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Evaluation of the efficiency of native plant species integrated with sand filters for greywater reclamation: a pilot study

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ABSTRACT

Here we report a novel sand filter incorporated with raw plant powders (SFPPs) and their biochars (SFBCs) from native plant species for the treatment of greywater. Their performance was compared with sand filter alone (SF) and sand filter using commercial activated carbon (SFAC). The filters were operated for 24 h at a hydraulic loading rate of 7.27 L m^{-2} d^{-1}. SFBC and SFAC showed efficient removal of hardness, turbidity, phosphate, biological oxygen demand (BOD), Cr, and Pb. Chemical oxygen demand (COD) removal was above 60% in all treatments, except SF (4%). BOD removal was highest in SFBC (81%) and lowest in SF (19%). The COD/BOD ratio of raw greywater (1.6) indicates the biodegradability of raw greywater. Nitrate and phosphorous removal were higher in SFPP and SFBC (>70%) than SF. The bacterial population was negative in SFPP, especially in SF incorporated with *Aegle marmelos* (*A. marmelos*) and *Azadirachta indica*. In a phytotoxicity study with *Vigna radiata*, 90% germination was observed when irrigated with treated greywater, which was only 70% in raw greywater. Among SFPPs, *A. marmelos* reduced the pollutants in raw greywater within permissible limits, making it fit for reuse for non-potable activities, thus reducing the cost associated with the preparation of activated carbon.

Keywords: Greywater; Biochar; Sand filter; Plant powder; Activated carbon

1. Introduction

Rapid population increase and water scarcity in urban areas throughout the world seems likely to continue to spur the development of water management practices [1,2], and greywater reclamation offers one sustainable water management strategy. Greywater comprises of physical and chemical characteristics that are similar to wastewater, but without fecal contamination. Toxic metals like Pb, Ni, Cd, Cu, Hg, and Cr are found in assessable levels in greywater [3,4]. In addition, the pathogens in stored untreated greywater can generate foul odors as well as induce a change in the water chemistry that can lead to anoxic conditions [5,6]. Many studies have focused on the reuse of greywater after subjecting it to appropriate treatment technologies so as to eliminate pollutants. Then, the treated greywater can be reused for selected outdoor activities, such as toilet flushing, gardening, irrigation purposes, and groundwater recharge, thereby reducing the risk to public health [7–9].

The treatment requirements for greywater varies depending on its biological and chemical composition. Therefore, based on its characteristics, physicochemical treatments (e.g., filtration [10], coagulation [11], adsorption [12], reverse osmosis [13], and photocatalytic oxidation [14]) and biological treatments (via sequencing batch reactors [15], constructed wetlands [16], lava rock filters [17], upflow

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anaerobic sludge blanket reactors [18], biological contractors [19], and membrane reactors [20]) have been studied. In this way, the recycling and reuse of wastewater can be adopted in many countries to solve water scarcity issues. Among the various treatment technologies, sand filters are of great interest to many researchers due to their low-cost operation and maintenance, as well as their efficient removal of total solids [1,21]. Therefore, it is recommended for developing countries and rural communities [22]. Sand filters act as aerobic, fixed-film bioreactors typically operating either as a single pass or recirculating vertical flow filter. Intermittent sand filters have been recommended for nitrogen and phosphorous removal [23]. Extensive use of soil-based wastewater treatment technologies owing to their low cost, increased treatment capacity, and ready availability of microbial communities have also been reported [24,25]. Also, a two-stage trickling filter system packed with zeolite and multi-soil layering bioreactors, sequential vertical flow trickling filters, and horizontal multisoil layering bioreactors have been proven to be efficient in the removal of chemical oxygen demand (COD) and ammonium-nitrogen [26,27] for a decentralized wastewater system. However, the performance of sand filters is greatly influenced by the particle size of the sand, hydraulic loading rate, and sand layer height [1,28]. In addition, the development of biofilms in sand filters might enhance their performance [28]. The diverse microbial communities in the biofilm affect the biodegradation and mineralization of organic matter [27], as well as the assimilation of nutrients [29,30] in the wastewater. On the other hand, it has to be ensured that the excess growth of biomass in the biofilm does not clog the biofilter, thus reducing its performance [29–31].

Three major mechanisms are involved in sand filtration technology: filtration (physical removal of particles from incoming greywater), chemical sorption (sorption of pollutants on the surface of the sand and the biofilm formation on the sand surface), and assimilation (conversion of nutrients to the volatile end product by aerobic microbes) [1]. To assess the suitability of the treated greywater for irrigation purpose, phytotoxicity analysis was done on the growth of mung bean (*Vigna radiata* (L.) Wilczek) irrigated with treated filtrates. The growth parameters of the mung bean irrigated with treated greywater were compared to that irrigated with raw greywater to assess its eligibility for irrigation. Therefore, to cover all of these aspects in a pilot-scale study, the present investigation focused on the evaluation of the efficiency of the native plant species *Chrysopogon zizanioides* (*C. zizanioides*) (vetiver), *Aegle marmelos* (*A. marmelos*) (vilvam or bael), *Strychnos potatorum* (tetrankottai), and *Azadirachta indica* (neem) integrated with sand filters for the treatment and reclamation of greywater. These plant species were selected based on their cleansing properties, the stability of supply, availability, and economic feasibility. Raw plant powders, as well as their respective biochars, were used, and the performance was compared with commercially available activated carbon for the treatment of greywater.

2. Materials and methods

2.1. Sample collection and characteristics of greywater

A plastic bucket (25 L) was placed at an outlet pipe to collect greywater (i.e., water from kitchens, bathrooms, and washing areas) from the urban residential apartments of Coimbatore (10° 12, 11° 24 N, 76° 39, 77° 30 E). The mouth of the outlet pipe was covered with a mesh to prevent the entry of solid materials. Ten samples were collected each day for three consecutive days within 2 h in the morning (6 to 8 am) during peak domestic activities. The samples were pooled and homogenized. The physical (color, temperature, and odor), electrochemical (pH, conductivity, total suspended solids (TSS), total dissolved solids (TDS), and total solids), and chemical properties (chloride, total hardness, acidity, alkalinity, COD, biological oxygen demand (BOD), nitrate, phosphate, iron, copper, lead, zinc and chromium) [31,32] of the greywater were analyzed before and after the treatment to evaluate the efficiency of the treatment materials.

2.2. Preparation of sand filter incorporation materials

Granular activated carbon was procured from Loba Chemie Ltd., Mumbai. Raw powders of the selected plant species and their respective biochars were prepared from the four commonly available native plant species: barks of *A. india* and *A. marmelos*, seeds of *S. potatorum*, and roots of *C. zizanioides*. The materials were cut into small pieces, air-dried for 5 d to remove moisture, and then pyrolyzed at 600°C for 2 h. The uniform-sized particles (1.0–1.5 mm) were selected by sieving, and washed with deionized water to remove the impurities. Finally, all materials were air-dried in an oven at 80°C and then stored in an airtight container after cooling. The pH (measured at a ratio of 1:20 (w/v) after stirring for 1 h), electrical conductivity (measured at a ratio of 1:10 (w/w,) and carbon, hydrogen, nitrogen and sulfur (Elementar Vario EL 3) of the activated carbon and biochar were analyzed (Table 1).

2.3. Experimental setup

Floating particles and settled heavier particles from the greywater were removed after allowing it to stand undisturbed for 24 h at room temperature. The supernatant was collected and used for the experiments. Ten 5 L plastic filter columns were used in this study. The sand filter (SF-1) was filled with fine sand (1–3 mm size) and gravel (8–12 mm size). To compare the performance of various setups, the sand filter was incorporated with raw plant powders of *C. zizanioides* roots (SFPP-2), *A. marmelos* bark (SFPP-3), *S. potatorum* seeds (SFPP-4), and *A. indica* bark (SFPP-5), commercial activated carbon (SFAC-6) and plant-based biochars of *C. zizanioides* roots (SFBC-7), *A. marmelos* bark (SFBC-8), *S. potatorum* seeds (SFBC-9), and *A. indica* bark (SFBC-10) (Fig. 1). The filter systems for greywater treatment was designed for a volume of 5 L capacity. Locally available and natural materials were chosen as the components of the filter media in the filtration unit, which includes fine sand of 0–3 mm, gravel of 8–12 mm and 20–25 mm size, biochar derived from plant materials, and commercial granular activated carbon. The bed height of each material was determined and finalized by the experimentation, which was fixed as 6 cm for gravel, 6 cm for small gravel, 8 cm for sand, 5 cm for the experimental plant powders and biochar, and 3 cm for the pebble (Fig. 1). For each treatment, 5 L of greywater was allowed to flow by gravity at

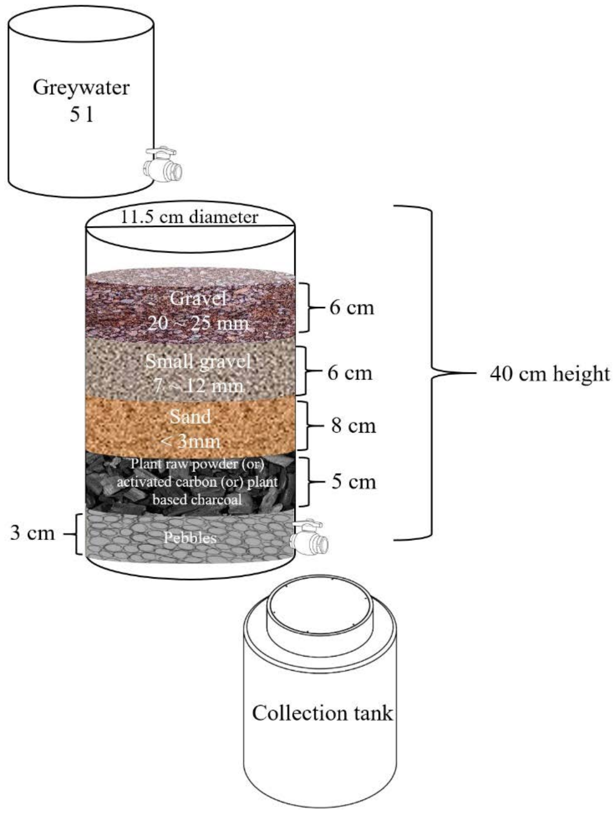

Fig. 1. Experimental design of the sand filter column.

the rate of 20 ml min^{-1}, at a hydraulic loading rate (HLR) of 7.27 L m^{-2} d^{-1}. The treated greywater was collected at the base of the filter using a tap. The physicochemical parameters of the filtrates were analyzed.

Growth of mung bean (*Vigna radiata* (L.) Wilczek) in greywater and in the treated filtrates.

The seeds of *V. radiata* exposed to ultraviolet (UV) light in a laminar flow chamber were surface sterilized with 70% ethanol for 3 min and then washed with mercuric chloride ($HgCl_2$) for 2 min to avoid fungal contamination. Finally, the seeds were washed five to six times with double-distilled water. Two-hundred grams of sieved garden soil collected from agricultural land (pH 7.2) were used for pot culture studies. Triplicate pots irrigated with treated waters from all sand filters were used to maintain the moisture content of 60%. Each pot was seeded with ten healthy seeds and observed for 7 d for germination. After 28 d, the shoot lengths and chlorophyll contents (SPAD 502 PLUS chlorophyll meter) of the different setups were measured.

2.4. Bacterial study in greywater

For the isolation and enumeration of bacteria, 1 mL of the final dilutions (10^{-2}) were aseptically transferred to sterile Petri plates, to which approximately 15 mL of sterile molten nutrient agar medium (3 g of beef and yeast extract, 5 g of peptone and sodium chloride, and 20 g of agar in 1 L of distilled water, pH 7.0 ± 0.2) was added, mixed thoroughly for uniform distribution, allowed to solidify at room temperature, and incubated for 24–48 h at 37°C. The developed bacterial colonies were isolated and counted at the end of the incubation period and expressed as colony-forming units per milliliter of grey water (CFU mL^{-1} greywater) [33].

2.5. Statistical analysis of the results

The results in triplicate (n = 3) were expressed as mean and standard deviation (mean ± SD) values. The data were subjected to one-way analysis of variance (ANOVA) with Duncan's multiple range test (DMRT) to evaluate the significance of the observed differences in the various physicochemical parameters and plant growth parameters between the raw greywater and the treated greywater groups by employing SPSS 23 statistical software.

3. Results and discussion

The color of the raw greywater was grey and possessed a highly offensive odor (Table 2). The intensity of color and odor were reduced with all treatments. However, in SFPPs, the odor of greywater was imparted with the aroma of the respective plant material after treatment, which made it aesthetically acceptable (Table 1). Figs. 2–9 show the characteristics of greywater before and after treatments (Tables 1–4). The alkaline pH (9.5), low acidity (below detection limit), and high alkalinity (1.49 mg L^{-1}) of the raw greywater might be due to the usage of bathing soap and detergents during the sampling time between 6 to 8 a.m. local time (Figs. 2 and 4) [34]. The pH was not altered by the sand filter (SF-1, pH 9.47), indicating that the sand neither absorbs nor releases any ions during treatment so as to alter the pH [28]. The pH reduction in the plant powder (SFPP 2~5, pH from 7.06 to 7.4) (Fig. 2) and biochar (SFBC-7~10, pH between 8.0 to 8.6) (Fig. 4) treatments might be due to the release of CO_2 by microbial respiration that would have gathered around

Table 1
Characteristics of commercial activated carbon and biochar prepared from various parts of plant materials

Materials	pH	Conductivity (mS cm^{-1})	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Surface area (m^2 g^{-1})
Commercial activated carbon	7.73	1.68	81.26	2.15	1.68	0.14	701.25
C. zizanioides (root)	9.66	1.67	65.26	1.96	2.56	0.10	354.12
A. marmelos (bark)	10.54	3.99	77.04	2.38	1.32	0.15	512.25
S. potatorum (seed)	10.38	10.38	70.04	0.63	2.56	0.12	256.31
A. indica (bark)	10.61	7.23	67.47	2.10	2.03	0.11	401.34

Table 2
Physical characteristics of greywater before and after treatment with sand filters and sand filters incorporated with raw plant powders

Greywater samples		Color	Odor	Temperature
Before treatment		Cloudy grey	Offensive	26.9 ± 0.15
After treatment	Sand filter (SF-1)	Pale grey	Mild offensive	27.0 ± 0.1
	Raw plant powder			
	C. zizanioides roots (SFPP-2)	Pale yellow	Aroma of herb	26.9 ± 0.06
	A. marmelos leaves (SFPP-3)	Pale brown	Aroma of herb	26.9 ± 0.1
	S. potatorum seeds (SFPP-4)	Pale green	Aroma of herb	27.0 ± 0.1
	A. indica leaves (SFPP-5)	Pale brown	Aroma of herb	26.9 ± 0.12
	Commercial activated carbon (SFAC-6)	Colourless	Odorless	26.9 ± 0.1
	Plant based charcol			
	C. zizanioides roots (SFPP-2)	Colourless	Odorless	26.9 ± 0.1
	A. marmelos leaves (SFPP-3)	Colourless	Odorless	26.8 ± 0.1
	S. potatorum seeds (SFPP-4)	Colourless	Odorless	26.9 ± 0.1
	A. indica bark (SFPP-5)	Colourless	Odorless	26.9 ± 0.06

the filter media [28]. The pH of the filtrate from the activated carbon treatment (SFAC-6) was 8.8, which was less than the other treatments. A similar result was reported for greywater treated with granular activated carbon [28]. Our results are compatible with the status of water quality in India (2011) reported by the central pollution control board in India, which fixes the permissible range of the pH value of treated wastewater for irrigation purposes to range between 5.5 to 9. The alkalinity reduction was 19% with SF-1, and the reduction was above 50% in SFAC (60% reduction), SFPP (54 to 60% reduction), and SFBC (58 to 64% reduction) treatments. This reduction was significant ($P < 0.05$) compared to the raw greywater (Figs 2 and 4).

The conductivity of raw greywater was 2.37 mS cm^{-1}, which was not significantly different when treated with SFPP and SFBC, whereas the conductivity significantly increased (8%) in SF-1 and significantly decreased (11%) with activated carbon (SFAC-6) treatment (Figs. 2 and 4). This might be due to the movement of ions between the filter materials and greywater. Increases or decreases in the conductivity can be attributed to the type of ions present in the filter materials. The turbidity of raw greywater (140 NTU) was reduced significantly (from 75% to 88%, Figs. 2 and 4) in all treatments, which might be due to the adsorption capacity of plant powders (SFPP-2~5), activated carbon (SFAC-6), and biochars (SFBC-7~10).

Significant COD reduction in raw greywater (433.67 mg L^{-1}) was observed when using SFPP (55%–68%), SFBC (50%–69%), and SFAC (64%) (Figs. 3 and 5). COD significantly reduced when using the sand filter treatment alone; however, it accounts for only 4% when compared to raw greywater (268.67 mg L^{-1}). BOD also significantly decreased with the SF (19%), SFPP (41%–61%), SFAC (59%), and SFBC (55%–81%) treatments (Figs. 3 and 5). Greywater treatment systems employing an up-flow anaerobic sludge blanket also showed a similar removal efficiency for COD (60%) and BOD (64.5%) [2]. When compared to SF, COD removal in municipal sewage water was significantly higher in SFBC (SF incorporated with *Miscanthus* biochar) [35]. This higher removal efficiency of COD in columns packed with biochar might be explained as because of the effects of biochar on the degradation process, as has been demonstrated for the anaerobic degradation process [35]. The decrease in BOD would have been attained by the degradation process and affected by the microorganisms adhered to the filter media [36], as it has been explained that sand filters act as biofilm driven systems encouraging the growth of diverse microbial communities, thus enhancing the biodegradation and mineralization of the organic matter [30,37]. The potential of the microorganisms harboring the biofilms in a vertical flow trickling filter, and a multi-soil-layering reactor was shown to decompose complex organic matter like sodium dodecylbenzene sulfonate from domestic wastewater [27]. The ratio of COD/BOD for the greywater was observed to be 1.6. A general assumption is that the ratio of COD/BOD_5 determines the rate of biodegradability of wastewater [28]. Therefore, a COD/BOD_5 ratio less than three indicates good biodegradation of wastewater, thus resulting in the reduction of COD and BOD (Figs. 3 and 5). The reduction of BOD in the treated filtrates is a healthy indication of a reduced microbial population. Removal of COD might also be facilitated by adsorption processes onto the filter media. Sato et al. [38] have reported enhanced removal of organic matters when wastewater comes into contact with soil mixture block, thus resulting in the removal of organic matters. The efficient removal of BOD_5 and COD in a multi-soil-layering system (MSL) was attributed to the high adsorption and decomposition capacity of the soils, which have high pore spaces and large specific surface areas [39] subsequently decomposed by microorganisms. Sato et al. [40] reported physicochemical mechanisms, such as filtration and adsorption, as major treatment processes at initial stages in MSL system, COD and BOD being easily trapped in the SML, because of the amount of pore space, large surface area and enhanced hydrophobic properties provided by the addition of charcoal. In the case of dissolved oxygen (DO), no difference in SF treatment was observed, but it significantly increased in SFBC (3.2–3.77 mg L^{-1}), SFAC (1.7), and SFPP (2.6–2.8 mg L^{-1}) (Figs. 3 and 5). Increases in the levels of DO of treated greywater might be due to a decrease in the BOD and COD in the treated greywater.

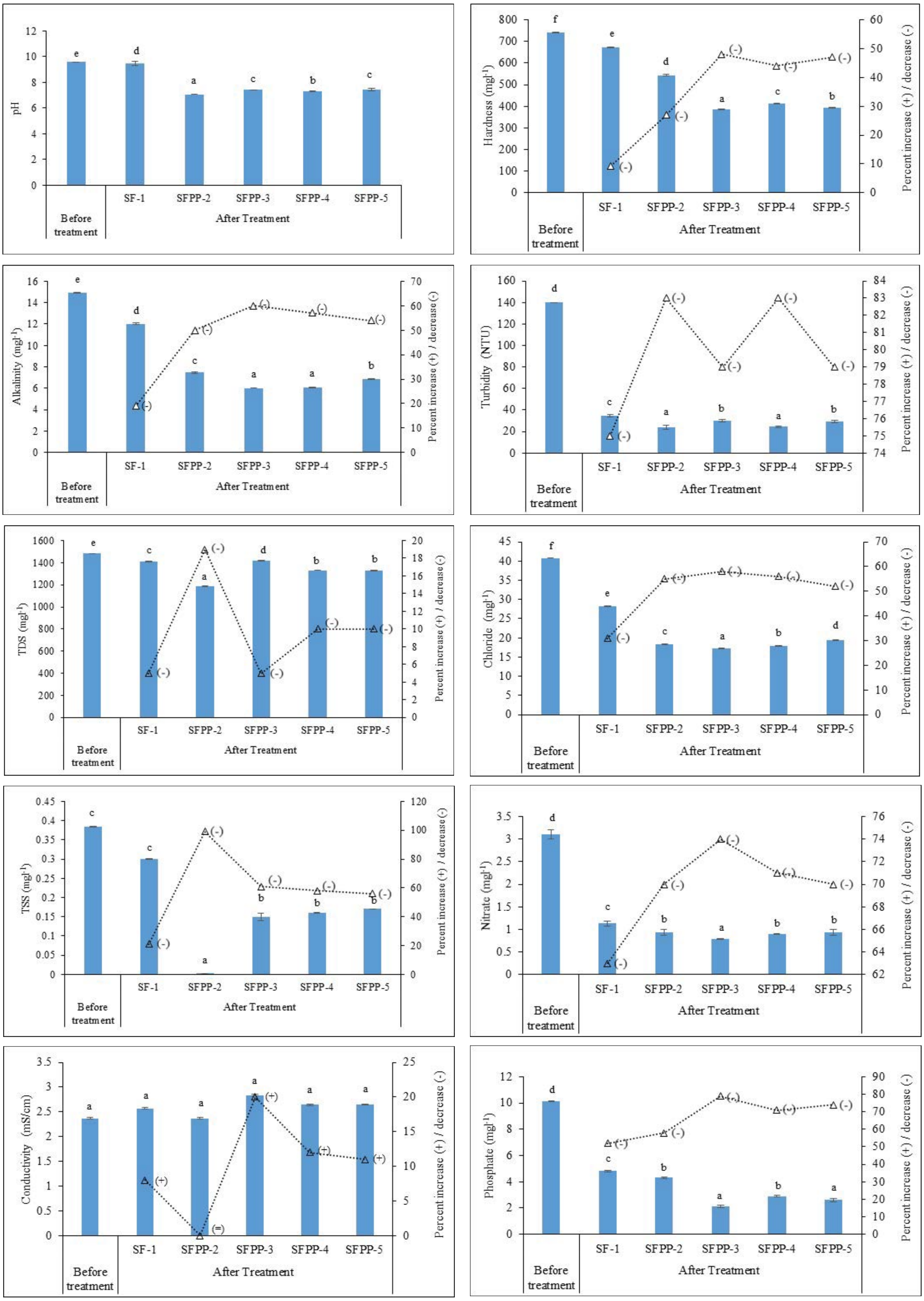

Fig. 2. pH, alkalinity, TDS, TSS, conductivity, hardness, turbidity, chloride, nitrate and phosphate of greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with raw plant powders (SFPP 2, SFPP 3, SFPP 4, SFPP 5). Percent decrease [Δ(–)] or increase [Δ(+)] or equal [Δ(=)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

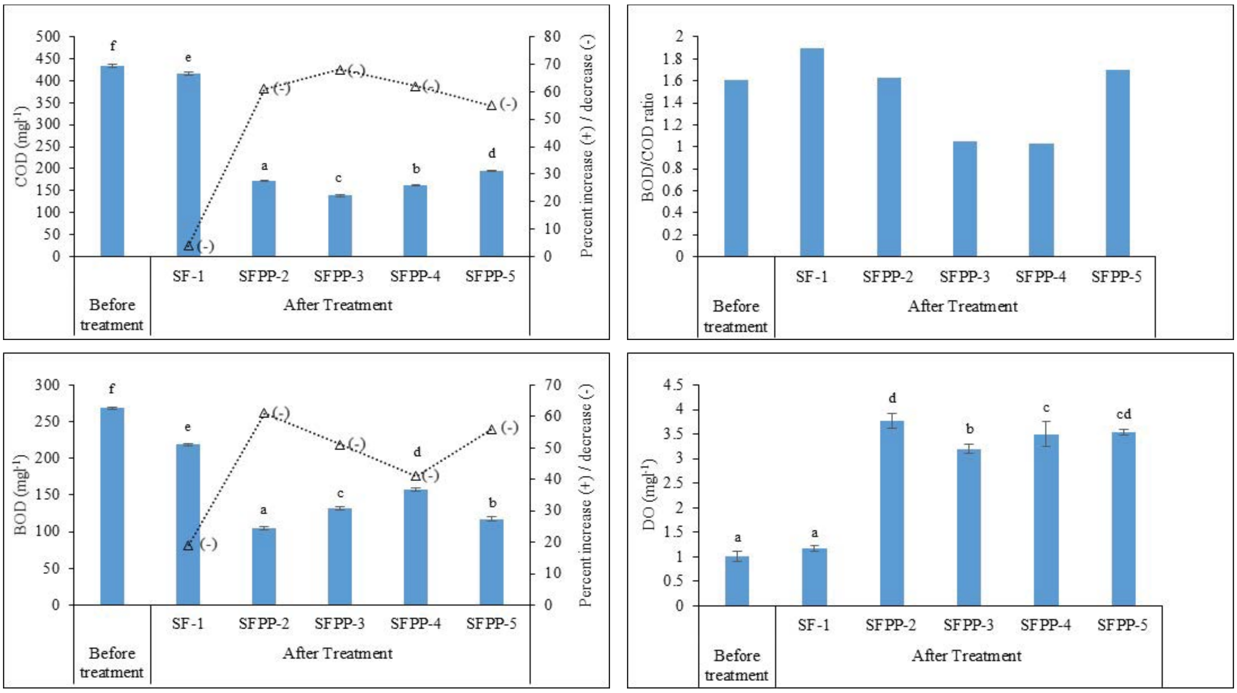

Fig. 3. COD, BOD, COD/BOD ratio, and DO of greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with raw plant powders (SFPP 2, SFPP 3, SFPP 4, SFPP 5). Percent decrease [Δ(–)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis for COD and BOD values. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$), according to DMRT.

The low concentration of phosphate (10.13 mg L^{-1}) in raw greywater is due to the recent adoption of phosphorus-free detergents by the majority of residents. As the effluent sample is from a pooled outlet, households using phosphorus-containing detergents explain their presence in the present sample. Sand filter (52%), SFPP (58%–79%), SFAC (73%), and SFBC (81%–86%) treatments reduced the phosphate level significantly (Figs. 2 and 4). The porous structure of biochar would have enabled the adsorption of phosphorous nutrients from the greywater, thus effectively reducing the phosphate concentration of the greywater [41]. However, the nitrate level was below the permitted level (3.1 mg L^{-1}); according to the World Health Organization (WHO), it reduced significantly in SF (63%), SFPP (70%–74%), SFAC (74%), and SFBC (68%–784%) treatments. The low concentration of TSS (0.384 mg L^{-1}) in our sample indicates that the contaminants are in a dissolved state in greywater [42], contributing up to 1,482 mg L^{-1} of TDS in our raw greywater samples. The TSS in the present study was 0.384 mg L^{-1}, which is less than the reported value of 17–511 mg L^{-1} [6]. The salts in personal care products and detergents would have contributed to the TDS in greywater. The significant reduction of TDS in SF (5%), SFPP (5%–19%), SFAC (29%), and SFBC (5%–20%) treatments might be attributed due to increased adsorption onto carbon and biochar (Figs. 2 and 4). As the surface area and the time of contact increases, the adsorption of dissolved solids also tends to increase [43].

Increased levels of hardness in greywater (742.3 mg L^{-1}) might be due to the presence of calcium and magnesium ions from personal care products, detergents, dishwashing soaps, and liquids. The presence of calcium and magnesium salts makes water temporarily hard. Treatment of greywater onto SF (9.4%), SFPP (27%–48%), SFAC (36%), and SFBC (39%–52%) exhibited a significant decrease in hardness (Figs. 2 and 4). The sand filter incorporated with *A. marmelos* showed more than 45% of hardness, which might be due to the presence of phytochemical substances that would have reacted to remove the hardness [44]. The presence of chloride is due to the usage of personal care products. The chloride content in raw greywater was 40.75 mg L^{-1}. The level of reduction in raw greywater (28.20 mg L^{-1}) varied between SF (31%), SFPP (52%–58%), SFAC (50%), and SFBC (50%–55%) treatments. For comparison, Apte et al. [45] reported a 40% removal of chloride using leaves of parthenium under mechanical agitation.

The elemental concentrations of greywater before and after treatments are shown in Figs. 6 and 7. A metal analysis (mg L^{-1}) of greywater revealed the presence of Fe, Zn, Pb, Cu, and Cr in the order Fe(0.351) > Zn(0.095) > Pb(0.055) > Cu(0.036) > Cr(0.014). The concentrations of these metals were below the maximum permissible limit, according to the Bureau of Indian Standards. Lead and Zn in greywater might have originated from personal care and dishwashing products. Moreover, lead pipes, solder, fittings, or service connections used for water supply systems in homes might also contribute Pb to greywater [46,47]. The removal of metals from the greywater was enhanced by the sand filters with plant powders when compared to sand filters incorporated with activated carbon and biochars. The decrease in metal contents in the treated greywater might be attributed to the adsorption of metal ions onto the filter materials [48,49].

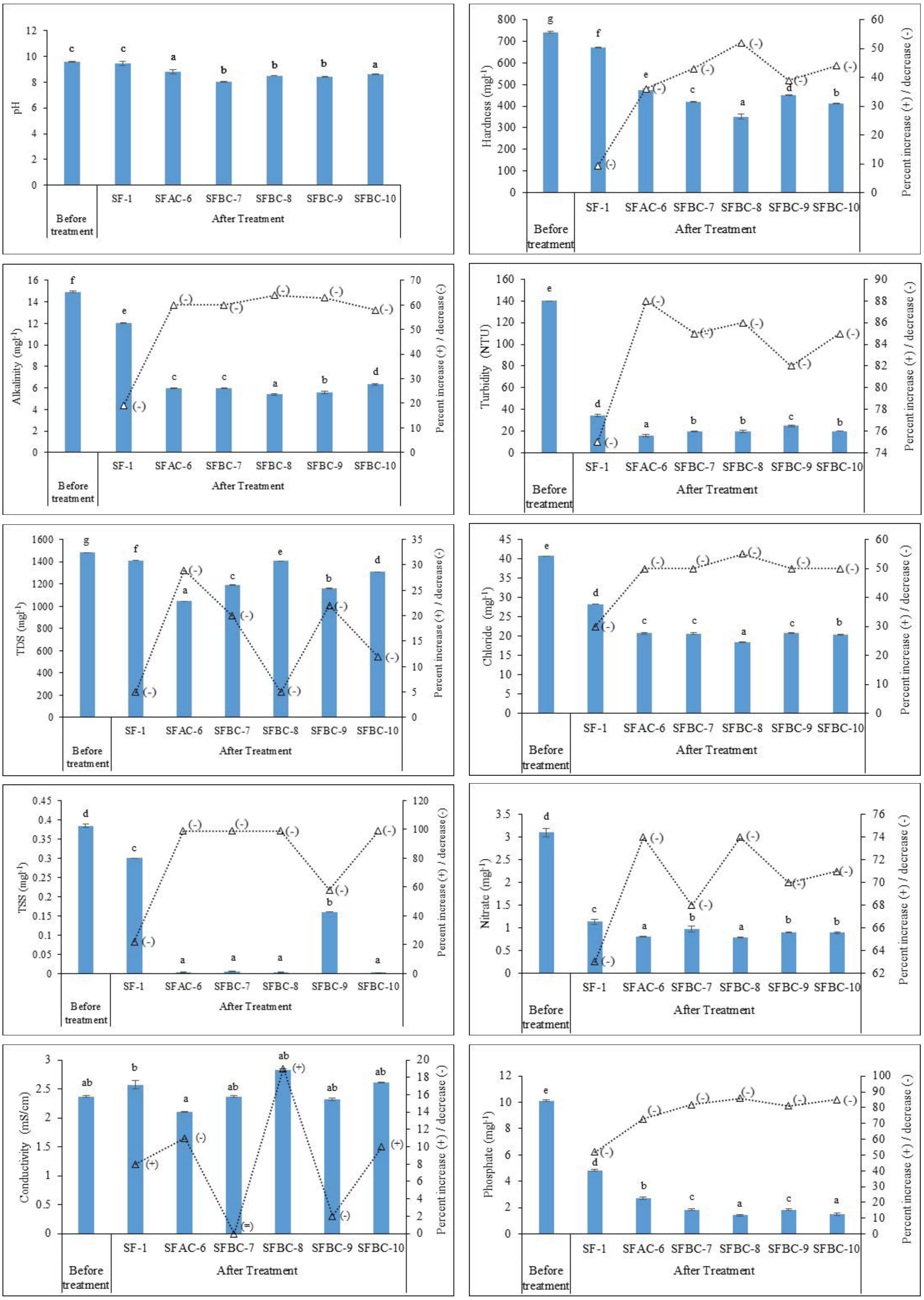

Fig. 4. pH, alkalinity, TDS, TSS, conductivity, hardness, turbidity, chloride, nitrate, and phosphate of greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with activated carbon (SFAC-6) and biochars (SFBC 7, SFBC 8, SFBC 9, SFBC 10). Percent decrease [Δ(–)] or increase [Δ(+)] or equal [Δ(=)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

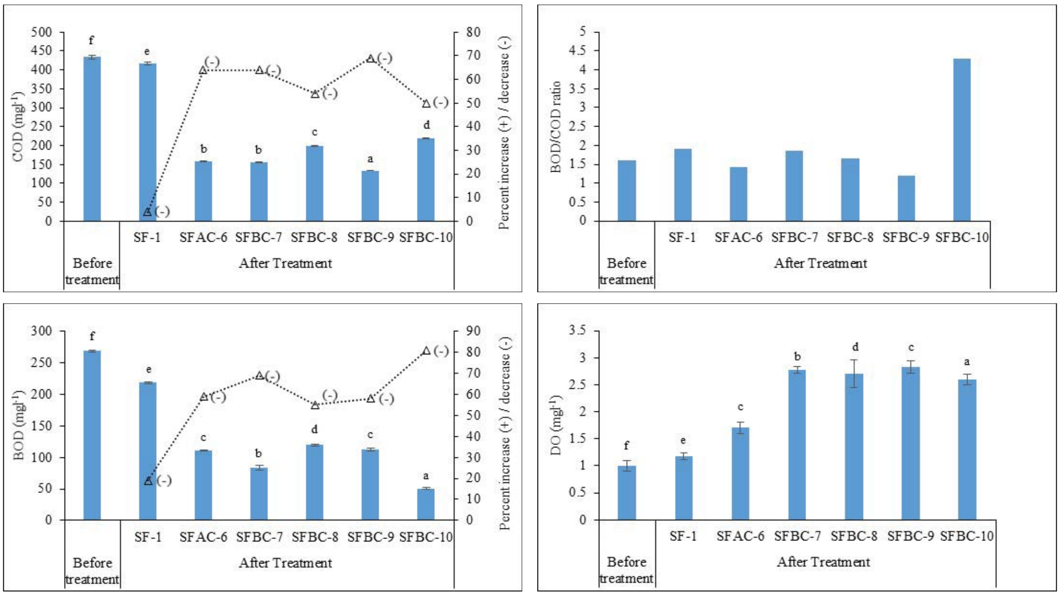

Fig. 5. COD, BOD, COD/BOD ratio, and DO of greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with activated carbon (SFAC-6) and biochars (SFBC 7, SFBC 8, SFBC 9, SFBC 10). Percent decrease [Δ(–)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

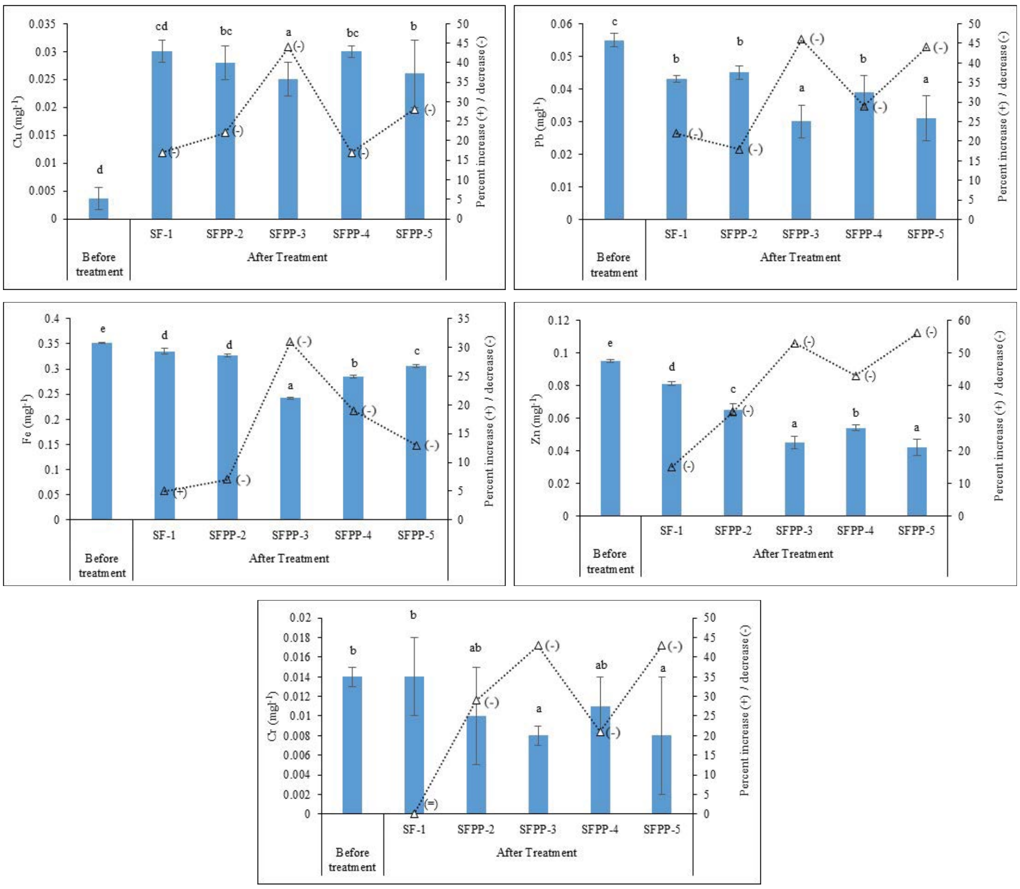

Fig. 6. Elemental concentrations (mg L⁻¹) in greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with raw plant powders (SFPP 2, SFPP 3, SFPP 4, SFPP 5). Percent decrease [Δ(–)] or increase [Δ(+)] or equal [Δ(=)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

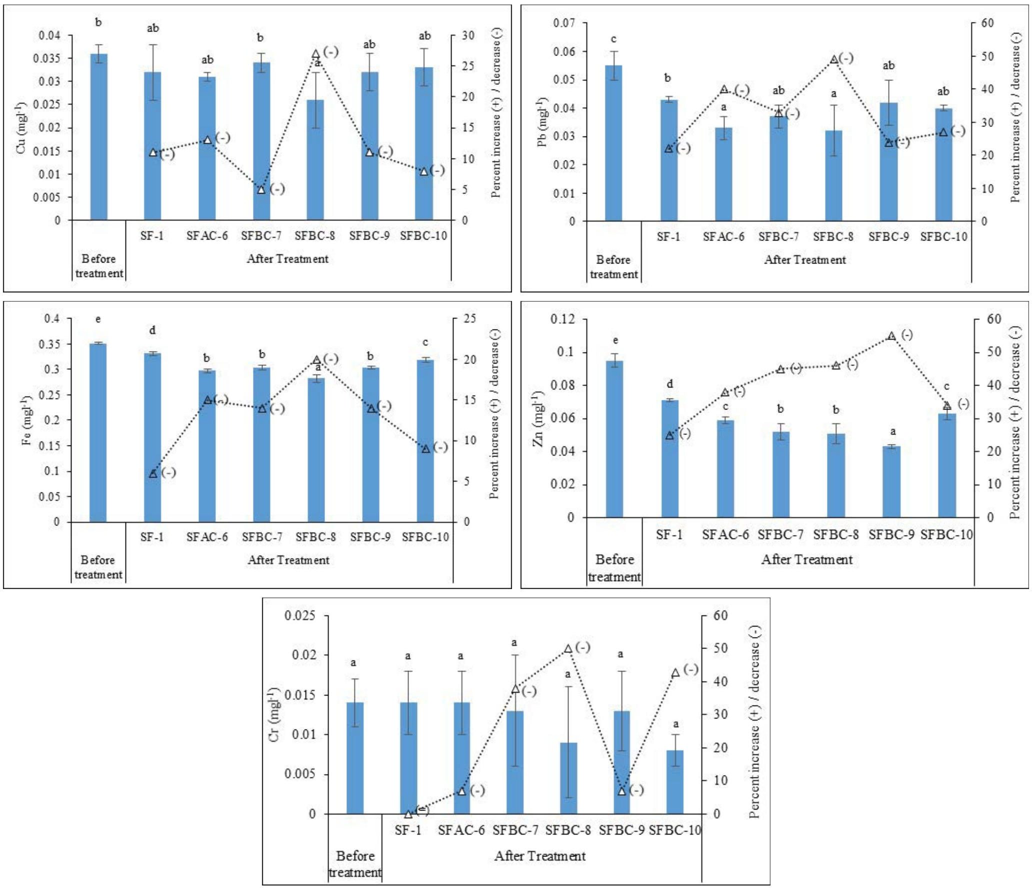

Fig. 7. Elemental concentrations in greywater before and after treatment with sand filters (SF-1) and sand filters incorporated with activated carbon (SFAC-6) and biochars (SFBC 7, SFBC 8, SFBC 9, SFBC 10). Percent decrease [Δ(–)] or increase [Δ(+)] or equal [Δ(=)] when compared to the value of raw greywater (before treatment) placed on the *z*-axis. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

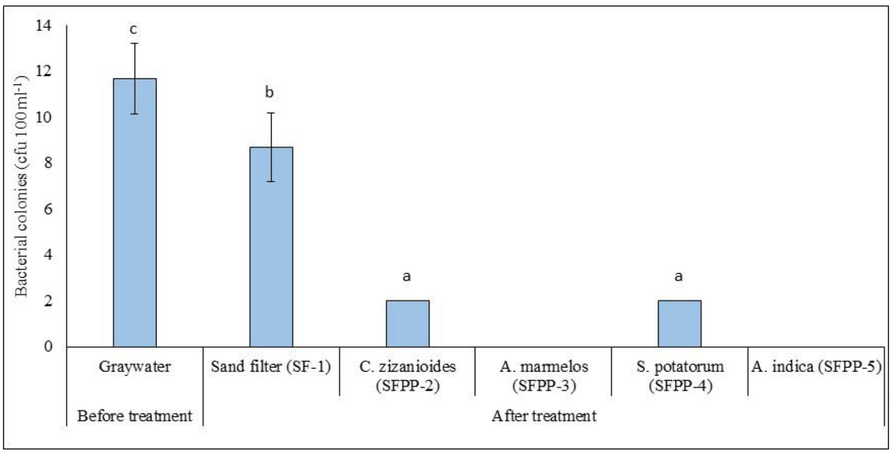

Fig. 8. Bacterial colonies in greywater before and after treatment with sand filters and sand filters incorporated with raw plant powders. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

Treatment of greywater onto SFPPs and SFBCs showed an effective decrease in bacterial populations (Figs. 8 and 9). SFAC and SFPP with *A. marmelos* and SFBC with *A. indica* were able to completely eliminate the bacterial population. This might be attributed to the antibacterial properties of these plants, as they are well known for their antimicrobial activities and for curing many diseases [50,51]. The ability of the filters to remove microbes depends on the adsorption capacity of the filter material, the characteristics of the biofilm formed on the filter surfaces, and the

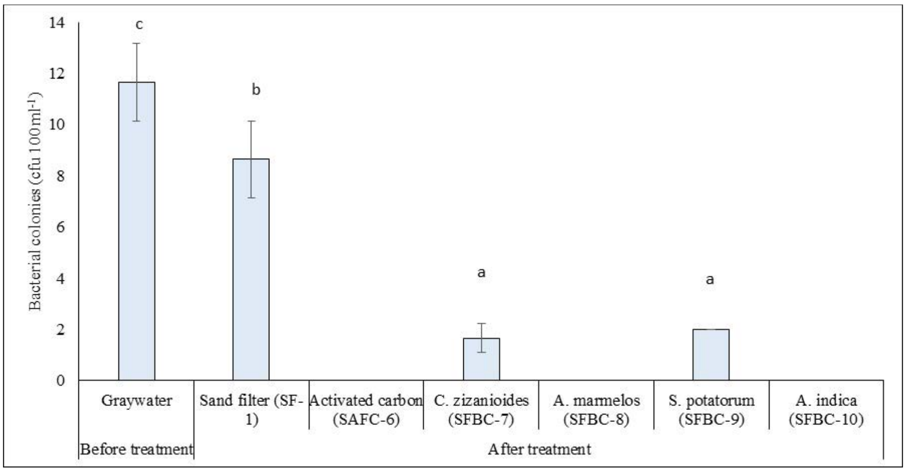

Fig. 9. Bacterial colonies in greywater before and after treatment with sand filters and sand filters incorporated with activated carbon and biochars (SFBC 7, SFBC 8, SFBC 9, SFBC 10). A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

physical entrapment (straining) in small pore spaces [52]. It depends on several characteristics of the filter material, some of which, like surface area, total porosity, size, and distribution of pores, might be more suitable in biochar than in sand [53]. There was no significant difference in the performance of SFAC, SFPPs, and SFBCs with *A. marmelos* and *A. indica* in the elimination of bacteria from the greywater, thus suggesting SFPPs with *A. marmelos* and *A. indica* are an efficient and cost-effective filter media.

3.1. Plant growth parameters

Greywater consists of several essential minerals for plant growth. However, only 70% germination was recorded for the seeds of *V. radiata* irrigated with raw greywater (Figs. 10 and 11), which might be due to the presence of toxic metals or culmination by microbial activity. However, the percent germination increased in the range of 75%–90% when irrigated with treated greywater (SF, SFPP, SFAC, and SFBC treatments) due to reductions of toxic elements (Figs. 10 and 11), thus enabling seed germination. The treated greywater resulted in an increase in seed germination as well as shoot and root biomass of plants [54,55]. The chlorophyll content in leaves of *V. radiata* irrigated with raw greywater was 24.13 Spad units. However, the chlorophyll content significantly was reduced in SFAC treated water and significantly increased in SFPP, SFAC, and SFBC treated waters (Figs. 10 and 11). Among the treatment groups, SFPPs showed a maximum increase of 23% with *S. potatorum*, and in SFBC, a maximum of 13% with *A. marmelos* and *A. indica*. The shoot length of *V. radiata* irrigated with raw greywater for 28 d was 10.2 cm. Irrigation with treated greywater showed a significant increase in shoot length over that of the control in all treatments, except SF and sand filter incorporated with *C. zizanioides* powder (SFPP-1) (Figs. 10 and 11). These results showed that

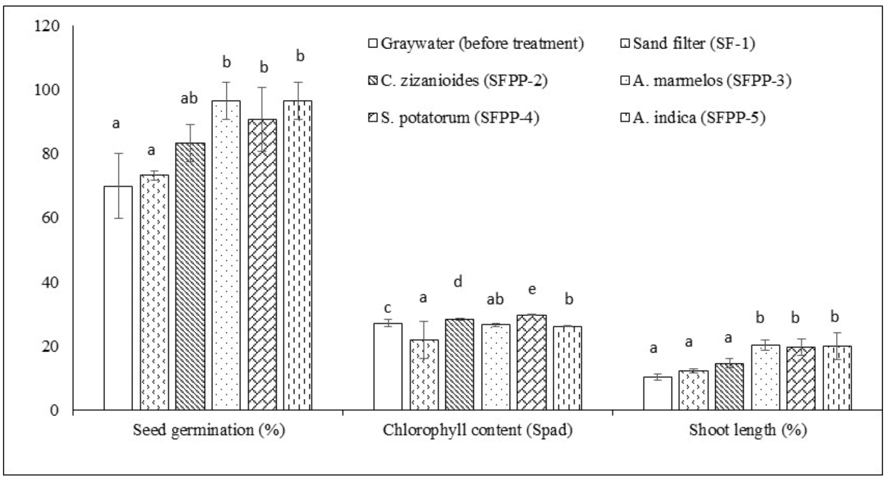

Fig. 10. Seed germination, chlorophyll content, and shoot length of *Vigna radiata* irrigated with untreated and treated (sand filter incorporated with plant power) greywater. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

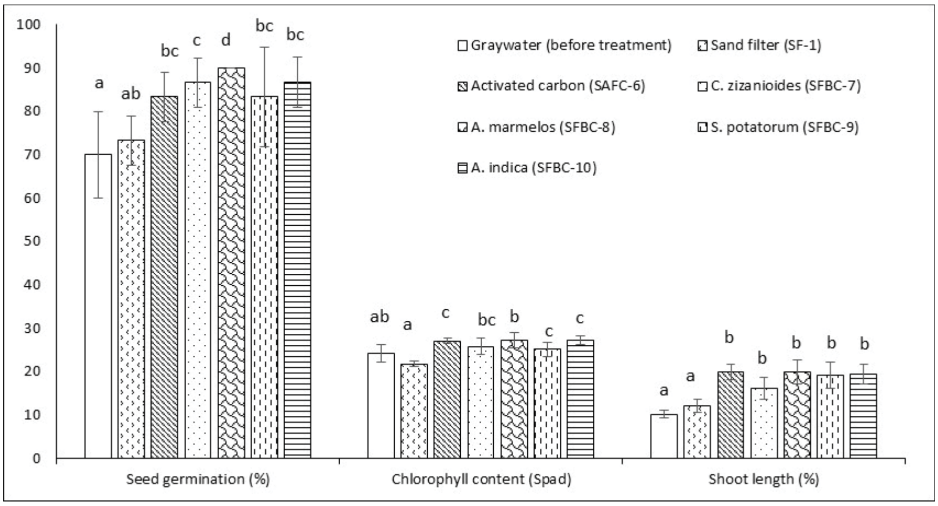

Fig. 11. Seed germination, chlorophyll content, and shoot length of *Vigna radiata* irrigated with untreated and treated (sand filter incorporated with biochars) greywater. A common letter or letters above the error bars indicates that the values do not significantly differ ($P < 0.05$) according to DMRT.

the raw powders prepared from *A. marmelos* are suitable candidates for effective, low-cost greywater treatment.

4. Conclusion

The results of this study show that the efficiency of sand filters in treating greywater was enhanced by the incorporation of plant powders for reducing the pH, TSS, chloride nitrate, and COD of greywater. Compared to SFBCs, SFPPs enhanced the DO level of treated greywater. Among metals, the higher removal efficiency was observed for Cu, Fe, and Zn by SFPP with *A. marmelos*. Irrigation of *V. radiata* with SFPP-treated greywater exhibited better performance for improving the percent germination, shoot length, and chlorophyll content. The hardness, turbidity, phosphate, BOD, and Cr and Pb among heavy metals in greywater showed better removal efficiency by treatment onto SFAC and SFBCs. Although the SFBCs showed higher percent removal for parameters like TDS, hardness and turbidity, these differences did not reach statistical significance (48% and 52% for hardness, 83% and 88% for turbidity and 29% and 19% for TDS, respectively, for SFPPs and SFBCs). The plant powders and biochars of *A. marmelos* and *A. indica* exhibited 100% antibacterial activity. These results suggest that the performance of SFBCs (sand filter with biochars) was comparable with the performance of sand filter with activated carbon, suggesting that biochars can be considered as an efficient alternative to activated carbon. However, among the SFPPs and SFBCs, owing to the energy costs associated with the production of biochar, availability of the material and the ease in the design of the filter, SFPP with *A. marmelos* can be suggested as a suitable filter with the least mechanized option for greywater treatment at household levels.

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Supplementary information

Table S1
Characteristics of greywater before and after treatment with sand filters and sand filters incorporated with raw plant powders

Parameters	Before treatment	After treatment				
	Greywater	Sand filter (SF-1)	Sand filter incorporated with raw plant powder			
			C. zizanioides (root) (SFPP-2)	*A. marmelos* (leaf) (SFPP-3)	*S. potatorum* (seed) (SFPP-4)	*A. indica* (leaf) (SFPP-5)
pH	9.57 ± 0.02^{e}	9.47 ± 0.15^{d}	7.06 ± 0.02^{a}	7.41 ± 0.01^{c}	7.3 ± 0.01^{b}	7.43 ± 0.12^{c}
Acidity	BDL	BDL	BDL	BDL	BDL	BDL
Alkalinity (mg L^{-1})	14.93 ± 0.06^{e}	12.03 ± 0.06^{d} (–19)	7.47 ± 0.06^{c} (–50)	6 ± 0^{a} (–60)	6.067 ± 0.058^{a} (–57)	6.87 ± 0.06^{b} (–54)
TDS (mg L^{-1})	$1,482 \pm 1^{e}$	$1,411.67 \pm 1.53^{c}$ (–5)	$1,186.67 \pm 0.58^{a}$ (–19)	$1,418 \pm 2.65^{d}$ (–5)	$1,331 \pm 1^{b}$ (–10)	$1,329 \pm 1.73^{b}$ (–10)
TSS (mg L^{-1})	0.384 ± 0.00^{c}	0.30 ± 0^{c} (–21)	0.001 ± 0.0001^{a} (–99)	0.15 ± 0.11^{b} (–61)	0.16 ± 0.00^{b} (–58)	0.17 ± 0^{b} (–56)
Conductivity (mS cm^{-1})	2.37 ± 0.01^{a}	2.57 ± 1.75^{a} (+8)	2.37 ± 0.02^{a}	2.84 ± 0.02^{a} (+20)	2.64 ± 0.02^{a} (+12)	2.65 ± 0.01^{a} (+11)
Hardness (mg L^{-1})	742.3 ± 2.51^{f}	672.33 ± 2.52^{e} (–9.4)	543.67 ± 3.21^{d} (–27)	386.33 ± 1.15^{a} (–48)	412.67 ± 2.52^{c} (–44)	393.67 ± 1.53^{b} (–47)
Turbidity (NTU)	140 ± 0.001^{d}	34.33 ± 1.15^{c} (–75)	24 ± 2^{a} (–83)	30 ± 1^{b} (–79)	24.33 ± 0.58^{a} (–83)	29.33 ± 1.15^{b} (–79)
Chlorides (mg L^{-1})	40.75 ± 0.02^{f}	28.20 ± 0.02^{e} (–31)	18.33 ± 0.15^{c} (–55)	17.2 ± 0.1^{a} (–58)	17.87 ± 0.15^{b} (–56)	19.4 ± 0.1^{d} (–52)
Nitrates (mg L^{-1})	3.1 ± 0.1^{d}	1.13 ± 0.06^{c} (–63)	0.93 ± 0.06^{b} (–70)	0.79 ± 0.01^{a} (–74)	0.90 ± 0.01^{b} (–71)	0.93 ± 0.06^{b} (–70)
Phosphates (mg L^{-1})	10.13 ± 0.06^{d}	4.82 ± 0.06^{c} (–52)	4.30 ± 0.06^{b} (–58)	2.1 ± 0.1^{a} (–79)	2.9 ± 0.06^{b} (–71)	2.6 ± 0.1^{a} (–74)
COD (mg L^{-1})	433.67 ± 4.16^{f}	416 ± 3.61^{e} (–4)	171.61 ± 1^{a} (–61)	138.67 ± 2.08^{c} (–68)	163 ± 1^{b} (–62)	195.3 ± 1.53^{d} (–55)
BOD (mg L^{-1})	268.67 ± 1.53^{f}	218.67 ± 1.53^{e} (–19)	105 ± 2^{a} (–61)	131.67 ± 2.08^{c} (–51)	157.33 ± 2.52^{d} (–41)	117 ± 3^{b} (–56)
BOD/COD ratio	1.61	1.9	1.63	1.05	1.03	1.7
DO (mg L^{-1})	1 ± 0.1^{a}	1.17 ± 0.06^{a}	3.77 ± 0.015^{d}	3.2 ± 0.1^{b}	3.5 ± 0.26^{c}	3.533 ± 0.058^{cd}

BDL – below detection limit; values in the parentheses indicate percent increase (+) or decrease (–) from control. In a column, means followed by a common letter(s) do not significantly differ ($P < 0.05$) according to DMRT.

Table S2
Physicochemical characteristics of greywater before and after treatment with sand filters and sand filters incorporated with activated carbon and charcoal prepared from different plant materials

Parameters	Before treatment	After treatment					
	Greywater	Sand filter (SF-1)	Activated carbon (SFAC-6)	Sand filter incorporated with raw plant powder			
				C. zizanioides (root) (SFBC-7)	*A. marmelos* (bark) (SFBC-8)	*S. potatorum* (seed) (SFBC-9)	*A. indica* (bark) (SFBC-10)
pH	9.57 ± 0.02^{c}	9.47 ± 0.15^{c}	8.8 ± 0.17^{a}	8.02 ± 0.02^{b}	8.5 ± 0.02^{b}	8.4 ± 0.02^{b}	8.60 ± 0.02^{a}
Acidity	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Alkalinity (mg L^{-1})	14.93 ± 0.06^{f}	12.03 ± 0.06^{e} (–19)	5.97 ± 0.06^{c} (–60)	5.97 ± 0.06^{c} (–60)	5.4 ± 0.1^{a} (–64)	5.6 ± 0.1^{b} (–63)	6.33 ± 0.06^{d} (–58)
TDS (mg L^{-1})	1,482 ± 1^{g}	1,411.67 ± 1.53^{f} (–5)	1,045.7 ± 0.6^{a} (–29)	1,189 ± 1.73^{c} (–20)	1,406.7 ± 1.5^{e} (–5)	1,162 ± 2^{b} (–22)	1,308 ± 1.53^{d} (–12)
TSS (mg L^{-1})	0.384 ± 0.004^{d}	0.30 ± 0^{c} (–22)	0.003 ± 0.00015^{a} (–99)	0.0041 ± 0.0001^{a} (–99)	0.003 ± 0.0002^{a} (–99)	0.16 ± 0^{b} (–58)	0.002 ± 0.0002^{a} (–99)
Conductivity (mS cm^{-1})	2.37 ± 0.01^{ab}	2.57 ± 1.75^{b} (+8)	2.1 ± 0.010^{a} (–11)	2.37 ± 0.01^{ab}	2.83 ± 0.02^{ab} (+19)	2.32 ± 0.02^{ab} (–2)	2.61 ± 0.01^{ab} (+10)
Hardness (mg L^{-1})	742.3 ± 2.51^{g}	672.33 ± 2.52^{f} (–9.4)	475.3 ± 4.7^{e} (–36)	420.67 ± 2.08^{c} (–43)	351.33 ± 1.05^{a} (–52)	450.67 ± 2.08^{d} (–39)	412.3 ± 2.52^{b} (–44)
Turbidity (NTU)	140 ± 0^{e}	34.33 ± 1.15^{d} (–75)	16 ± 1^{a} (–88)	19.67 ± 0.58^{b} (–85)	19.33 ± 1.15^{b} (–86)	24.67 ± 0.58^{c} (–82)	20 ± 0^{b} (–85)
Chlorides (mg L^{-1})	40.75 ± 0.02^{e}	28.20 ± 0.02^{d} (–30)	20.7 ± 0.2^{c} (–50)	20.67 ± 0.15^{c} (–50)	18.33 ± 0.15^{a} (–55)	20.7 ± 0.1^{c} (–50)	20.4 ± 0.1^{b} (–50)
Nitrates (mg L^{-1})	3.1 ± 0.1^{c}	1.13 ± 0.06^{c} (–63)	0.8 ± 0.01^{a} (–74)	0.97 ± 0.06^{b} (–68)	0.79 ± 0.01^{a} (–74)	0.90 ± 0.01^{b} (–70)	0.89 ± 0.02^{b} (–71)
Phosphates (mg L^{-1})	10.13 ± 0.06^{e}	4.82 ± 0.06^{d} (–52)	2.7 ± 0.1^{b} (–73)	1.83 ± 0.06^{c} (–82)	1.43 ± 0.06^{a} (–86)	1.83 ± 0.06^{c} (–81)	1.5 ± 0.1^{a} (–85)
COD (mg L^{-1})	433.67 ± 4.16^{f}	416 ± 3.61^{e} (-4)	158 ± 1^{b} (–64)	156 ± 1^{b} (–64)	198.33 ± 1.53^{c} (–54)	134 ± 1^{a} (–69)	219 ± 1^{d} (–50)
BOD (mg L^{-1})	268.67 ± 1.53^{f}	218.67 ± 1.53^{e} (–19)	110.7 ± 1.2^{c} (–59)	84 ± 3.61^{b} (–69)	119.67 ± 1.53^{d} (–55)	112.3 ± 2.52^{c} (–58)	50.67 ± 1.15^{a} (–81)
BOD/COD ratio	1.61	1.9	1.43	1.86	1.66	1.19	4.3
DO (mg L^{-1})	1 ± 0.1^{a}	1.17 ± 0.06^{a}	1.7 ± 0.1^{b}	2.77 ± 0.06^{c}	2.7 ± 0.26^{c}	2.83 ± 0.12^{c}	2.6 ± 0.1^{c}

BDL – below detection limit; values in the parentheses indicate percent increase (+) or decrease (–) from control. In a column, means followed by a common letter(s) do not significantly differ ($P < 0.05$) according to DMRT.

Table S3
Elemental concentrations in greywater before and after treatment with sand filters and sand filters incorporated with raw plant powders

Elements ($mg L^{-1}$)	Before treatment	After treatment				
	Greywater	Sand filter (SF-1)	Sand filter incorporated with raw plant powder			
			C. zizanioides (root) (SFPP-2)	*A. marmelos* (leaf) (SFPP-3)	*S. potatorum* (seed) (SFPP-4)	*A. indica* (leaf) (SFPP-5)
Cu	0.036 ± 0.002^{d}	0.030 ± 0.002^{cd} (–17)	0.028 ± 0.003^{bc} (–22)	0.025 ± 0.003^{a} (–44)	0.030 ± 0.001^{bc} (–17)	0.026 ± 0.006^{b} (–28)
Fe	0.351 ± 0.001^{e}	0.335 ± 0.006^{d} (+5)	0.327 ± 0.003^{d} (–7)	0.242 ± 0.002^{a} (–31)	0.284 ± 0.003^{b} (–19)	0.305 ± 0.003^{c} (–13)
Pb	0.055 ± 0.002^{c}	0.043 ± 0.001^{b} (–22)	0.045 ± 0.002^{b} (-18)	0.030 ± 0.005^{a} (–46)	0.039 ± 0.005^{b} (–29)	0.031 ± 0.007^{a} (–44)
Zn	0.095 ± 0.001^{e}	0.081 ± 0.001^{d} (–15)	0.065 ± 0.004^{c} (–32)	0.045 ± 0.004^{a} (–53)	0.054 ± 0.002^{b} (–43)	0.042 ± 0.005^{a} (–56)
Cr	0.014 ± 0.001^{b}	0.014 ± 0.004^{b}	0.010 ± 0.005^{ab} (–29)	0.008 ± 0.001^{a} (–43)	0.011 ± 0.003^{ab} (–21)	0.008 ± 0.006^{a} (–43)

Values in the parentheses indicate percent increase (+) or decrease (–) from control. In a column, means followed by a common letter(s) do not significantly differ ($P < 0.05$) according to DMRT.

Table S4
Elemental concentrations in greywater before and after treatment with sand filters and sand filters incorporated with activated carbon and charcoal prepared from different plant materials

Elements ($mg L^{-1}$)	Before treatment	After treatment					
	Greywater	Sand filter (SF-1)	Activated carbon (SFAC-6)	Sand filter incorporated with plant based charcoal			
				C. zizanioides (root) (SFBC-7)	*A. marmelos* (bark) (SFBC-8)	*S. potatorum* (seed) (SFBC-9)	*A. indica* (bark) (SFBC-10)
Cu	0.036 ± 0.002^{b}	0.032 ± 0.006^{ab} (–11)	0.031 ± 0.001^{ab} (–13)	0.034 ± 0.002^{b} (–5)	0.026 ± 0.006^{a} (-27)	0.032 ± 0.004^{ab} (–11)	0.033 ± 0.004^{ab} (-8)
Fe	0.351 ± 0.002^{e}	0.331 ± 0.004^{d} (–6)	0.297 ± 0.003^{b} (–15)	$0. 303 \pm 0.005^{b}$ (–14)	0.282 ± 0.007^{a} (-20)	0.304 ± 0.003^{b} (–14)	0.319 ± 0.005^{c} (-9)
Pb	0.055 ± 0.005^{c}	0.043 ± 0.001^{b} (–22)	0.033 ± 0.004^{a} (–40)	0.037 ± 0.004^{ab} (–33)	0.032 ± 0.009^{a} (-49)	0.042 ± 0.008^{ab} (–24)	0.040 ± 0.001^{ab} (-27)
Zn	0.095 ± 0.004^{e}	0.071 ± 0.001^{d} (–25)	0.059 ± 0.002^{c} (–38)	0.052 ± 0.005^{b} (–45)	0.051 ± 0.006^{b} (-46)	0.043 ± 0.001^{a} (–55)	0.063 ± 0.004^{c} (-34)
Cr	0.014 ± 0.003^{a}	0.014 ± 0.004^{a}	0.014 ± 0.004^{a} (–7)	0.013 ± 0.007^{a} (–38)	0.009 ± 0.007^{a} (-50)	0.013 ± 0.005^{a} (–7)	0.008 ± 0.002^{a} (-43)

Values in the parentheses indicate percent increase (+) or decrease (–) from control. In a column, means followed by a common letter(s) do not significantly differ ($P < 0.05$) according to DMRT.