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Use of biochar-based column filtration systems for greywater treatment: A systematic literature review

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ABSTRACT

Biochar-based column filtration systems (BCFS) for greywater treatment have gained attention in the last decade. However, a review of the state-of-the-art on this subject has not been conducted, leaving the analysis and limitations of the available research still unexplored. This paper reviews the current literature to give insights into the technology and identify new areas of investigation. This study used a systematic review approach to evaluate the documentation relating to the technology's worldwide status, configuration, removal mechanisms, removal efficiency, and water reuse applications. In total, 28 studies were reported in 16 countries including India and Sweden as leading ones. Three filter column configurations were identified: single biochar filter, multilayer filter, and polishing step in the treatment chain. The pollutant removal efficiency of BCFS ranged between 50 and 99%. Treated greywater is reused mainly for non-potable purposes such as toilet flushing, cloth washing, and crop irrigation. Overall, this technology can be a feasible and sustainable alternative for greywater treatment and application in water-scarce regions. However, further research is needed on social perception toward potable water reuse, new feedstocks for biochar production, the scaling-up and long-term assessment, evaluation of additional water microbial indicators, and the modification of biochar to target specific water reuse purposes.

1. Introduction

Water is an essential resource for the functioning of ecosystem services that benefit human beings [1]. Nevertheless, nearly 4 billion people faced water scarcity and 2 billion people were settled in countries with water stress by 2019 [2]. As the world population grows, places are urbanized, and industry expands quickly, both the water demand and amount of wastewater rise significantly [3]. Wastewater is of concern when discharged untreated in water bodies or soil as it is associated with eutrophication, pathogenic pollution, damage to soil's properties, and mosquito breeding [4]. However, there are sustainable opportunities for water reclamation from wastewater that could help minimize the freshwater needs and preserve water bodies and soil, leading to green development in society [5].

As a type of wastewater, greywater includes outflows from washbasins, bathrooms, kitchen sinks, and laundry machines, and accounts for 50–80% of the total wastewater generated in households and residential buildings [6]. Unlike sewage wastewater, it contains less organic matter and harmful pathogens as it excludes water from toilets which includes urine and faces [7]. Therefore, greywater is safer to manipulate and simpler to treat for reuse in non-potable purposes such as crop irrigation, garden watering, toilet flushing, and discharge into water bodies [8–10]. Biological processes such as Membrane Bioreactor (MBR), Upflow Anaerobic Sludge Blanket (UASB), and Rotating Biological Contactor (RBC) have been widely used to remove organic matter/contaminants in greywater due to their high efficiency. However, as they are mechanized, they tend to be more appropriate for centralized treatment systems [5].

Efforts to promote a circular economy in the water sector have focused on searching sustainable on-site wastewater treatment technologies over the last two decades [11]. When compared to centralized systems, locally based treatment solutions are characterized by requiring fewer capital costs and energy, less maintenance and operation, and are affordable in terms of local material availability [12]. In the case of greywater, nature-based solutions such as constructed wetlands (CW), green walls (GW), vertical gardens (VG) and green roofs

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(GR), have been used as sustainable treatment techniques, resulting in less carbon footprint and less new water demand [13,14]. Recently, the reuse and recycling of waste materials as adsorbents for wastewater treatment has gained attention to find synergistic strategies to boost the circular economy in both the water and waste sectors [15].

Biochar, a charcoal-like substance produced by the thermal decomposition of organic material from agricultural and forestry wastes (also called biomass) in the absence of oxygen (pyrolysis) is an example of waste-based adsorbent material. It is widely used as a fertilizer for soil conditioning and carbon sequestration [16,17]. New studies, however, have demonstrated its potential as an adsorbent in wastewater treatment due to its high surface area, high porosity, and reactive surface functional group [18,19]. For instance, biochar has been employed in the treatment of stormwater [20,21], municipal [22], agricultural [23], and industrial wastewaters [24]. When it comes to greywater treatment, several treatment technologies such as CW, VG, and GR have incorporated biochar as a filter media proving to remove organic and inorganic water pollutants [25–27].

Over the last decade, the use of BCFS for greywater treatment has experienced a surge in interest from the academia community. However, there is a lack of in-depth knowledge about the available literature on this topic. Therefore, the main objective of this study is to systematically gather the available literature from a broad range of publications to provide insights into the existing research and identify new areas of investigation. Four research questions (RQ) have been proposed to orientate the research process:

RQ1: What is the world's status of research on the use of BCFS to treat greywater?
RQ2: What are the types of configurations and style of operation of BCFS?
RQ3: What is the pollutant removal potential by BCFS in comparison to conventional adsorbents?
RQ4: What are the actual and potential applications of greywater once treated in BCFS?

2. Methods

This study employed the systematic literature review (SLR) approach to assess the existing literature on the topic of greywater treatment technologies and narrow it to the application of BCFS. To answer the research questions, the study adopted a modified version of the fourteen-step approach by Tawfik et al. [28] and the five-step outlined by Denyer & Tranfield [29]. In the first phase, four objectives were formulated: 1) investigate the world's status of research about the use of BCFS for greywater treatment; 2) describe the configuration and operation of the treatment system; 3) evaluate the suitability of BCFS to remove pollutants in greywater, and 4) describe the applications of BCFS in the reuse of treated greywater.

The second phase comprised the formulation of the research strategy where search terms were defined. To carefully examine the existing literature, initially, subject area-related keywords were established and divided into three sets. The first one was related to biochar: 'bio-char', 'biochar', 'charcoal', 'char'; the second one to greywater: 'greywater', 'graywater', 'grey water', 'grey water', 'laundry wastewater', 'hand-washing wastewater', 'washbasin wastewater', 'dishwashing wastewater', 'cloth washing wastewater', 'kitchen wastewater', 'bathroom wastewater', 'bathroom wastewater', 'shower wastewater'; and the last one to treatment: 'treatment', 'reclamation', and 'recycling'. After that, sophisticated search strings were constructed using Boolean Logic 'AND' 'OR' with all possible combinations among the three sets of keywords. A total of 180 search terms were composed before searching in databases (Supplementary material – Table S.1). It is worth mentioning that some search strings were redefined to deal with the search format of databases.

As part of the third phase, seven well-known online publisher databases were selected for literature search: Google Scholar, ResearchGate, BASE, ScienceDirect, INGENTA, Scopus, and Locate (Coventry University, UK). In addition, the identification of relevant studies from the publication databases by using the search strings took place. In the fourth phase, a vigorous channelling process using inclusion-exclusion criteria and quality attributes (checklist of questions) was performed to select the most adequate from the existing literature. A total list of eight inclusion-exclusion criteria with their rationale was suggested (Table 1), while a total of four quality attributes (QA) were applied to the potential studies: (QA1) Does the study discuss the use of biochar in greywater treatment?; (QA2) Does the study refer to the use of biochar-based column filtration systems in greywater treatment?; (QA3) Does the study show empirical results concerning the removal of pollutants in greywater treated in biochar-based column filtration units?; and (QA4) Does the study provide information about the reuse of treated greywater in potable and/or non-potable water reuse applications?

The channelling processing consisted mainly of two steps: screening and eligibility. At first, the total articles and dissertations were identified and stored in the reference management software Zotero, and duplicated articles were excluded. Afterwards, a title and abstract screening was carried out to narrow the findings to those addressing the publication scope. Next, the eligibility of the articles and dissertations was evaluated, thus, irrelevant, duplicates and non-full available texts were removed. Within the framework of established inclusion and exclusion criteria, manual searching was conducted by searching reference lists from the articles and dissertations already screened and doing citation tracking.

Data extraction was the fifth phase and consisted of an in-depth reviewing and information collection of the filtered articles and dissertations. A data extraction form in the shape of an Excel spreadsheet was designed and six categories were proposed to guide the data collection process. Finally, the most relevant studies were analysed and

Table 1
Inclusion and exclusion criteria for selection of studies.

Criteria	Inclusion	Exclusion	Rationale
Quality	Peer-reviewed articles and dissertations	Non-peer-reviewed articles, unpublished articles, abstract-only papers, conference papers	Peer-reviewed articles and dissertations are reviewed by high-qualified professionals who verify the validity of the study
Length	Full-available articles and dissertations	Non-full-available articles and dissertations	Availability for reading and analysis of the whole content
Language	English	All other languages	English is the universal academic language
Publication type	Empirical studies	Non-empirical studies	Collect information on the experimental methodology
Publication date	2010–2021 (until April)	Before 2010	Evaluate the most current state-of-the-art literature
Publication scope	Articles and dissertations whose research address the use of biochar for greywater treatment	Articles and dissertations whose research did not address the study subject	The study assesses the application of biochar as an organic adsorbent for greywater reclamation
Publication focus	Articles and dissertations whose research employed biochar-based column filtration systems in particular	Articles and dissertations whose research refer to other greywater treatment technologies	Gives response to the study's main goal

interpreted. Valuable data to answer the research questions was summarized in an Excel spreadsheet. Then, the results and discussion of the thematic content of the chosen studies were reported in a manuscript for further revision and submission to a peer-review journal.

3. Results and discussion

3.1. Descriptive analysis

At the beginning, 4130 sources were found using the set of all possible combinations between the three main sets of keywords. This number was shortlisted to 1476 by deleting duplicates manually (233) and through the automatized option in the software Zotero (2421). Then this number was title-and-abstract screened, and 1415 sources were removed. Thus, a total of 61 sources were assessed for eligibility and 36 were eliminated for being irrelevant to the study focus (31) and lacking full-text availability (5). Manually, 3 sources were added leaving 28 studies for further analysis (Fig. 1). Table 2 presents general information and a summary of the studies found.

3.1.1. Year of publication

Fig. 2 illustrates the yearly distribution of the reviewed studies. Overall, the number of publications fluctuated over the study period of the review (2010−2021). The record of publications had two peaks in 2014 and 2019 when six and seven studies were published, respectively. The observed increase in the first half could be attributed to an emerging interest in the water sector to seek replacement filter media for activated carbon in wastewater treatment after concerns related to high footprint and high production cost [31,39]. Unlike the period 2010–2015, toward the end of the second period, in 2019, another increase in publishing was observed. This result may be explained by the fact the water scarcity problem gained attention worldwide, especially in water-stress and low-and-middle-income countries, promoting the search for locally based materials in the process of decentralized wastewater treatment [7,41,43,45].

3.1.2. Geographical distribution

The geographical distribution of the reviewed studies, both by country and continent, is represented in Figs. 3 and 4, respectively. Fig. 3 provides the number of publications based on the authors' country of affiliation. Overall, publications were done in 16 countries (including Palestine). Sweden and India are the countries with notable contributions with 6 and 5 publications, respectively, followed by Malaysia (3) and Ghana (2), while the remaining territories only produced one study each. Further analysis demonstrated that although Sweden and India share similar production in number, their research efforts concentrated differently over time. Nearly 84% of Swedish studies (5) were conducted in the period 2012–2016 while 80% of Indian publications (4) were finalized between 2016 and 2020.

This high research interest in biochar application for greywater remediation in Sweden and generally in Europe, as can be observed in Figs. 3 and 4, might be due to the implementation of the European Union (EU) circular economy strategy that aims to develop sustainable water recycling systems [50,51]. A closer analysis of the European publications that represent 32% of the reviewed studies (Fig. 4) reveals interesting facts. They demonstrated that biochar use in greywater remediation has the potential to discharge safely treated wastewater into the environment avoid eutrophication in water bodies [31,36],

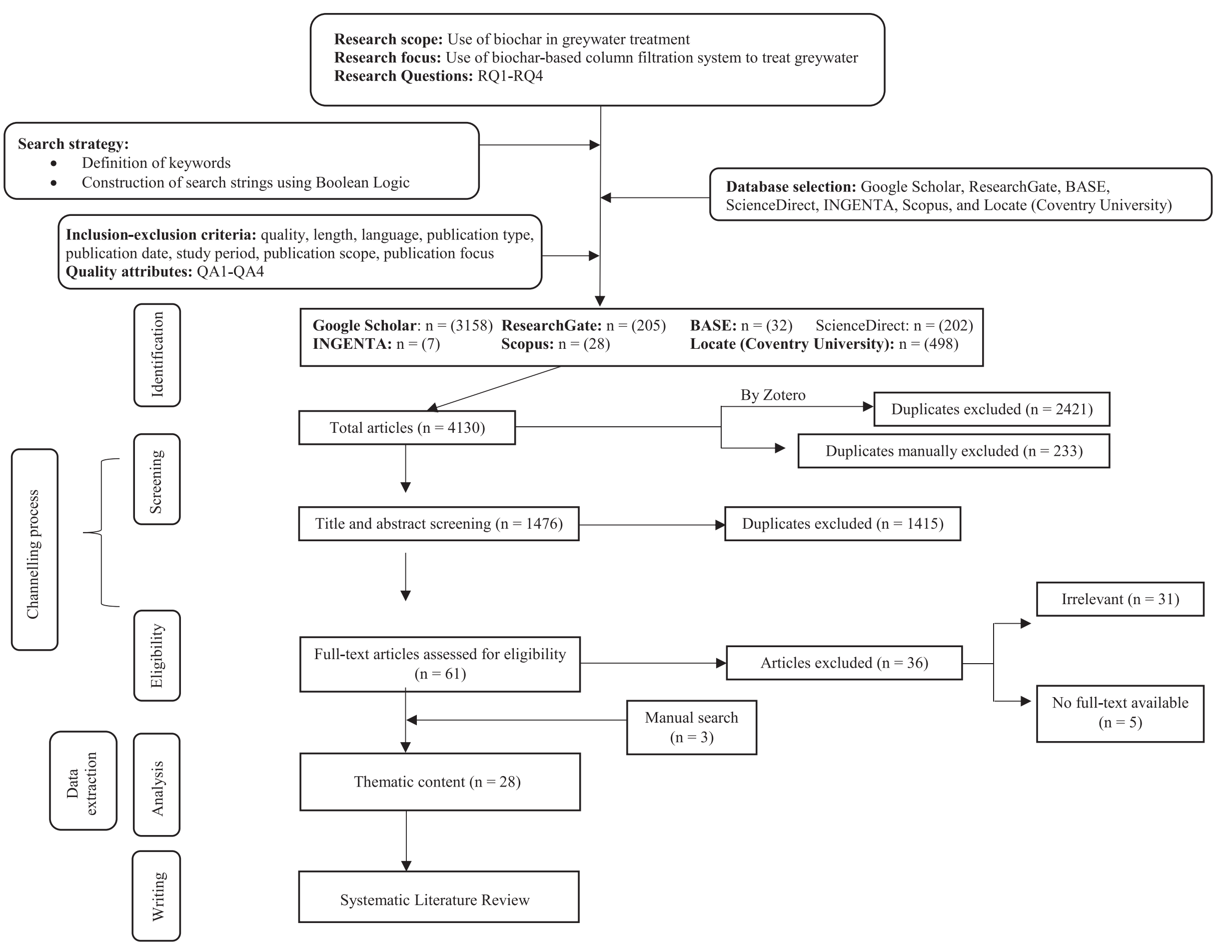

Fig. 1. Schematic summary of the methodology.

Table 2
Summary of the 28 analysed studies.

Country	Type	Summary	Reference
India	Article	This study investigates the performance of a multilayer filter consisting of coconut, sawdust, charcoal, bricks, and sand, in the treatment of greywater for a rural college	[30]
Sweden	Masters dissertation	This study contrasts the utilization of biochar and activated carbon for synthetic greywater treatment in column filtration systems	[31]
India	Article	This study proposes a greywater treatment chain composed of sieve, foam, charcoal (secondary treatment), and sand filtrations, followed by UV disinfection for reuse in non-potable purposes	[32]
Sweden	Masters dissertation	This study compares the use of bark, activated charcoal, and biochar filter systems in the upgrading of greywater for irrigation purposes	[6]
Uganda	Article	This study analyses the performance of a pilot multilayer treatment tank composed of gravel, charcoal, and mulch) in the treatment of household greywater for garden irrigation	[8]
Sweden	Masters dissertation	This study compares the microbial removal in synthetic greywater by biochar, bark, activated carbon, and bark/activated carbon filters	[4]
Ghana	Article	This study compares the use of beach sand, oyster shells, and charcoal filters systems in the treatment of greywater from university residential halls for irrigation reuse	[33]
Malaysia	Article	This study investigates the use of a two-stage filter media composed of pre-treatment (gravel and sand) and peat-based filter (peat, charcoal, and gravel) in household greywater treatment.	[34]
Finland	Undergraduate dissertation	This study compares the application of pure and enriched commercial biochars to recycle N and P from synthetic greywater	[35]
Norway	Article	This study evaluates and compares the use of biochar and filtralite filter as a tertiary treatment in a commercial compact greywater treatment plant	[1]
Sweden	Scientific report	This study evaluates the effect of different loading conditions and biochar types in the treatment of greywater in filter beds	[36]
India	Article	This study shows the potential of an up-flow charcoal filter as a tertiary treatment for hostel greywater for reuse for land application	[5]
Sweden (Jordan-based)	Article	This study examines the use of an on-site biochar filter for household greywater treatment and performs a risk assessment of gastroenteritis to exposure to treated and non-treated greywater reuse in irrigation	[37]
Malaysia	Article	This study evaluates the use of charcoal fibrous filter as a primary treatment followed by UV disinfection in the treatment of Musta'mal water for recycling in ablution activity	[38]
Nigeria	Masters dissertation	This study evaluates the use of activated and non-activated tropical trees biochars on filtration systems for greywater treatment from student hostels	[39]
India	Article	This study evaluates the application of a filter composed of sand and charcoal as a polishing step of greywater treated in a series of bio-bed	[40]
Canada	Masters dissertation	This study evaluates the influence of biochar addition in biosand filters with several layering arrangements for synthetic greywater treatment	[41]
Sweden (Bolivia-based)	Article	This study tests the influence of biochar size, hydraulic loading rate, and salinity in the removal of microbial indicators from greywater	[42]
Botswana	Undergraduate dissertation	This study examines the application of charcoal-based filter as a polishing system in the tertiary treatment of greywater	[43]
Palestine	Masters dissertation	This study evaluates the performance of two-layers (sand and biochar) microfilters in the treatment of artificial greywater for domestic and agricultural reuse	[7]
Ethiopia	Masters dissertation	This study assesses and contrasts sand and banana peel biochar of different particle sizes (fine, medium, and coarse) in the treatment of greywater	[44]
Vietnam	Scientific report	This study evaluates a three-stage filtration system made up of eucalyptus wood biochar, tef straw, and sand in the treatment of laundry wastewater under various flow rates.	[10]
India	Article	This study examines the performance of a five-layers filter composed of pebbles, gravel, sand, Soil Mixture Block (soil, powdered charcoal, sawdust, and iron scraps), and sand in the treatment of greywater	[45]
Malaysia	Article	This study develops a filtration prototype using biochar in the filter media for the treatment and reuse of greywater in flushing toilets.	[46]
United States	Article	This study assesses the impact of pre-treatment (coagulation and biodegradation) and sorption of five wood-based biochar in greywater treatment	[9]
Ghana	Article	This study assesses and compares the utilization of	[47]

(continued on next page)

Table 2 (*continued*)

Country	Type	Summary	Reference
		sand, charcoal, and sawdust filters in the remediation of greywater safe discharge and non-potable purposes	
Brazil	Article	This study examines the use of tree pruning biochar in a greywater filtration unit after coagulation, flocculation, and decantation processes	[48]
United Kingdom (Nigeria-based)	Article	This study evaluates the influence of hydraulic loading (rapid and slow) and filter type (rice husk, rice husk biochar, and activated carbon) in household greywater treatment	[49]

reuse greywater in irrigation without risk to human health [4,6,37,42], ensure access to safe drinking water [49], and recycle nutrients [35].

India and other Asian countries such as Malaysia and Vietnam have also invested in biochar-based greywater treatment research. Asian studies, in this literature review, accounted for 36% of the total publications (Fig. 4) with India being the leader country. Unlike Europe, Asian efforts have focused on using biochar in greywater treatment to cope with water shortages [5,32,46], and the absence of sewage systems in small cities to stop pouring untreated wastewater to open land [5,40]. Fig. 4 also shows that several authors based in African countries have investigated the properties of biochar to reclaim greywater and thus reduce the consumption of limited freshwater sources [8,33,44]. These efforts are helping African countries to meet the 2030 Agenda for Sustainable Development Goals (SDGs), especially in achieving SDG 3 (good health and well-being) and SDG 6 (clean water and sanitation).

3.1.3. Distribution by type of study

Fig. 5 denotes the distribution by source type of the publications reviewed in this study. Article-type is the main source of information (17 studies), followed by dissertations (9) and lastly scientific reports (2). Generally, scholars mainly published in journals with an approach to zero waste management, water and wastewater management, and environmental technologies. Dissertation studies were fragmented into two levels: undergraduate (2), and postgraduate (7), while 2 publications were categorized as scientific reports. This low number of studies found may be due to the study's focus which includes only publications on the use of biochar-based column filtration systems for greywater treatment (Table 1). Although biochar has been widely used in the treatment of different types of wastewater and remediation technologies, this study focused only on identifying the state-of-art only for BCFS used in the regeneration, principally, of greywater.

3.2. Content analysis

3.2.1. Biochar in filtration systems for greywater treatment

Biochar can be defined as a carbon-rich (~85%), porous, and complex material produced from the pyrolysis, hydrothermal carbonization, gasification, and torrefaction of several types of waste biomass such as agriculture, forestry, and municipal waste [52,53]. Today, the use of biochar in the water sector has become increasingly popular due to biochar's enhanced physicochemical properties for water/wastewater decontamination and remediation [54]. Specific surface area, high porosity, high cation exchange capacity, pH, surface functional groups, surface reactivity, and mineral composition are the main biochar properties that affect its capability to adsorb organic, inorganic, and

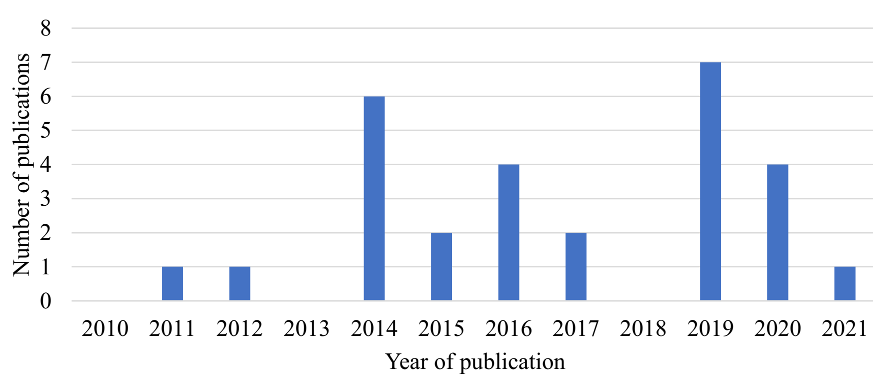

Fig. 2. Year distribution of the reviewed studies.

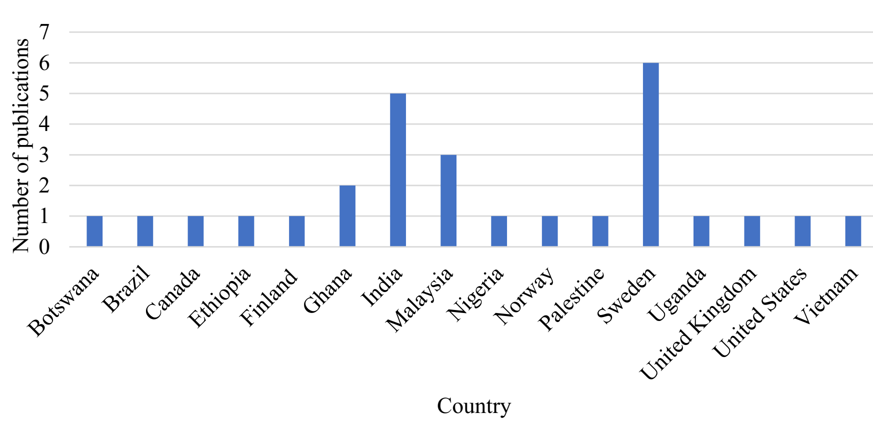

Fig. 3. Country distribution of the reviewed studies.

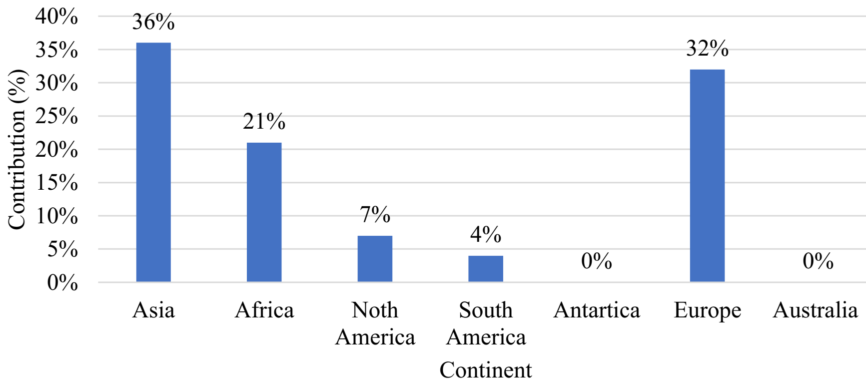

Fig. 4. Continent distribution of the reviewed studies.

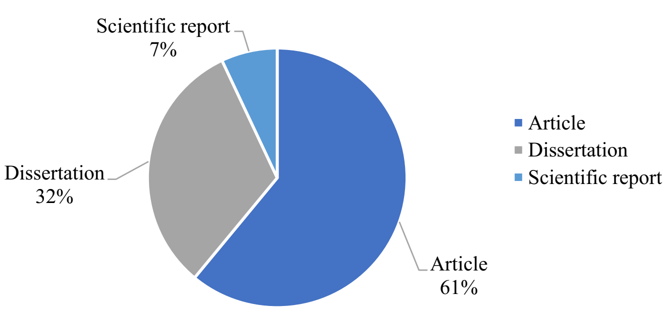

Fig. 5. Source type distribution of the reviewed studies.

even pathogenic contaminants in water [18].

According to Yaashikaa et al. [55], several factors influence biochar's properties during production, including the type of biomass, temperature, rate of heating, retention time, and pressure. For instance, Enaime et al. [18] concluded that high-temperature pyrolysis commonly results in biochar with a larger surface area and pore volume, making it ideal for the sorption of organic contaminants, while inorganic pollutants can be removed more effectively by biochar produced at low-temperature pyrolysis since it has more oxygen-containing functional groups. Given all that has been mentioned, identifying biochar characteristics is relevant to assessing its potential in the removal of pollutants from greywater.

As can be seen in Table 3, in this literature review, out of the 28 reviewed studies, 21 provided information on the biochar used either about its feedstock source or physicochemical properties, whereas 7

Table 3
Summary of biochar characteristics.

Biomass source	Biochar size (mm)	Effective particle size (mm)	Specific surface area (m^2/g)	Particle density (kg/m^3)	Total porosity (%)	Bulk Density (kg/m^3)	pH	Reference
Tree pruning	–	–	–	–	–	–	–	[48]
n.m.	0.25–2	–	–	–	–	–	–	[41]
Biolan (Alder sp. and Aspen sp.)	–	–	–	–	–	800.2	9.46	[35]
RPK Hilli Oy (Betula sp.)	–	–	–	–	–	244.9	9.16	
Salix	A mixture of 1–1.4 and 2.8–5	–	–	740	63.3	270	–	[31]
Hardwood (undefined wood)	1–5	–	–	–	–	–	–	[37]
Wood from undefined sources	–	1.4, 2.8, and 5	170–200	–	48–53	–	–	[42]
Willow (Salix)	1–1.4 and 2.8–5	–	–	740	63.3	270	–	[36]
Hardwood (undefined wood)	1.4–5	–	170–200	–	72–74	187	–	
Willow (Salix) leaves	1–1.4 and 2.8–5	1.4	–	740	63.3	270	–	[6]
n.m.	–	–	–	200	42	–	–	[43]
Blend of hardwood and softwood pellets	≤3 and ≤ 6	–	–	–	–	–	–	[9]
Dried leaves of figs (*Ficus carcica*) and lemon (*Olea europaea*)	–	–	–	–	6.77[a]	420	–	[7]
n.m.	0.7–1.0	–	–	–	–	–	–	[32]
n.m.	–	1.4 and 3.1	–	–	–	–	–	[8]
Banana peel	>1, 1–3 and 3<	–	118	–	–	400	–	[44]
Eucalyptus wood (*E. camaldulensis* and *E. Globulus*)	1–5	–	–	–	–	–	–	[10]
n.m.	11.92	–	–	–	–	–	–	[33]
Salix and pine	1–1.4 and 2.8–5 mm	1.4		740	63.3	270	~9	[4]
n.m.	–	10–25	–	–	–	–	–	[5]
Commercial (Carbon Terra GmbH)	–	2–5	–	–	–	–	–	[1]
Shea tree (*Vitellaria paradoxa*)	2–4.7 and < 2	–	–	1694	–	296–307	–	[39]
African Mahogany tree (*Khaya senegalenses*)	2–4.7 and < 2	–	–	1810	–	270–283	–	
Fig tree (*Ficus sycomous*)	2–4.7 and < 2	–	–	1940	–	261–296	–	
n.m.	4.75–9.5	–	–	–	–	–	–	[45]

n.m.: not mentioned.
[a] in Φ unit.

studies fail to acknowledge this information. It is apparent from Table 3 that almost all the studies utilized wood-based biochar, either pruning residues [48], leaves [7], or chopped trees. Among the authors, only Salihu Wamdeo [39] pointed out that the selection of biochar from high lignin-containing feedstock exhibited a molecular structure similar to that of activated carbon and may therefore replace it, while the rest of them argued the selection was based primarily on local availability reasons.

Comparing the results of biochar size, overall, the most common range was 1–5 mm. However, smaller, and larger particle sizes of 0.25 mm [41] and 9.5 mm [45], respectively, have also been reported. This result may be explained by the fact that in thinner porous media the straining is greater, and adsorption sites are abundant, which can result in more reduction of pathogens [4,31,37]. The specific surface area is another property of great importance as it contributes to the removal of pollutants, and determines the suitability of filtration material to allow biofilm growth and consequently biological degradation processes for organic pollutants. In this study, it ranged from 118 to 200 m^2/g, and as expected, it was higher and lower than sand (0.152 m^2/g) and activated carbon (1000 m^2/g), respectively [37]. The total porosity varied from 42 to 74% and was higher than the typical porosity of sand particles (35%). This implies that biochar has a better capacity for both water retention and biofilm development [31].

3.2.2. Configuration and set up of the filtration systems

Several treatment systems (CW, GW, VG, GR) have incorporated biochar as a filter material in their configuration to remove organic, inorganic, and microbiological pollutants from greywater [25–27]. Three main types of configurations were identified: single biochar filter (10 studies), multilayer-based filter (8 studies), and step in chain treatment (10 studies). Table 4 presents an overview of the system configuration and dimension evaluated in every single study.

The single biochar filter used a cylinder-like shape container made of plastic and glass material. It included five parts: influent input, top gravel layer, biochar layer, drainage gravel layer, and effluent output. The top gravel provided uniform distribution of the influent and prevented flotation of biochar particles and water evaporation [36,42]. Generally, water flowed downward under non-saturated and intermittent conditions. Most of the studies used a 2.5 cm depth of gravel in both the top and bottom sections of the filter to facilitate the flow of influent and effluent greywater, respectively. However, depths of 5 cm [36] and 1.4 cm [44] were also reported. Among the studies, the biochar section had a usual bed size of 50–60 cm, except for Biruktawit [44] and Adonadaga et al. [47] who used smaller bed heights. To prevent the washing of smaller grains of media, mosquito nets and wire mesh were installed between the gravel and biochar [47]. In addition, aluminium foil was used to pack the filters to impede light transmission and hence algae development [31,44]. The typical height of the filter was 55–70 cm, and although no reason was given, columns of long lengths are assumed to provide longer biochar-greywater contact time, favouring the adsorption of pollutants [36] (Fig. 6A).

The multilayer filters had a similar configuration to that of single biochar filters. Main differences were the number, height, and content of layers. A simple multilayer filter composed of sand and biochar [7,39] as well as a complex six-layer filter [8] were identified in this study (Fig. 6B). Sand was among the most common filter material used probably due to its proven superior physicochemical properties to remove water pollutants [10]. A broad variety of filter materials has been used in combination with biochar, from organic (mulch, sawdust, coconut shell, and teff straw), inorganic (sponge, sand, gravel, iron dust, bricks, and pebbles), up to living one (earthworms and soil). Arguments concerning the height selection of the layers were not further discussed by the authors, however, the distribution of the filter materials within the filter was reported to follow a particle-size basis. Typically, larger particles were in the upper layers while smaller grains in the lower ones favoured the filtering of contaminants as water flows downwards [8]. Between the studies, only Niwagaba et al. [8] assessed the performance of a large-scale multilayer filter as opposed to Basnet [35] who did it in a small filter built in a laboratory funnel.

This literature review also found the use of biochar in filtration processes within defined greywater treatment chain treatment. Biochar has been utilized either as a single biochar filter [1,5,32,37,43] or a multilayer filter [38,40,48,56] with the same configuration as described previously. As can be seen in Table 4, typically, biochar-based column filters were used as a secondary treatment after preliminary and primary treatments with screening and sedimentation, respectively (Fig. 6C). However, some studies employed them as tertiary treatment mainly as a polishing step after biological treatment with CW [5] or bio-bed [40], or after remediation with commercial A02 GWTP Ecomotive greywater treatment unit [1] (Fig. 6D). Unlike the two previous configurations that had a primary laboratory approach, in this third type, several authors evaluated the performance of biochar-containing filters at large-scale and on-site greywater treatment systems [5,37,38].

3.2.3. Operating conditions of the filtration systems

The operational parameters of both the biochar and biochar-based filters are different from the studies reported in this literature review. Some authors evaluated the filter's capacity to withstand variations in the range of organic loading rate (OLR) and hydraulic loading rate (HLR) [5,8,37,42], while others have assessed fixed values that simulate filter conditions at a large-scale. High HLR was associated with biofilm washing whereas low HLR caused thinner biofilm and consequently narrowed the internal pores reducing the straining of bacterial particles [6,37]. In terms of the period of study, each had a different time for performance analysis of the filters. From Table 4, it can also be seen that 13, 4, and 8 studies were carried out in periods longer than 30, between 8 and 29, and shorter than 7 days, respectively. As expected, lab-based experiments had shorter assessment times than large-scale on-site treatment systems [1,5,32,37]. The hydraulic residence time (HRT) was another parameter examined as it is associated with biochar physicochemical properties such as water holding capacity and porosity. A minimum and maximum HRT of 30 and 240 h, respectively, were identified in the literature [5,8]. As Table 4 shows, all reported HRT values were higher than conventional HRT values in the sand (0.5 h) and some lower than activated carbon (119 h) [31,37]. A high HRT value is responsible for the degradation and nitrification of organic matter as it prolongs the contact between greywater and the biochar-attached biofilm [44].

3.2.4. Untreated greywater characteristics

Greywater refers to wastewater generated in handwashing basins, bathrooms, washing machines, showers, kitchen sinks, and dishwashers, but excluding wastewater streams from toilets [57]. According to its source and constituents, greywater can be categorized as light and dark greywater. The former includes wastewater with high pollutants strength such as laundry and kitchen sink wastewater, while the latter includes wastewater with low pollutants concentrations like bathroom and washbasin wastewater [58]. Due to the absence of urine and faces (contained in toilet wastewater) in greywater, it does not require the same in-depth, expensive, and centralized treatment process as domestic wastewater [59]. With the increasing demand for freshwater, treated greywater reuse may reduce water needs for crop irrigation, laundry, and toilet flushing, thus leaving the consumption of freshwater sources for primary activities [31].

A considerable amount of literature has been published on the physical, chemical, and microbiological characteristics of greywater. Overall, these studies indicate that the composition of greywater relies on factors such as quality of water source, point of origin (kitchen, bathroom, laundry, or mixture), water consumption style, location (household, industry, schools, church), and geographic location (developed and developing countries) [57,60]. In this literature review, the greywater came from various origins (Table 5), thus, its composition

Table 4
Summary of the system's configuration and operating conditions.

Configuration of system	Dimension	Time (day)	OLR (gBOD$_5$/m^2.day)	HLR/Flow Rate	HRT (h)	Reference
Single biochar filter						
n.m.	h: 23 cm	30–50	–	0.74 φ	–	[41]
2.5 cm depth of gravel (top) + 50 cm depth of biochar/activated carbon (centre) + 2.5 cm depth of gravel (bottom)	h: 65 cm ø: 4.3 cm	65	–	43 π	108 φ	[31]
2.5 cm depth of gravel (top) + 60 cm depth of biochar (centre) + 2.5 cm depth of gravel (bottom)	h: 70 cm ø: 7.5 cm	39–77	3.9–19.4	34–400 π	66–85	[42]
5 cm depth of gravel (top) + 55–60 cm depth of biochar/activated carbon/sand (centre) + 5 cm depth of gravel (bottom)	h: 55–60 cm ø: 5–20 cm	365	5–20	32–200 π	66–108	[36]
2.5 cm depth of gravel (top) + 50 cm depth of biochar/activated carbon/bark (centre) + 2.5 cm depth of gravel (bottom)	h: 65 cm ø: 4.3 cm	70	76	32 π	–	[6]
n.m.	–	–	–	3–5 φ	–	[49]
16 cm depth of biochar/sand/saw dust (top) + mosquito net and wire mesh + gravel	h: 22 cm ø: 19 cm	30	–	–	48	[47]
1.4 cm depth of gravel (top) + 27 cm depth of biochar/sand/biochar+sand +1.4 cm depth of gravel (bottom)	h: 36 cm ø: 7 cm	4	–	–	146.4	[44]
2.5 cm depth of gravel (top) + 50 cm depth of biochar/bark/activated carbon/bark+activated carbon (centre) + 2.5 cm depth of gravel (bottom)	h: 65 cm ø: 4.3 cm	63	76	32 π	90 φ and 170 ω	[4]
Doses: 0.25–2 g of (biochar/activated carbon)/L, contact time: 2 h, Mixing rate: 120 rpm	–	140	–	–	–	[9]
Multilayer-based filter						
L0: Filter paper + L1: pure biochar/enriched biochar + L2: sand + L3: Sponge	–	1	–	–	–	[35]
L1: a mixture of 2.5 g of biochar and 0.5 kg of sand	h: 400 cm ø: 1.27 cm	–	–	0.6 φ	–	[7]
L1: 100 mm height of bottom gravel (5–10 mm) + L2: 600 mm height of biochar (D10 = 1.4 mm, D60 = 3.1 mm) + L3: 2 mm height of Geotextile polymer + L4: 80 mm height of mulch + L5: 70 mm height of top gravel (5–10 mm) + L6: Earthworms	h: 85 cm ø: 60 cm	90	519–1580	60 π	30	[8]
L1: 20 cm height of medium sand + L2: 20 cm height of Soil Mixture Block (soil, charcoal, sawdust, and iron dust) + L3: 20 heights of coarse sand + L4: 20 cm height of fine gravel + L5: 20 cm height of pebbles	h: 100 cm ø: 7.5 cm	7	–	24.3 φ	–	[45]
L1: 15cm height of crushed oyster shells (7.49 mm) + L2: 15 cm height of charcoal (11.92 mm) + L3: 50 cm height of beach sand	h: 100 cm ø: 5.08 cm	21	–	–	–	[33]
L0: 212 μm mesh and filter membrane of 20 mm thick + L1: 50 mm height of sand + L2: 350 mm height of biochar/activated carbon	h: 40 cm ø: 10.16 cm	2	–	33 π	–	[39]
L1: Crushed stone sand (0.1–10 mm), L2: Crushed biochar (1–5 mm), L3: Teff-straw (0.25–1.0 mm)	V: 100	7	–	24 φ	–	[10]
L1: 0.15 m height of sand, L2: 0.1 m height of bricks, L3: 0.2 cm height of charcoal, L4: 0.15 cm height of sawdust, L5: 0.2 cm height of coconut shell covers	–	30	327 ₪	180 φ	–	[30]
Step in chain treatment						
(1) Screening, (2) Decantation process, (3) Filtration (coconut coals, biochar, gravel, and sand)	–	1	–	–	–	[46]
(1) Coagulation/flocculation/decantation process, (2) Filtration (sand 10 g sand and 10 g biochar)	h: 11 cm ø: 2.0 cm	–	–	0.3 φ	–	[48]
(1) Sedimentation tank (Inlet chamber: 100 L, Outlet chamber: 50L), (2) Conventional filter system with gravel and sand (0.5 m3), (3) Polishing filter with charcoal, Kqalaqadi Sand, and Makoro waste brick materials (25–50 L)	h: 70 cm ø: 8 cm	7	–	0.2 φ	–	[43]
(1) Settling/filtration), (2) Constructed wetland, (3) Adsorption with charcoal filter (contained 0.60 m deep hyacinth plants)	w: 150 cm d: 900 cm h: 900 cm	365	10–350 β	–	30–240	[5]
(1) Collection tank, (2) Filtration (charcoal and slow sand filters), (3) Ultraviolet disinfection unit	h: 90 cm ø: 50 cm	6	–	–	–	[38]
(1) Sieve filtration (5–2 mm mesh), (2) Foam and synthetic fibre (particle size – 200/100/50 μm), (3) Charcoal filtration (bed size: 25 cm, particle size: 0.7–1.0 mm), Sand filtration (bed size: 20 cm, particle size: 0.1–0.2 mm), (4) UV Lamp (253.7 nm wavelength)	–	300	–	16–20 φ	–	[32]
(1) Gravel (7.62 cm height) and sand (10.16 cm height) pre-treatment, (2) Peat soil (7.62 cm height), charcoal (5.08 cm height) and sand (5.08 cm height)	w: 41 cm d: 25.5 cm h: 30 cm	28	–	–	–	[34]
(1) Bio-bed 1, (2) Bio-bed 2, (3) Bio-bed 3, (4) Filtration (L1: 8 cm height of sand, L2: 7 cm height of charcoal, L3: 5 cm height of sand)	w: 39.5 cm d: 23 cm h: 55 cm	35	–	12.24 φ	–	[40]
(1) A02 GWTP Ecomotive, (2) Filtration (2.5 cm depth of gravel (top) + 60 cm depth of biochar/filtralite +2.5 cm depth of gravel (bottom))	h: 60 cm d: 14 cm	180	–	280 π	–	[1]
(1) Septic tank, (2) Filtration (60 cm depth of biochar (top) + 15 cm depth of gravel (bottom))	w: 240 cm d: 60 cm h: 180 cm	90	40	114 π	–	[37]

n.m.: not mentioned.
L#: number of the layer.
OLR (β: in kg COD/ha/day, ₪: in mg COD/L).
HLR (π: in L/m^2.day, φ: in L/h).
Φ: mean residence time.
ω: longest residence time.

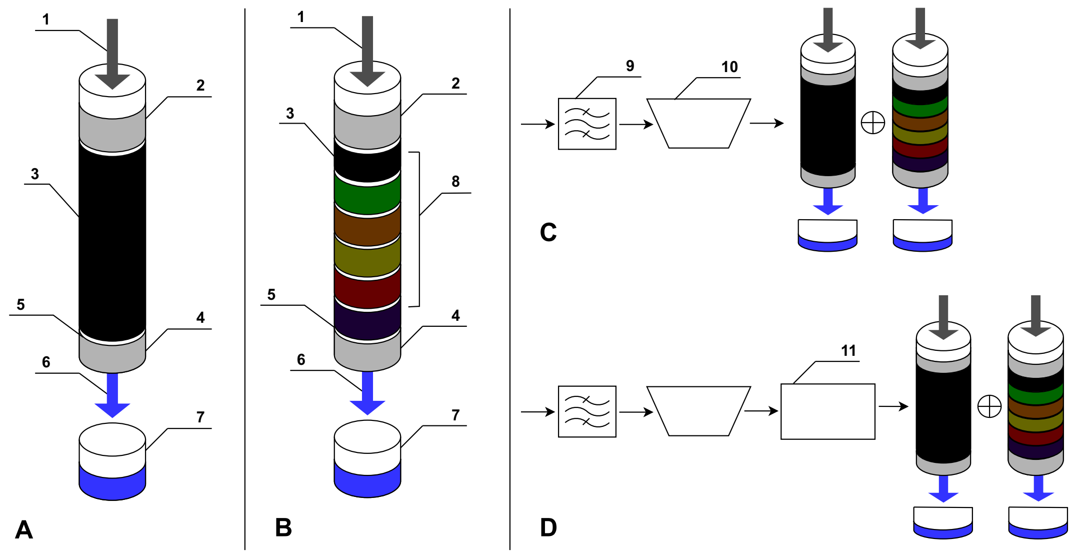

Fig. 6. Configuration and set up of the filtration systems. (1) influent, (2) top gravel, (3) biochar material, (4) drainage gravel layer, (5) wire mesh, (6) effluent, (7) container, (8) filter materials, (9) preliminary (screening), (10) primary clarifier (sedimenter), (11) secondary clarifier (constructed wetland).

was expected to be distinct.

3.2.4.1. Physical characteristics. Regarding the physical characteristics (Table 6), the range of turbidity, total dissolved solids (TDS), and total suspended solids (TSS) were 1.24–791 NTU, 141–1683 mg/L, and 5.84–5176 mg/L, respectively. As stated previously, these observed high-end ranges were associated with the origin of greywater. For instance, a biochar filtration system operated with Musta'mal water or greywater from foot-washing [38], while Qrenawi & Mahmoud [7] employed kitchen greywater which contains food particles. Regarding TDS, Owusu-Boateng et al. [33] identified 141–206 mg/L in a mixture of greywater in student residence halls, and although the value is lower compared to Adonadaga et al. [47] and Chithra & Dandapani [40], a possible explanation for this might be the demographics and water consumption habits of the water users in the study of Owusu-Boateng et al. [33]. Likewise, when it comes to TSS, the high value of 5176 mg/L found by Niwagaba et al. [8] in a mixture of greywater agrees with the 996 mg/L of TSS identified by Katukiza [61].

3.2.4.2. Chemical characteristics. Turning now to the chemical characteristics, pH was the parameter measured in most of the studies. As can be seen from the Table 7, the pH value is close to neutral in most of the greywater samples [1,5,7,44], except for an acidic and alkaline raw greywater of 4.8 and 8.5 reported by Mohamed et al. [34] and Berger [31], respectively. Although there is no reason given by Mohamed et al. [34] to explain the acidity of the water, it is assumed that it comes from organic compounds in foods, however, the alkaline greywater from Berger [31] is attributed to the detergents and soaps used to prepare the raw synthetic greywater. In the case of Biological Oxygen Demand (BOD_5), Niwagaba et al. [8] and Qrenawi & Mahmoud [7] obtained the highest values with 4667 ± 2198 mg/L and 1175 ± 25 mg/L, respectively. It seems possible that the former value is due to a mixture of the kitchen, laundry, and bathroom streams, whereas the latter value is higher than the average value of 604.5 mg/L for kitchen greywater suggested by Shaikh & Ahammed [57] and Ghaitidak et al. [60]. Similar behaviour was observed for Chemical Oxygen Demand (COD), however, the COD value of 1908 ± 108 mg/L described in Qrenawi & Mahmoud [7] is below the average value of 2074.5 mg/L stated in Shaikh & Ahammed [57].

Table 5
Origin of greywater used in the reviewed studies.

Origin	Reference
Real mixture of kitchen, bathroom, and laundry wastewater	Parjane & Sane [30]; Nigam et al. [32]; Mohamed et al. [34]; Niwagaba et al. [8]; Owusu-Boateng et al. [33]; Moges et al. [1]; Dalahmeh [36]; Dalahmeh et al. [37]; Patil & Munavalli [5]; Chithra & Dandapani [40]; Salihu Wamdeo [39]; Biruktawit [44]; Deepa et al. [45]; Perez-Mercado et al. [42]; Adonadaga et al. [47]; Roslan & Saji [46]; and Pedroza et al. [48]
Synthetic	Berger [31]; Molaei [4]; Sidibe [6]; Basnet [35]; Emslie [41]; and Thompson et al. [9]
Kitchen	Kadenge [43]; Qrenawi & Mahmoud [7]
Bathroom	Abd Rahman et al. [38]
Laundry	Yaseen et al. [10]

3.2.4.3. Nutrients. As shown in Table 8, the concentration of nutrients, nitrogen (N) and phosphorus (P) differ broadly in line with the type of streams. As expected, most of the reviewed studies indicated total nitrogen (TN) values below the average range in domestic wastewater (20–80 mg/L) mainly because of the exclusion of urine faces in greywater [62]. High concentrations of TN as shown by Berger [31] may be associated with the usage of protein-containing cleaning materials employed in the synthetic greywater. The concentration of total phosphorus (TP) also varied from 0.53 ± 0.18 mg/L [1] to 90 mg/L [39]. High TP values are related to the usage of phosphorus-containing washing products (detergents and soaps) in countries where they have not been banned, mainly in low-and-middle-income countries [35].

3.2.4.4. Microbiological characteristics. According to Maimon et al. [63], the presence of pathogenic organisms in greywater represents a risk to people's health when in contact, thus the monitoring of microbial pollutants is essential to ensure greywater for safety reuse. The main potential sources of microbial contamination are faecal pollution, handwashing after using the toilet, nappy washing, raw food products (e.g., meat), and washing children's clothes [39,57,60]. Table 9 shows the levels of microbial indicators and pathogens in greywater identified in the reviewed studies. A total of twelve microbial indicators have been characterized in eight out of the 28 studies including Dalahmeh [36], Dalahmeh et al. [37], and Perez-Mercado et al. [42]. Faecal coliform (FC) concentrations reported by Niwagaba et al. [8] ($4.2 \times 10^7 \pm 3.79 \times 10^7$ CFU/100 mL) and Biruktawit [44] (2.88×10^3–3.76×10^3 CFU/100 mL) were found above and below than FC value of 5.4×10^7

Table 6
Physical characteristics of untreated greywater.

Volatile Solids (mg/L)	Temperature (°C)	Turbidity (NTU)	Color (HU)	TDS (mg/L)	TSS (mg/L)	Total Solids (mg/L)	Fixed Solids (mg/L)	Reference
–	–	–	–	308	35.3	–	–	[46]
82	25.0	1.2*	–	–	–	788	706	[48]
–	25	–	–	–	–	–	–	[6]
–	–	468.5	–	–	5.84	–	–	[49]
–	–	791	–	1683	–	–	–	[7] ¥
–	–	–	–	769 ± 326	5176 ± 3518	6071 ± 3904	–	[8]
–	–	229.17	–	–	–	–	–	[44]
–	–	–	–	196.3	182.5	378.8	–	[10] μ
–	25	–	–	–	–	–	–	[4]
–	27 ± 1	3.22 ± 0.80	–	203 ± 30	–	–	–	[5]
–	–	5.55 ± 2.54	–	–	–	–	–	[1]
–	–	–	–	–	118 ± 59	–	–	[37]
–	–	1.24	50.67	–	7.33	–	–	[36]
–	–	–	–	575	186	–	–	[32]
–	–	–	–	141–206	–	–	–	[33] α
–	–	243.25	–	–	263.5	–	–	[34] π
–	–	–	–	573	184	–	–	[30]
–	–	–	–	1172	–	–	–	[47]
–	12.2	96.8	–	595	–	–	–	[43] ₪
–	–	–	–	–	–	–	–	[39]
–	–	–	–	572.2	254	826.3	–	[45] Ш
–	–	–	–	1130 ± 00.06	–	–	–	[40]

*: Measured in μT.
¥: Values reported for the 5 m microfilter.
Ш: Average of four cycles.
₪: Assumed to be the effluent of the "conventional filtration" system.
α: Values reported in the residence hall called Africa.
π: Average of values reported weekly.
μ: Average of values reported for sample 2 (S2).

Table 7
Chemical characteristics of untreated greywater.

pH	EC (μS/cm)	Alkalinity (mg $CaCO_3$/L)	Total Hardness (mg/L)	BOD_5 (mg/L)	COD (mg/L)	DO (mg/L)	Sulphates (mg SO_4^{2-}/L)	Chloride (mg Cl^-/L)	Reference
6.29	–	–	–	500	–	–	–	–	[46]
6.7	–	89	–	–	45.7	–	–	–	[48] ¥
5.7	–	–	–	–	–	–	105.9	151.3	[41] Ш
8.5	1800	–	–	–	1389	–	–	–	[31]
–	592 ± 69–1015 ± 27	–	–	24 ± 13	–	–	–	–	[42]
–	–	–	–	131 ± 50	496 ± 87	–	–	–	[36] Ψ
8.04 ± 0.23	5820 ± 360	–	–	–	4630.5 ± 232.8	–	–	–	[6]
7.3	2511	–	–	1175 ± 25	1908 ± 108	–	–	–	[7]
6.23 ± 0.51	1540 ± 652	–	–	4667 ± 2198	7307 ± 1102	–	–	–	[8]
7.5	–	–	–	–	2004	–	–	–	[44] φ
7.06	319.2	168.9	–	446.8	1276.4	4.48	–	–	[10] μ
7.08 ± 0.45	277 ± 55	101 ± 25	–	68 ± 15	84 ± 14	–	–	46 ± 11	[5]
7.28 ± 0.19	269 ± 28	–	–	–	55.13 ± 20.55	–	–	–	[1]
8.0 ± 0.5	–	–	–	377 ± 85	–	–	–	–	[37]
6.63	–	–	–	–	–	6.67	–	–	[38]
8.40	–	–	380	–	330	–	22.33	–	[32]
6.77–7.57	246–319	–	–	–	–	–	–	–	[33] α
4.48	–	–	–	70.75	138.75	–	–	–	[34] π
8.5	7231	–	–	400	600	–	–	–	[39]
8.12	–	–	374	–	327	–	21.3	–	[30]
6.31	824	–	–	–	1040	–	–	–	[43]
–	–	–	–	183	–	–	–	–	[47]
–	–	–	–	124.1	268.2	–	–	53.4	[45]
8.33 ± 00.21	1812.00 ± 92.86	272.00 ± 32.00	384.29 ± 36.74	137.69 ± 10.65	362.91 ± 29.56	3.93 ± 00.51	45.20 ± 03.27	–	[40]

¥: The inflow values are the average of values reported for point 3 (P3).
Ш: Values reported for Test 5.
Ψ: Values of COD and BOD_5 reported for HLR of 37 ± 7 L/m^2.day.
Φ: Values reported for Fine biochar (FBC) and Fine biochar with sand (FBCS).
π: The inflow values are the average of values reported weekly.
μ: The inflow values are the average of values reported for sample 2 (S2).
α: Values reported in the residence hall called Africa.

Table 8
Nutrients in untreated greywater.

NH_4-N (mg/L)	NO_3-N (mg/L)	TKN (mg/L)	PO_4-P (mg/L)	TN (mg/L)	TP (mg/L)	Reference
–	–	–	–	50.4	18	[35]
3.7	1.3	–	2.6	95	3.6	[31]
6.5 ± 4.2–10.1 ± 8.3	–	–	–	–	–	[42]
–	–	–	1.87 ± 4	30 ± 4	–	[36] Ψ
23.9 ± 15.6	1.2 ± 0.6	–	–	9.4 ± 1.04	–	[6]
–	–	87 ± 3	–	–	–	[7] φ
28.7 ± 28.1	–	–	–	28.7 ± 64.2	24.1 ± 7.9	[8]
–	–	–	–	1.02	16.9	[44]
–	–	5.54 ± 0.0.59	–	–	0.68 ± 0.07	[5]
3.81 ± 0.68	1.44 ± 1.21	–	–	10.03 ± 2.26	0.53 ± 0.18	[1]
72.0 ± 14.0	–	–	–	–	6.4 ± 2.1	[37]
0.79	0.68	–	0.011	–	–	[32]
13.54	–	–	–	–	–	[34] π
1.9	125	–	275.85	35	90	[39]
0.79	0.67	–	0.012	–	–	[30]
–	2.548	–	1.255	–	–	[47]
11.6	–	–	1.33	–	–	[45]
–	18.09 ± 03.33	–	3.55 ± 00.17	–	–	[40]

Ψ: Values of COD and BOD_5 reported for HLR of 37 ± 7 L/m^2.day.
φ: Values reported only for 4 m microfilter.
π: Average of values reported weekly.

CFU/100 mL described by Kariuki et al. [64] in a study with similar greywater source and geography.

3.2.5. Removal mechanisms of pollutants from greywater in BCFS

Biochar adsorption mechanism is dependent on the heterogeneity of the adsorbent surface and the nature of the pollutant (adsorbate). In the case of organic contaminants, electrostatic attraction, hydrophobic sorption, hydrogen bond, π-π electron-donor acceptor interactions and pores fillings facilitate the adsorption process [18]. The production of biochar at high temperatures causes the dissociation of oxygen-containing groups which charges biochar negatively and facilitates its electrostatic attraction toward positively charged pollutants. Additionally, high-temperature biochar production originates in biochar surfaces with fewer oxygen-and hydrogen-containing functional groups which make them less suitable for removing polar organic compounds as their polarity is lowered [18,19,55]. Under this condition, adsorption can take place by hydrogen bonding because of the electrostatic repulsion between both negatively-charged biochar and organic compounds. In pore-filling, adsorbate condensation occurs in adsorbent pores depending on their micropore and mesopore volumes [18,42]. A low ionic radius of some pollutants promotes their penetration into biochar and, as a result, biochar's adsorption capacity is increased [18]. In the case of soluble contaminants containing hydrophobic functional groups, they can be removed by hydrophobic sorption when they are attached to hydrophobic sites from biochar [18]. For the removal of inorganic pollutants, mainly heavy metals, the adsorption occurs through electrostatic attraction, ion exchange, complexation and co-precipitation, and physical adsorption mechanisms. In complexation and co-precipitation, metals present in greywater can form either complex with oxide minerals or free carboxyl and hydroxyl functional groups available on the biochar surface. Then they settle (physical sorption) or form layers (precipitation) on the biochar surface [18].

Fig. 7 depicts the estimated removal mechanisms happening in BCFS based on existing literature on biochar application for wastewater treatment. When biochar is used as a filtration support media in BCFS for greywater treatment, several mechanisms are responsible for pollutant removal. Although the dominant removal mechanism is dependent on

Table 9
Microbiological characteristics of untreated greywater.

Reference	[42]	[36] Ш	[6]	[8]	[44]	[4]	[5]	[1]	[37]
Total Bacteria Count (MPN/100 mL)	–	–	–	–	–	–	–	8.30 × 10^4	–
Most Probable Number (No./100 mL)	–	–	–	–	–	–	131 ± 48	–	–
Somatic coliphages (PFU/100 mL)	–	–	–	–	–	–	–	–	2 ± 2
Salmonella typhi (MPN/100 mL)	–	–	–	–	–	–	–	–	<1.1 ± 1
MS2 concentration (PFU/100 mL)	3.6 × 10^6–1.9 × 10^8	10^6–10^8	3.07 × 10^6–3.68 × 10^7	–	–	3.5 × 10^7	–	–	<1 ± 0
Faecal enterococcus (log_{10} MPN/100 mL)	–	10–10^6*	–	–	–	10^5*	–	–	0.77 ± 0.75
E. coli concentration (CFU/100 mL)	3.3 × 10^3–9.0 × 10^6	10^2–10^6	–	–	–	–	–	2.64 × 10^4¥	5.1 ± 1.2£
Salmonella spp. (CFU/mL)	–	10^5–10^7	1.59 × 10^5–1.01 × 10^7	–	–	7 × 10^7	–	–	–
Enterococcus spp. concentration (CFU/mL)	7.6 × 10^2–3.1 × 10^5	–	4.68 × 10^4–9.44 × 10^6	–	–	–	–	–	–
ϕX174 concentration (PFU/mL)	2.6 × 10^5–1.9 × 10^6	10^5–10^7	3.79 × 10^5–1.57 × 10^7	–	–	2 × 10^6	–	–	–
FC (CFU/100 mL)	–	–	–	4.2 × 10^7 ± 3.79 × 10^7	2.88 × 10^3–3.76 × 10^3	–	–	–	–
S. cerevisiae concentration (CFU/mL)	4.0 × 10^2–1.4 × 10^3	–	–	–	–	–	–	–	–

*: Expressed in CFU/mL.
Ш: Values reported for HLR and OLR of 32 L/m^2.day and 70 g BOD/m^2.day, except for *E. coli* (HLR: 34 L/m^2.day, OLR: 20 g BOD/m^2.day).
£: Expressed in log_{10} MPN/100 mL.
¥: Expressed in MPN/100 mL.

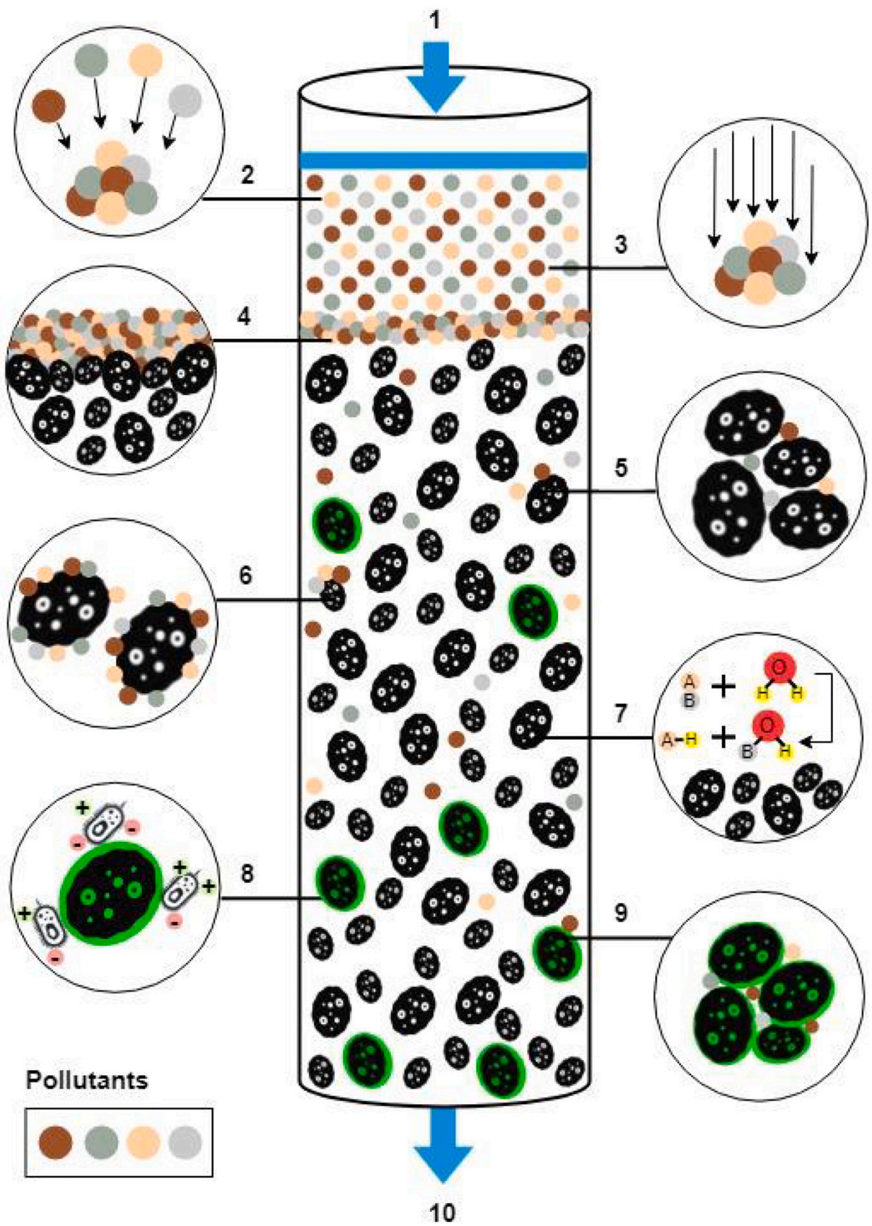

Fig. 7. The pollutant removal mechanisms in BCFS. (1) influent, (2), agglomeration, (3), sedimentation/precipitation, (4) surface filtration, (5) straining, (6) adsorption, (7) hydrolysis, (8) biofilm adsorption, (9) biofilm straining, (10) effluent.

several factors such as biochar's physicochemical properties, system configuration, and operation condition [18]. Initially suspended solids agglomerate forming large particles that precipitate on the filter surface [18,42,65]. Next, as the smaller particles continue their flow downwards, they are strained and adsorbed on the biochar surface, while the anaerobic conditions on the deeper filter zones promote the removal of organic matter by hydrolysis [18,36,37]. Pathogen removal takes place under different mechanisms. For instance, biofilm formation on the attachment sites of the biochar surface enhances the reduction of pathogens by adsorbing viruses and bacteria through electrostatic attraction [18]. Likewise, the presence of several layers of biofilm on biochar reduces the pore size between biochar particles allowing a larger number of pathogens to be removed by filtration and adsorption [8,18,42].

3.2.5.1. Physical characteristics of effluent greywater. As can be seen in Table 10, the two most common parameters to assess the physical aspect of the treated greywater were turbidity and TDS. Overall, the removal percentage of turbidity ranged between 70 and 96% in most studies. Similar reductions of 73.4 and 71.2% were reported in biochar filters operated at rapid (5 L/h) and slow (3 L/h) flow rates, respectively. Biochar also had a better performance in removing turbidity than other filter media. Qrenawi & Mahmoud [7] and Moges et al. [1] described a decrease of 95.5 and 84%, respectively, compared to sand, sawdust and filtralite. TDS was also highly reduced up to 83.4% [45], and although no explanation for those values was provided by the studies included in this literature review, Kaetzl et al. [65] argued that both turbidity and TDS are removed through successive steps starting with the agglomeration and sedimentation of coarse particles, followed by filtration on the upper filter zone, and straining and adsorption of fine particles on the biochar locate along the deeper zones of the biochar filter. Nevertheless, an increase in TDS was reported by Niwagaba et al. [8] and Yaseen et al. [10] possibly due to the lack of biochar rinsing to remove biochar dust from the filter before functioning or the release of particles from biochar natural degradation over time. TSS was also reduced at high levels between 55 and 99.1%. For instance, Niwagaba et al. [8] showed a TSS

Table 10
Physical characteristics of the effluent greywater (average value, % removal).

Temperature (°C)	Turbidity (NTU)	Color (HU)	TDS (mg/L)	TSS (mg/L)	Total Solids (mg/L)	Fixed Solids (mg/L)	Volatile Solids (mg/L)	Reference
–	–	–	100.3 (67.4%)	3.0 (91.5%)	–	–	–	[46]
24.9	0.7* (41.7%)	–	–	–	679 (13.8%)	601 (14.9%)	78 (4.9%)	[48]
25	–	–	–	–	–	–	–	[6]
–	RF: 124.66 (73.4%) SF: 135.00 (71.2%)	–	–	0.05 (99.1%)	–	–	–	[49] Ψ
–	35.5 (95.5%)	–	1616 (3.9%)	–	–	–	–	[7] ¥
–	–	–	1428 (−85.7%)	689 (86.7%)	2271 (62.6%)	–	–	[8]
–	FBC: 9.17 (92%) FBCS: 19.17 (96%)	–	–	–	–	–	–	[44] **
–	–	–	198.9 (−1.34%)	25.4 (86.1%)	224.3 (40.8%)	–	–	[10] μ
27 ± 1	1.35 ± 0.18 (58%)	–	141 ± 31 (30.5%)	–	–	–	–	[5]
–	0.87 ± 0.23 (84.3%)	–	–	–	–	–	–	[1]
–	–	–	–	17 ± 8 (86%)	–	–	–	[37]
–	1.17 (5.6%)	45.50 (10.2%)	–	6.33 (13.6%)	–	–	–	[38]
–	–	–	174 (70%)	40 (78.5%)	–	–	–	[32]
–	–	–	234–368	–	–	–	–	[33] α
–	108.25 (55.5%)	–	–	118.5 (55%)	–	–	–	[34] π
–	–	–	172 (70%)	32 (82.6%)	–	–	–	[30]
10.6	–	–	456 (23.4%)	–	–	–	–	[43]
–	–	–	1079 (7.94%)	–	–	–	–	[47]
–	–	–	95 (83.4%)	52.4 (79.4%)	147.4 (82.2%)	–	–	[45] Ш
–	–	–	410 (64%)	–	–	–	–	[40]

*: Measured in μT.
¥: Values reported for the 5 m microfilter.
Ш: Average of four cycles.
**: Values reported for fine biochar (FBC) and fine biochar including sand (FBCS).
Ψ: Values reported for rapid flow or RF (3.207 L/h) and slow flow of SF (0.534 L/h) flow rate, respectively.
α: Values reported in the residence hall called Africa.
π: Average of values reported weekly.
μ: Average of values reported for sample 3 (S3).

reduction of 86.7% for a biochar filter operated at 36 h HRT. The same removal mechanisms for turbidity and TDS are accountable for TSS reduction. Temperature is another physical parameter of relevance since it influences bacteria adsorption to porous media. According to Sidibe [6], bacterial surface polymers become viscous at low temperatures, chemisorption and certain types of physical adsorption are reduced, and the organisms' physiology is altered. Overall, room temperature (25 °C) was the most common among the reviewed studies (Table 10).

3.2.5.2. Chemical characteristics of effluent greywater. Several chemical parameters were evaluated to assess the efficiency of biochar filters in removing chemical pollutants (Table 11). In the case of pH, the lowest and highest values reported were 6.15 [43] and 10.5 [44], respectively, while most of the reviewed studies reported values closely to 7 (neutral). Large reductions of organic matter (COD and BOD_5) were also achieved with removal above 80% and up to 98.9 and 99.1% reported in most studies, respectively. Several studies have concluded that a large specific surface area is the main driven mechanism for organic matter removal since better adsorption capacity and biofilm development were observed in biochar with smaller effective particle sizes [18,36,66]. The decrease in organic matter (COD and BOD_5) was attributed to two consecutive periods driven by physicochemical and biological processes. Initially, the organic matter is absorbed into the reactive sites on the surface of the biochar but as they deplete and biofilm layers develop, biological processes are responsible for the breakdown of organic matter.

3.2.5.3. Nutrient removal from greywater. The removal of nitrogen is accomplished through several processes, mainly ammonium adsorption, microbial assimilation, and molecule breakdown through denitrification [36]. As can be seen in Table 12, the removal of nutrients such as N and P varied in each study. Basnet [35] reported low total N and P removal of up to 10 and 27% compared to ferric sulphate-enriched biochar which was able to reduce N and P concentrations up to 23 and 41%, respectively. However, high removal percentages of 90.94 and 89.3% have also been reported, respectively [31]. Several factors influence the decrease of N and P inside the biochar filter. Biruktawit [44] found that significant N and P reductions of 94 and 78.8% were achieved in a neutral environment (pH 7). Biochar grain size also plays a role in nutrient removal. Fine biochar particles (<1 mm) eliminated more N (62%) and P (52%) than medium (1–3 mm) and coarse (>3 mm) biochar [44]. However, a similar study to Biruktawit [44] did not find significant differences in the removal of total N and P when <2 mm and 2–4.7 mm biochar size were evaluated [39]. As the size of the biochar particles decreases, the surface area increases, promoting both, adsorption of ammonium and biofilm development. In the majority of the studies reviewed, the level of ammonium reduction was particularly high as values above 62% were described except for Berger [31] who reported 2.7% removal (Table 12). Moreover, as noted in Table 12, the nitrate concentration removal was more than 60% in various studies and even reached 94.4% in Salihu Wamdeo [39], meaning that biochar increases nutrient removal rates, thereby reducing design residence time. This is due to the activity of heterotrophic denitrifying bacteria developed under anaerobic conditions on the deeper filter zones which enhances nitrate removal by reducing it to ammonium. However, although most of the revised studies in this review reported high nitrate reductions, other studies such as Sidibe [6] and Yao et al. [67] found biochar without the ability to sorb nitrate perhaps because of a rapid occupation of active adsorption sites on biochar surface which limit the formation of denitrifying bacteria. The high nitrate removal reported by Salihu Wamdeo [39] can be related to the addition of sand into the biochar filter media as previously described by Bock et al. [68] in studies on denitrifying bioreactors with biochar-sand mixtures where nitrate

Table 11
Chemical characteristics of the effluent greywater (average value, % removal).

pH	EC (μS/cm)	Alkalinity (mg $CaCO_3$/L)	Total Hardness (mg/L)	BOD_5 (mg/L)	COD (mg/L)	DO (mg/L)	Sulphate (mg SO_4^{2-} /L)	Chloride (mg Cl^-/L)	Reference
6.80	–	–	–	97 ± 3 (80.6%)	–	–	–	–	[46]
6.4	–	78 (12.4%)	–	–	5.8 (87.4%)	–	–	–	[48] ¥
8.52	–	–	–	–	–	–	94.6 (10.6%)	149.5 (1.19%)	[41] Щ
8.1	1842	–	–	–	13 (99.1%)	–	–	–	[31]
–	–	–	–	5 ± 2 (96.2%)	23 ± 14 (95.4%)	–	–	–	[36] Ψ
8.13 ± 0.15	4100 ± 1200 (29.6%)	–	–	–	463.5 (90%)	–	–	–	[6]
8.2	2411 (3.98%)	–	–	12.5 ± 2.5 (98.9%)	691.5 ± 151.5 (63.67%)	–	–	–	[7]
–	–	–	–	182 (96.1%)	672 (90.8%)	–	–	–	[8] ω
FBC: 10.5 FBCS: 9.55	–	–	–	–	FBC: 581.16 (71%) FBCS: 1062 0.12 (47%)	–	–	–	[44] **
6.5	372.5 (−16.7%)	118.9 (29.6%)	–	398.9 (10.7%)	840.8 (34.1%)	5.8 (−22.3%)	–	–	[10] μ
6.95 ± 0.44	194 ± 49 (30%)	73 ± 19 (27.7%)	–	51 ± 17 (25%)	63 ± 15 (25%)	–	–	33 ± 10 (28.2%)	[5]
7.66 ± 0.127	311 ± 43.76 (−15.6%)	–	–	–	10.99 ± 5.51 (80.1%)	–	–	–	[1]
7.8 ± 0.3	–	–	–	28 ± 25 (93%)	–	–	–	–	[37]
6.39	–	–	–	–	–	7.54 (−13%)	–	–	[38]
7.35	–	–	188 (50%)	–	60 (81.8%)	–	11.6 (88.4%)	–	[32]
8.13–8.41	374–724	–	–	–	–	–	–	–	[33] α
6.8	–	–	–	44.5 (37.1%)	120.75 (13%)	–	–	–	[34] π
FIG*: 7.1 FIG**: 7.2 MAH*: 7.2 MAH**: 7.3 SHEA*: 7.3 SHEA**7.41	FIG*: 3161 (56.3%) FIG**: 4017 (44.4%) MAH*: 4132 (42.9%) MAH**: 4712 (34.8%) SHEA*: 274 (96.2%) SHEA**: 3192 (55.9%)	–	–	FIG*: 50 (87.5%) FIG**: 60 (85%) MAH*: 110 (72.5%) MAH**: 190 (52.5%) SHEA*: 90 (77.5%) SHEA**: 60 (85%)	FIG*: 40 (93.3%) FIG**: 50 (91.6%) MAH*: 60 (90%) MAH**: 60 (90%) SHEA*: 20 (96.7%) SHEA**: 10 (98.3%)	–	–	–	[39] ˆ
7.43	–	–	187 (50%)	–	58 (82.3%)	–	10.66 (50%)	–	[30]
6.15	644 (21.8%)	–	–	–	1290 (24%)	–	–	–	[43]
–	–	–	–	71 (61.20%)	–	–	–	–	[47]
–	–	–	–	20 (84%)	45.9 (82.6%)	–	–	20.1 (62.4%)	[45]
7.94 ± 00.10	642.29 ± 60.30 (65%)	136.00 ± 12.59 (100%)	139.66 ± 14.31 (64%)	16.34 ± 2.76 (88%)	68.23 ± 6.70 (81%)	3.93 ± 00.51 (95%)	8.89 ± 01.13 (80%)	–	[40]

ˆ: Values reported for Fig tree biochar (FIG), Mahogany tree biochar (MAH) and Shea tree biochar (SHEA) of 2–4.7 mm (*) and < 2 mm (**).
**: Values reported for fine biochar (FBC) and fine biochar including sand (FBCS).
¥: Average of values reported for point 4 (P4).
Щ: Values reported for Test 5.
Ψ: Values of COD and BOD reported for HLR of 37 ± 7 L/m^2.day.
ω: Values reported at HRT of 36 h.
α: Values reported in the residence hall called Africa.
π: Average of values reported weekly.
μ: Average of values reported for sample 3 (S3).

reduction was enhanced.

3.2.5.4. Microbiological characteristics of effluent greywater. Several studies have assessed the efficiency of biochar filters in removing model bacterial (*Escherichia coli* and *Enterococcus* spp.), viral (bacteriophages MS2 and ϕX174), and protozoan-oocyst (*Saccharomyces cerevisiae*) as they are indicators of faecal contamination, presence of human viruses, and surrogates for the intestinal track of pathogenic *Cryptosporidium parvum*, respectively [36]. Other studies evaluated microbial removal using a non-specific microorganism and a general microbial counting test Total Bacterial Count (No./100 mL) and Most Probable Number (MPN/100 mL) [1,5].

Low $\log_{10}$ reductions of viruses ϕX174 (0.9 ± 0.5), and MS2 (1.4 ± 0.8) were reported by Dalahmeh [36]. It was suggested that the low adsorption of the viruses was influenced by the pH of the filter media (Table 13) which affected the isoelectric point of the viruses (pH where a virus molecule is chargeless). As the isoelectric point (ISP) of both ϕX174 and MS2 occurs in acidic conditions, the alkali medium in the filters limited the adsorption of the viruses [71]. Additionally, the straining process carried out inside the filter media is not effective as the bacterial viruses are of small size (0.02–0.25 μm). On the other hand, a similar relatively high reduction of *Salmonella* spp. was observed in Sidibe [6], Dalahmeh [36] and Molaei [4] of 2.7, 2.4, and 3 $\log_{10}$, respectively (Table 13). These results are likely to be related to a

Table 12
Nutrients in the effluent greywater (average value, % removal).

NH_4-N (mg/L)	NO_3-N (mg/L)	PO_4-P (mg/L)	TN (mg/L)	TP (mg/L)	Reference
–	–	–	Biolan: 45.9 (9%) RPK: 45.4 (10%)	Biolan: 13.1 (27%) RPK: 13.5 (25%)	[35]
3.60 (2.7%)	1.08 (19.8%)	0.37 (85.87%)	8.61 (90.94%)	0.39 (89.3%)	[31]
–	–	0.83 ± 0.50 (55.6%)	15 ± 10 (50.0%)	–	[36] Ψ
0.8 (96.6%)	152 (−99.3%)	–	166.8 (−94.4%)	–	[6]
–	–	–	–	–	[7] φ
–	–	–	0.39 (62%)	8.11 (52%)	[44]
–	–	–	–	0.56 ± 0.14 (17.6%)	[5]
2.17 ± 0.72 (43%)	0.32 ± 0.19 (77.8%)	–	3.41 ± 0.92 (66%)	0.22 ± 0.03 (58.5%)	[1]
9.2 ± 4.6 (89%)	–	–	–	3.7 ± 1.4 (42%)	[37]
0.20 (74.7%)	0.20 (70.6%)	0 (100%)	–	–	[32]
3.97 (96%)	–	–	–	–	[34] π
FIG*: 0.44 (76.8%)	FIG*: 14 (88.8%)	FIG*: 3.71 (98.7%)	FIG*: 7 (80%)	FIG*: 1.21 (98.7%)	[39] ^
FIG**: 0.72 (62.1%)	FIG**: 7 (94.4%)	FIG**: 5.03 (98.3%)	FIG**: 7 (80%)	FIG**: 1.64 (98.2%)	
MAH*: 0.52 (72.6%)	MAH*: 7 (94.4%)	MAH*: 8.0 (97.2%)	MAH*: 7 (80%)	MAH*: 2.61 (97.1%)	
MAH**: 0.52 (72.6%)	MAH**: 7 (94.4%)	MAH**: 8.09 (97.2%)	MAH**: 7 (80%)	MAH**: 2.64 (97.1%)	
SHEA*: 0.64 (66.3%)	SHEA*: 10.5 (91.6%)	SHEA*: 7.17 (97.5%)	SHEA*: 7 (80%)	SHEA*: 2.34 (97.4%)	
SHEA**: 0.52 (72.6%)	SHEA**: 7 (94.4%)	SHEA**: 8.34 (97.1%)	SHEA**: 7 (80%)	SHEA**: 2.72 (97%)	
0.21 (73.4%)	0.21 (68.7%)	0 (100%)	–	–	[30]
–	0.201 (83.98%)	–	–	–	[47]
11.6 (85.3%)	–	0.23 (82.5%)	–	–	[45]
–	5.57 ± 00.85 (69%)	0.93 ± 00.09 (74%)	–	–	[40]

^: Values reported for Fig tree biochar (FIG), Mahogany tree biochar (MAH) and Shea tree biochar (SHEA) of 2–4.7 mm (*) and < 2 mm (**).
Ψ: Values of COD and BOD reported for HLR of 37 ± 7 L/m^2.day.
φ: Values reported for 4 m microfilter.
π: Average of values reported weekly.

straining mechanism of *Salmonella* spp. when flowing through the microspores within the filter media.

3.2.6. Comparison between biochar and conventional filter media

Some studies evaluated the use of biochar filters as a replacement for conventional filter media used for greywater cleaning such as activated carbon, sand, bark, rice husk, filtralite, and sawdust. The TSS removal percentages above 90% were reported in rice husk, rice husk biochar, and rice husk activated carbon filters operating with rapid (3.207 L/h) and slow (0.534 L/h) flow rates, respectively. Similarly, Moges et al. [1] found that biochar filters performed best in removing turbidity from greywater when used as polishing material.

In terms of the chemical pollutants, both Berger [31] and Dalahmeh [36] reported similar high COD reductions of 99% and above 94% in biochar and activated carbon filters functioning at an HLR of 0.043 and 0.032–0.2 m^3/m^2/day, respectively. Salihu Wamdeo [39] also reported high treatment efficiencies for both types of filters, however, found higher COD removal (85–95%) in activated carbon filter than in biochar filter (76–90%). Similarly, Sidibe [6] found that activated carbon filters were most effective in reducing COD levels than biochar and bark since they reached removals of 96%, 90%, and 82%, respectively. Adonadaga et al. [47], on the other hand, identified a low COD reduction of 60% in both biochar and sawdust filters, but high removal in sand filter (97.65%).

The presence of nutrients (N and P) in the effluent greywater was another parameter compared among the filters. Berger [31] pointed out that filters made from biochar were best at removing TP and phosphate (PO_4^{3-}) (89 and 86%, respectively) than activated carbon filter (78 and 70%, respectively). Salihu Wamdeo [39] found an opposite result, however, emphasizing a decrease in TP content up to 92%. Similarly to COD removal in Adonadaga et al. (2020), phosphate removal was higher in the sand (99.92%) than in biochar (83.98%) filters, with the latter better than the sawdust filter (20.52%). In the case of nitrogen, contradictory findings were described. Berger [31] and Salihu Wamdeo [39] achieved removal above 90% in both biochar and activated carbon filters while Sidibe [6] reported no reduction. Again, when compared to sand, the biochar filter appeared to remove more total nitrogen. Dalahmeh [36] and Adonadaga et al. [47] reported reduction percentages of 52.0 and 58.8% compared to 3.0 and 28.3%, respectively.

Lastly, in terms of microbe reduction, biochar removed more *Salmonella* spp. (2.72 $\log_{10}$ reductions) and *E. faecalis* (1.51 $\log_{10}$ reduction) than activated carbon (1.55 and 1.32 $\log_{10}$ reduction respectively) and bark (1.43 and 1.26 $\log_{10}$ reduction respectively) filters. Nevertheless, biochar filters removed less MS2 and similar ϕX174 compared to the rest of the filters. Although operating at the same HLR, Molaei [4] reported that activated carbon filters performed best at removing all microbe pollution parameters previously mentioned.

3.2.7. Influence of biochar characteristics on removal efficiency

Biochar's parental material and production conditions determine its physicochemical properties. To analyse the influence of biochar characteristics on removal efficiency, only the physical properties (e.g., size, density, and porosity) will be considered. The impact of chemical properties (e.g., surface functional group) will not be discussed since that information was not provided by the studies revised for this literature review. Dalahmeh [36] reported a converse relationship between biochar particle size and HRT. For instance, a shorter (66 h) HRT was found on BCFS filled with 2.8 mm biochar in comparison to longer (85 h and 87 h) ones reported for BCFS using 0.7 mm and 1.4 mm biochar, respectively. Macropores with large particle sizes usually connect creating channels for wastewater flow without enough contact time between pollutants and the filter media. Under such conditions, effluents from filters will contain some non-treated greywater since the removal mechanisms will be limited.

As biochar particle size and fraction within BCFS rule the HRT of the system, fine particle sizes (smaller than 0.1 mm) can lead to clogging and biochar dust, affecting the effluent quality. In the present review, the most common range of particle size was 1–5 mm, except for Emslie [41] who used particle size of 0.25–2 mm. As can be seen in Table 3, although particle size is a determinant factor for pollutant removal, nine studies in this review failed to provide that information to help understand their relationship with reduction efficiency. Additionally, information regarding the pre-rinsing of BCFS filled with >1 mm particle size to remove the biochar dusty fraction was not stated [32,41,44]. This means that further studies comparing pre-rinsed and non-pre-rinsed BCFS filled with fine biochar particles and operated under similar conditions are required to understand better the effect of size on insufficient hydraulic conductivity within BCFS.

Table 13
Microbiological characteristics of the effluent greywater (Log_{10} reduction).

Reference	[42]	[36] ꟺ	[6]	[8]	[44] ₪	[4]	[5]	[1]	[37]
Total Bacteria Count	–	–	–	–	–	–	–	6.4 × 10^2 ¥ (99.2%)	–
Most Probable Number	–	–	–	–	–	–	64 ± 14 β (51.1%)	–	–
Somatic coliphages	–	–	–	–	–	–	–	–	0.6
MS2 concentration	0.2–2.3	1.4 ± 0.8	0.94	–	–	<1–3	–	–	–
Faecal enterococcus	–	2.4 ± 1.3	–	–	–	1–4	–	–	−1.44
E. coli concentration	0.2–4.5	>4	–	–	–	–	–	1.46 × 10^2¥ (99.4%)	0.66
Salmonella spp.	–	2.4 ± 1.0	2.72 ± 0.74	–	–	3	–	–	–
Enterococcus spp. concentration	0.3–4.4	–	1.51 ± 0.73	–	–	–	–	–	–
ϕX174 concentration	0.2–1.3	0.9 ± 0.5	–	–	–	<1–4	–	–	–
FC	–	–	–	1.85 × 10^6 ∞ (95.5%)	FBC: (87%) FBCS: (90%)	–	–	–	–
S. cerevisiae concentration	0.3–1.9	–	5	–	–	–	–	–	–

ꟺ: Values reported for HLR and OLR of 32 L/m^2.day and 70 g BOD/m^2.day, except for *E. coli* (HLR: 34 L/m^2.day, OLR: 20 g BOD/m^2.day).
₪: Values reported for fine biochar (FBC) and fine biochar including sand (FBCS).
(%): the value of removal expressed in %.
¥: Expressed in MPN/100 mL.
β: value expressed in No./100 mL.
∞: value expressed in CFU/100 mL.

In terms of pollutant removal, Perez Mercado et al. [42] found that smaller biochar particles indicate higher fractions of micropores which enhances microbe removal by increasing the contact between microbes and adsorption sites on both biofilm and filter media (biochar). Moreover, the removal of smaller microorganisms (e.g., bacteria) is dominated by adsorption on the biofilm surface. Nevertheless, as reported by Sidibe [6], the reduction of larger microbes such as *Salmonella* spp. in BCFS is driven by straining processes which are associated with the size and proportion of pores in the filter media. Similarly, the reduction of organic matter and nutrients by biological activity is favoured on the high specific surface area of biochar (in this literature review the reported range varied from 118 to 200 m^2/g). This is because more surface area is available for biofilm to grow and degrade organic matter (hydrolysis) or remove TN by denitrification routes in anaerobic zones [36].

Although biochar particle size affects the removal mechanisms taking place on biochar surface, it is not possible to conclude what is the exact range of size that allows better removal efficiency since every BCFS reported in this literature review is different in configuration and operating conditions (Table 4). Therefore, future research should focus on the optimization of BCFS using a mathematical model to estimate the effect of BCFS's characteristics (independent variables) on pollutant removal (dependent variable).

3.2.8. Influence of operating conditions on removal efficiency

The operating conditions in terms of OLR, HLR, and HRT play a key role in the removal efficiency of greywater pollutants by BCFS. For the case of physical pollutants such as TSS, a longer HRT allows better agglomeration and followed sedimentation of the suspended solids present in the supernatant water [8,18]. As sediments settle onto the biochar surface, the pore space between biochar particles is reduced enabling the straining of coarse solids and larges microorganisms (e.g., protozoa and amoebas) [42]. Additionally, when BCFS treats high strength greywater containing salts and bulking agents from detergents at high HLR, salts resulting from the greywater degradation are released increasing the concentration of TDS [8].

The removal of organic matter under the effect of operating conditions for BCFS was also studied. Similar BOD_5 removal percentages of 96.1 and 93% were reported at low (64 L/m^2.day) and high (114 L/m^2.day) HLR, respectively. Similarly, Dalahmeh [36] found no differences in the decrease of COD and BOD_5 at HLR of 37–200 L/m^2.day. Likewise, the OLR did not affect the biochar filter's performance to reduce organic matter. A reduction above 90% was noted even though the OLR ranged from 3.9 to 1580 g BOD_5/m^2.day [4,6,8,37]. Nevertheless, higher COD removal was observed at higher OLR, suggesting that higher organic loads speed up the microbiological activity, thus stimulating the mineralization process [36,67,70]. In the case of HRT, the elimination of COD and BOD_5 above 90% was promoted with a longer HRT [8,36,44].

The removal of nutrients such as nitrogen and phosphorus depends on the HLR and the physicochemical properties of biochar. For instance, Dalahmeh [36] evaluated the removal of TN and TP in a BCFS operated at 32–200 L/m^2.day of HLR and found that higher TN removal was achieved at HLR below 50 L/m^2.day and biochar particle size of 1.4 mm. This loading rate and particle size avoided biofilm washing, thus favouring TN removal by adsorption of NH_4-N on biochar surface, biological assimilation and denitrification activity on anaerobic zones. The removal of TP, on the other hand, was less dependent on the HLR but the chemical properties of biochar. For instance, when sand and biochar filters operate at similar HLR and OLR, sand filter removes more TP due to its capacity to bind phosphorus with Ca, Fe and Al located on the sand surface [36].

The operating conditions of biochar filters also play a significant role in the removal of microbes. Perez-Mercado et al. [42] evaluated the removal of bacterial and viral indicators at HLR higher (200 and 400 L/m^2.day) than conventional HLR for sand filtration treatment (34 L/m^2.day). It was demonstrated that high HLR decreased both the biofilm straining process and contact time between microbes and active sites as thinner biofilm layers formed. This affected the microbe removal as a consistent low reduction of 1 log_{10} was found in each microorganism analysed. Nevertheless, the low OLR at which the biochar filter operated (4, 5, and 15 g BOD_5/m^2.day) caused thinning of the biofilm layers, affecting the straining process like the influence of high HLR. Likewise, Niwagaba et al. [8] observed increases in the elimination of faecal coliforms (FC) as the retention time increased. Reduction of up to 95.6% was achieved at 36 h of retention time in comparison to 43.3% at one third retention time (Table 13). This observed increase in FC removal was attributed to higher microbial retention in the pores of the filter media and biofilm maturity as time prolonged. Similarly, Biruktawit [44] identified removal efficiencies of 87 and 90% in filters composed of purely biochar and a mixture of biochar and sand, respectively, when they functioned at residence times of 6 days.

Overall, the studies in this review analysed the effect of operating conditions of BCFS on removal efficiency and drawn reasonings as to how they affected or enhanced the removal mechanisms responsible for pollutants reductions. However, since the characteristics of BCFS in terms of the type of biochar, operation time, loading rates, layer configuration, composition of wastewater, and scale are different among the BCFS used in the studies, the influence of operating conditions on removal efficiency cannot be generalized but specific to each study. Therefore, further studies are needed to develop integrated design criteria for the construction of BCFS treating greywater for water reuse.

3.2.9. *Influence of filter configuration on removal efficiency*

As stated previously, three types of BCFS configuration were used in the reviewed studies: single biochar filter, multilayer-based filter, and as a polishing step for tertiary greywater treatment. None of the studies explained the selection of bed size (range of 20–70 cm) and filter diameter (range of 4.3–20 cm) and their role in enhancing pollutant removal mechanisms. It is assumed that longer columns provide better contact between greywater and active adsorption sites from biochar favouring the physical, chemical, and biological removal routes to take place [36]. The influence of the ratio between bed size and filter diameter on removal efficiency was unexplored in all studies (Table 4). This is a relevant design parameter considering that airspace can be formed along the filter's walls under non-optimum filter diameter, leading to the creation of artificial channels where water flows rapidly with less contact with active adsorption sites [69].

The operation time is known to determine the maturity of the biochar filter system in terms of the biofilm formation on the biochar surface. The operation time in the studies analysed in this review paper oscillates from days to months. Typically, long-operated filters develop thinner biofilm layers affecting positively the removal of organic matter, nutrients (TN), and pathogens. For instance, Niwagaba et al. [8] reported that extended operation of biochar filters creates anaerobic zones for the denitrifying microorganism in the micro-and nanopores of biochar. Likewise, longer assessment periods are useful to determine the maximum adsorption capacity of biochar and the robustness of BCFS under sudden changes in operating conditions when greywater flows continuously. Regarding this, all the studies lacked the provision of breakthrough curves to estimate the time when pollutant removal starts to decrease and therefore biochar's capacity has been reached. This means that the removal efficiencies described in Tables 10–13 must be carefully analysed as they may not be representative of a particular configuration type.

Besides the use of biochar as a unique filter media, biochar has also been used together and as part of a mixture with other filter media (Table 4). Although the removal efficiency among multilayers filters described in this review is not comparable due to differences mainly in layer disposition, operation time and loading rate, it can be generally assumed that filter media with distinct physicochemical characteristics than biochar boost the pollutant efficiency of BCFS. For example, the addition of sand layer or sand-including mixtures has been shown to diminish the concentration of TP by binding phosphorus with Ca, Fe and Al present on sand [36]. However, further studies are required to determine whether the removal efficiency and longevity of BCFS operating under similar conditions are dependent on the addition of different kinds of filter media. Particularly, an in-depth study is needed to understand the existence of changes in removal mechanism dynamics concerning layers' disposition and depth.

Table 4 also shows that ten of the reviewed studies evaluated the use of BCFS as part of a greywater treatment chain. When comparing the removal efficiency between this type of configuration and single or multilayer BCFSs, special attention should be given to removal efficiency data given by the authors to represent the overall pollutant removal efficiency of the whole treatment chain or only from the biochar-containing filter used as tertiary treatment. Higher removal efficiencies can be observed for BCFS functioning as a tertiary treatment [5,40]; however, these values can be overestimated as influent pollutant concentrations were reduced during preliminary treatment (screening), primary clarifier (sedimentation tank) and secondary treatment (constructed wetlands) (Fig. 6). As this type of configuration involves successive steps for greywater treatment, further investigation is needed to determine the relationship between durability and cost when compared to the other configuration types. Additionally, the use of biochar along the treatment chain, for instance as both adsorbent filter media and substrate for phytoremediation in constructed wetlands, can be further explored.

3.2.10. *Treated greywater for water reuse*

Table 14 summarizes the different purposes of reuse of treated greywater that are described in each of the studies reviewed as well as the regulations and suitability of reuse achieved. Greywater was mainly treated for non-potable reuse such as toilet flushing, floor washing, car washing, cloth washing, and irrigation of land, garden, and edible crops. However, minor reuse purposes for safety effluent discharge [36,45,47], nutrient recycling [35], and potable purposes (for ablution) [38] were also identified.

The suitability of treated greywater reuse was assessed, mostly, under local guidelines of reuse, however, international wastewater reuse standards such as World Health Organization (WHO), United States Environmental Protection Agency (USEPA), Food Agricultural Organization (FAO), EU guidelines were also used to evaluate compliance with water quality regulations in treated greywater. Most studies reviewed achieved the reuse regulations, meaning that all parameters (physical, chemical, nutrients, and microbiological) chosen to measure the water quality were met, while others emphasized the parameters below the limits established in the regulations [41,47,49].

Although most studies met reuse standards, the meaning of these results must be critically addressed. Several studies were performed at lab-scale filters operated in the short term. Although high contaminants removal was reached, still the performance of the filter at up-scale and long-term conditions remains unknown. Additionally, a weakness observed in all studies is the failure to address the reasons on which the selection of water quality parameters is based. The authors do not explain whether this selection is driven by economic, technical, or regulatory-based reasons. The differences in number and type of quality parameters can be seen in Tables 6-9.

Moreover, the replicability of biochar filters and successful compliance for greywater reclamation in various studies appears to be limited to national levels since governmental greywater reuse guidelines were used to conclude the suitability of water for reuse. Only two studies compared the compliance of their results to international wastewater reuse standards [31,39]. In a few studies, on the other hand, authors argued the possibility of reuse based on the positive result of a limited number of water quality parameters. For instance, both Abd Rahman et al. [38] and Emslie [41], concluded that effluent greywater meets drinking water regulations. Nevertheless, very few quality parameters for this category of reuse were analysed to reach this conclusion. Lastly, some studies would appear to be over-ambitious in their claims of achieving water quality for crop irrigation. Out of ten studies treating greywater for irrigation (either restricted or unrestricted), half of them did not evaluate microbial contamination necessary to prevent reclaimed greywater from harming human health [7,9,32,33,49].

3.2.11. *Potential new areas of research*

Various topics for further investigation could be identified in the reviewed studies. Perceptions toward greywater reuse among users are fundamental to measuring social acceptability for on-site reclaimed greywater treatment systems [72]. However, only two of the revised

Table 14
Summary of the reuse purposes for the treated greywater in the reviewed studies.

Regulation	Purpose	Outcome	Reference
Malaysia Standard and water classes	Toilet flushing	Achieved	[46]
n.m.	Toilet flushing, floor washing, car washing, garden irrigation	n.m.	[48]
WHO guidelines for safe use of wastewater	Drinking water	Achieved	[41]
n.m.	Recycling of nutrients (N and P)	Achieved	[35]
International Wastewater Reuse Standards	EU: Discharge from urban wastewater treatment plants Jordan: Reclaimed domestic reuse Egypt: Unrestricted agricultural irrigation Italy: Agricultural irrigation, urban reuse China: Impoundments and lakes	Depends on regulation	[31]
WHO guidelines for safe use of wastewater	Agricultural irrigation	Not achieved	[42]
Swedish Environmental Protection Agency	Wastewater effluent discharge	Achieved (only organic matter)	[36]
WHO guidelines for safe use of wastewater	Agricultural irrigation (unrestricted)	Achieved	[6]
Botswana Bureau of Standards (BOS 93:2012)	Toilet flushing, floor washing, car washing, garden irrigation	Not achieved	[43]
Jordanian Standard for Reclaimed Domestic Wastewater	Agricultural irrigation	Achieved (only turbidity and TSS)	[49]
Palestinian Water Authority Standards	Agricultural irrigation and domestic reuse	Achieved	[7]
FAO Discharge Standards	Agricultural irrigation	Not achieved	[8]
n.m.	Toilet flushing, floor washing, car washing, garden irrigation	n.m.	[44]
South African Water Quality Standards and Australian Water Quality Criteria for Irrigation	Cloth washing	Achieved	[10]
WHO guidelines for safe use of wastewater	Agricultural irrigation (sub-surface)	Achieved	[4]
Indian Effluent standards (Ministry of Environment and Forest)	Land irrigation	Achieved	[5]
WHO guidelines for safe use of wastewater	Agricultural irrigation (unrestricted) and land irrigation	Achieved	[1]
Jordanian Standard for Reclaimed Domestic Wastewater	Garden irrigation	Achieved	[37]
Malaysian Drinking Water Quality Standard	Drinking water (use in ablution)	Achieved	[38]
USEPA Guidelines for water reuse and			[9]

Table 14 (*continued*)

Regulation	Purpose	Outcome	Reference
	Agricultural irrigation and toilet flushing	Achieved (after pre-treatment with biodegradation)	
Indian Standards of Water Quality	Agricultural irrigation, cloth washing, floor cleaning	Achieved	[32]
USEPA: Guidelines for water reuse and Food and Agriculture Organization Discharge Standards	Agricultural irrigation	Achieved	[33]
Malaysian Standard (Standard B)	Wastewater effluent discharge	Achieved	[34]
International Wastewater Reuse Standards	FAO: Agricultural irrigation (unrestricted) EU: Discharge from urban wastewater treatment plants Jordan: Reclaimed domestic reuse Egypt: Unrestricted agricultural irrigation Italy: Agricultural irrigation, urban reuse China: Impoundments and lakes	Depends on regulation	[39]
Indian Standards of Water Quality	Toilet flushing, floor washing, cloth washing, garden irrigation	Achieved	[30]
WHO guidelines for safe use of wastewater	Wastewater effluent discharge and non-potable	Achieved (only organic matter)	[47]
Indian Standards of Water Quality	Wastewater effluent discharge and non-potable	Achieved	[45]
Indian standard specification for drinking water and WHO Guidelines for Safe Recreational Water Environments: Coastal and Fresh Waters	Flushing toilets, floor washing, car washing, garden irrigation	Achieved	[40]

studies evaluated this area focusing on greywater reuse for non-potable purposes [8,49]. Further research should be undertaken to investigate the level of social acceptability for greywater reuse for potable purposes.

Additionally, future work is required to determine the effect of operating conditions such as water quality on the efficiency of biochar filters to remove pollutants from greywater. Strong focus should be given to the influence of higher hydraulic and organic loading rates on the cleaning capacity of biochar filters. This type of study could help solve unanswered questions about the robustness of biochar filters when exposed to sudden high loads of greywater and organic matter content. An optimization study using a mathematical model could help assess the individual influence of BCFS's characteristics on pollutant removal.

As mentioned earlier, the technical and environmental feasibility of biochar filters for greywater reclamation was determined through lab-based and short-term experiments. Thus, further studies on the same topic but at a pilot and on-site scales of long-term duration are therefore recommended [7,31,44]. In addition, there is also plenty of room for further research on the creation of integrated design criteria to dimension biochar filters for greywater treatment which lacked in the studies [36]. Concerning this, single biochar filter could explore the cleaning capacity of smaller biochar particle size and biochar whose parent material is other than wood (the main feedstock source in the reviewed studies). Multilayer biochar filters, on the other hand, should test different layer configurations, mainly position and depth. For configurations where BCFS is part of a treatment chain, the potential use of biochar as a growth medium for phytoremediation plants in coupled systems between constructed wetlands and BCFS can be explored further.

As can be seen in Table 14, the reuse of treated greywater for non-potable purposes has been widely explored. There is still much to be done in determining the technical, environmental, and economic feasibility of using biochar filters to obtain treated greywater of high quality for human-contact reuse purposes such as handwashing. This implies that microbial removal must comply with strict microbiological local and/or international regulations to ensure contact with treated water is safe for human health [73,74]. Further studies should identify and evaluate the removal of microorganisms other than the limited number seen in the studies reviewed. The study of potential natural synergist and antagonist microorganisms is another field with unresolved questions but is highly important as they may induce and enhance the removal of microbial pollution.

Additionally, because of the susceptibility of biofilm to sudden changes in environmental conditions, its degradation at high and low HLR and OLR must be investigated. There is also a need for further studies to determine if the removal efficiency and longevity of BCFS under similar conditions vary with the addition of different types of filter media. An in-depth study is specifically required to better understand the dynamics of layers' disposition and depth with removal mechanisms. Additionally, the negative effects of both natural degradation of biochar on effluent quality can be further explored to provide insight into the maximum time of use for potential BCFS users.

Moreover, the effect of alkaline greywater resulting from the usage of cleaning products such as detergents and soaps, on biofilm degradation should be assessed to ensure biological processes inside the filter are maintained. Lastly, as most of the methods to modify the surface of biochar are of physical and chemical character [75], the search for natural or biological methods is highly necessary. They could favour the removal of greywater pollutants and be of easy replicability in low- and middle-income countries where low-cost and nature-based onsite wastewater treatment prevail.

4. Conclusion

Through a systematic literature review, 28 studies from different source types such as articles, dissertations, and scientific reports have been identified to use biochar in column filtration systems for greywater treatment. Out of a 10-years period of study, a predominance of studies was observed in the last five years and particularly in regions such as Asia, Europe, and Africa. The treatment of greywater from different sources has predominantly been performed in three types of filter configuration: single layer biochar filter, multilayer biochar-based filter, and as part of an integrated greywater treatment chain. Differences in operation conditions have been identified throughout the reviewed studies owing to strategies to achieve country-specific water quality for greywater reclamation. However, the main similarity observed in most of the studies was the use of wood as the main feedstock material. Several removal processes take place within BCFS such as agglomeration, precipitation/sedimentation, straining, adsorption, hydrolysis, and biological assimilation. Overall, BCFS showed high efficiency in the removal of nutrients, and physical and chemical pollutants, but not microbial pollutants, which still surpass countries' permissible limits for greywater reuse. The use of treated greywater for non-potable purposes such as irrigation, toilet flushing, laundry, and cleaning has been widely studied, however, the field of greywater treatment for potable purposes is still largely unexplored. In general, the BCFS technology can be a feasible and sustainable alternative for greywater treatment and application in water-scarce regions.

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Credit authorship contribution statement

Jhonny Ismael Bautista Quispe: Methodology, Data collection, Data visualization, Artwork, Writing – original draft. **Anna Bogush:** Supervision, Writing – review & editing, Conceptualization. **Luiza Campos:** Supervision, Writing – review & editing. **Ondrej Masek:** Supervision, Writing – review & editing.

Data availability

A reasonable request should be made of the corresponding author for access to the data.

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.

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