochar filtration would rely on the presence of small-scale pyrolysis reactors for biochar production and the knowledge of users regarding their construction and operation. Notably, the UK Biochar Research Centre has developed prototypes of small-scale pyrolysis units for local biochar production [98]. Therefore, the successful implementation of biochar filtration would necessitate the involvement of various stakeholders, including local government offices, universities and private companies, to establish pyrolysis reactors capable of consistently supplying biochar as a filter media.

Another crucial aspect to consider is the management of biochar filter media once it has reached the end of its lifespan. Used biochar filter media can be repurposed as a soil improver. However, pre-treatment processes (e.g., thermal treatment) aiming to eliminate adsorbed organic chemical compounds (e.g., SDS) and pathogens (e.g., *E. coli*) would be necessary to prevent potential damage to soil properties and plant germination [8]. Additionally, it is vital to safely dispose of regenerated handwashing wastewater that does not meet the requirements for reuse for handwashing. This objective can be achieved by constructing covered soak-pit systems to filter regenerated handwashing wastewater [99]. By combining a soak-pit system with biochar filtration, direct human contact, stagnant water, unpleasant odours and the breeding of vector mosquitoes can be effectively prevented [9].

4.2. Future research

This study primarily focused on determining the optimal parameters for biochar filtration to effectively remove colour, turbidity, phosphates, and *E. coli* from handwashing wastewater for potential water reuse in handwashing applications. However, further research on biochar filtration is necessary to promote its widespread implementation. Additionally, studying the long-term performance of optimised biochar filtration systems would provide insights into system stability over time and the interactions involved in pollutant removal processes. Exploring the optimisation of additional filtration parameters (e.g., organic loading rate, hydraulic retention time) would enhance understanding of how operational conditions impact pollutant removal. Furthermore, evaluating a broader range of microbial water quality parameters (e.g., heterotrophic bacteria, viruses, thermotolerant bacteria) is crucial to ensure the microbial safety of treated handwashing wastewater. Improving the performance of biochar filtration can be achieved by conducting optimisation studies on biochar production conditions to yield biochar with desirable physicochemical properties for efficient pollutant removal. Additionally, further characterisation of the biochar filter media after filtration is necessary to gain a comprehensive understanding of pollutant adsorption on the biochar surface (e.g., XPS analysis). Conducting an economic assessment would facilitate a comparison of the costs and benefits between biochar filtration and other available wastewater treatment technologies. Moreover, exploring sustainable strategies for the regeneration and reuse of used biochar filter media as a soil amendment for common crop cultivation in developing countries should be undertaken. By addressing these areas in future research, a broader understanding of optimised biochar filtration can be achieved, which would enhance its implementation as a decentralised wastewater treatment technology for water reuse in water-scarce community settings in resource-poor countries.

5. Conclusion

This study used RSM to optimise biochar filtration parameters such as particle size (range 0.5–2 mm), filter depth (range 15–30 cm) and flow rate (range 1–2.5 L/h) for the removal of colour, turbidity, phosphates and *E. coli* from synthetic handwashing wastewater. Fifteen biochar filtration configurations were suggested by the Design-Expert Software to evaluate the combined impact of filtration parameters on selected pollutants removal. A quadratic regression model ($p < 0.05$) was proposed by the Design-Expert Software to predict the removal of each parameter under the influence of filtration operating conditions. Statistical and practical significance tests demonstrated that the models fit the experimental data and are accurate in predicting pollutant removal. Optimal biochar filtration conditions for particle size, filter depth and flow rate were found to be 1.25 mm, 30 cm and 1 L/h, respectively. Models predicted removal efficiencies of 97.06, 97.50, 82.67 and 73.06 % for colour, turbidity, phosphates and *E. coli*, respectively. The models were validated by examining biochar filter performance under optimal operating conditions. Experimental data showed removal efficiencies of 97.63, 99.85, 85.94 and 76.08 % for colour, turbidity, phosphates and *E. coli*, respectively. Removal values were within the range of 95 % PI low and 95 % PI high validating the predictive capability of the developed models. Biochar filter operated at optimal conditions also achieved 56.3, 94.5, 6.1, 92.4, 61.3, 54.7 and 4.3 % removal for COD, TSS, nitrates, ammonium, hardness, sulphates and chloride, respectively. The concentrations of several water quality parameters were below acceptable limits for available water quality standards (e.g., drinking water and water reuse applications). This innovative approach can help manage wastewater sustainably while providing clean water for handwashing purposes (SDG 6) in poor settings lacking handwashing infrastructure, continued water service and good-quality water sources. However, further studies should focus on studying the long-term stability of biochar filtration, monitoring a wider range of water quality parameters, enhancing the properties of biochar filter media, deepening the understanding of pollutant adsorption on biochar surface and performing a cost-benefit analysis of this technology.

CRediT authorship contribution statement

Jhonny Ismael Bautista Quispe: Conceptualisation, Methodology, Data collection, Data analysis, Data visualisation, Artwork, Writing – original draft. **Anna Bogush:** Supervision, Conceptualisation, Funding, Resources, Data collection (FTIR analysis), Writing, Review & editing. **Luiza Campos:** Supervision, Review & editing. **Ondrej Mašek:** Supervision, Review & editing, Resources (standard wheat straw biochar).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

If data access is needed, a reasonable request should be made to the corresponding author.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2023.104001.

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