Biochar

Integration of high-rate filtration using waste-derived biochar as a potential sustainable technology for drinking water supply

Fernando García-Ávila[1,2]*, Andrés Galarza-Guamán[1], Mónica Barros-Bermeo[1],
Emigdio Antonio Alfaro-Paredes[3], Alex Avilés-Añazco[1,2] and Sergio Iglesias-Abad[4]

Abstract

This research aimed to evaluate the efficiency of eucalyptus (E) and bamboo (B) residual biomass biochars as filter materials for drinking water treatment. The efficiencies of these two biochars in the rapid filtration process were evaluated using water (raw, flocculated and settled) at the rate of 120 $m^3/m^2/d$. Finding that bamboo biochar manufactured under a slow pyrolysis process "b" (Bb) had the best performance. Subsequently, Bb was evaluated with three different granulometries, and it was found that the effective size with the best performance was the finest (0.6–1.18 mm). Subsequently, this biochar was compared with conventional filter materials such as gravel, sand and anthracite, using different types of water (raw, flocculated and settled) and at different filtration rates (120 and 240 $m^3/m^2/d$), and it was found that the filter material with the best performance was precisely biochar, with average removal efficiencies of 64.37% turbidity and 45.08% colour for raw water; 93.9% turbidity and 90.75% colour for flocculated water, and 80.79% turbidity and 69.03% colour for settled water. The efficiency using simple beds of sand, biochar, anthracite and gravel at the rate of 180 $m^3/m^2/d$ was 75.9% copper, 90.72% aluminium, 95.7% iron, 10.9% nitrates, 94.3% total coliforms and 88.9% fecal coliforms. The efficiencies achieved by biochar were higher compared to those of conventional filter materials. It was also found that biochar contributes to improving the performance of sand and anthracite in mixed beds. Additionally, it was possible to demonstrate that the volume of washing water required for the biochar is lower compared to the other filter beds. Finally, it is recommended to carry out more tests for the purification of water with biochars from rural areas affected by the mining and oil exploitation, as well as the purification of seawater with biochars from coastal areas with residues from dry forests and organic residues from municipalities.

Article Highlights

- Biochar had higher efficiency than conventional filter media.
- Biochar had high efficiencies in removing copper, iron, aluminium, and total coliforms.
- Biochar in mixed beds substantially improved haze and colour removal.

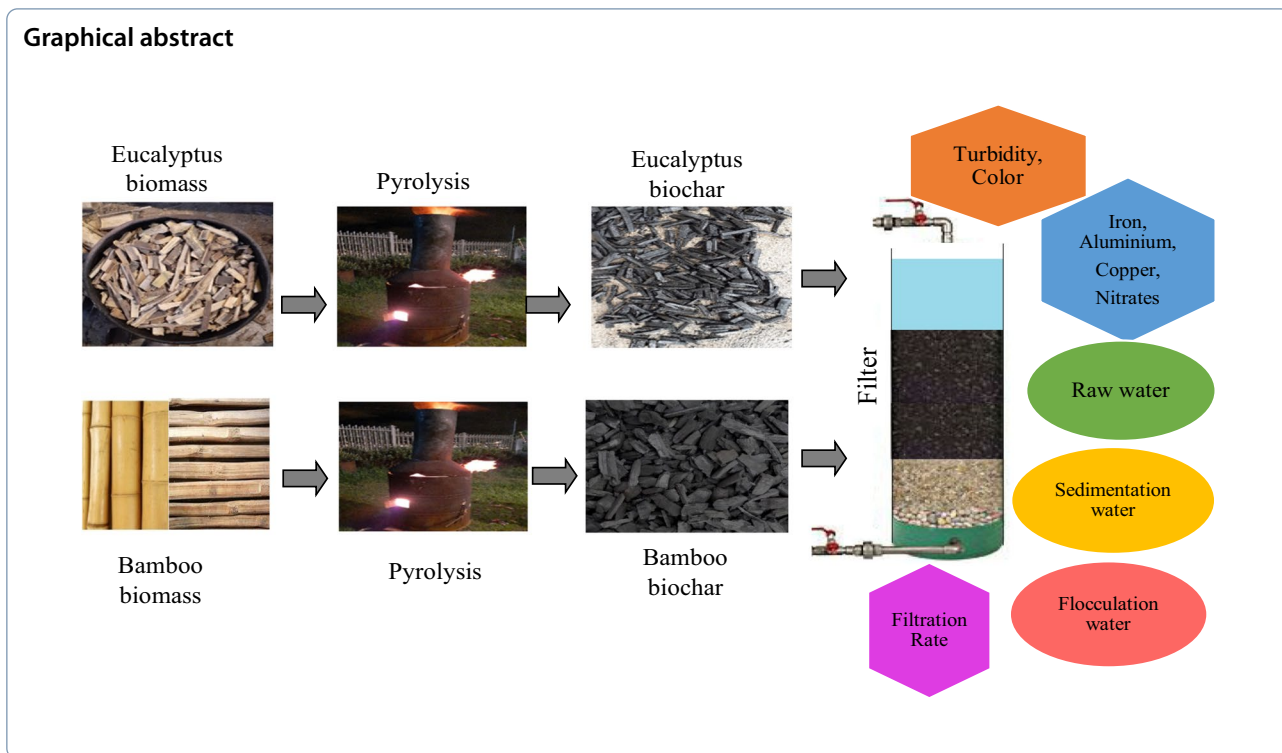**Keywords** Biochar, Filter medium, Rapid filtration, Pyrolysis, Eucalyptus, Bamboo

*Correspondence:
Fernando García-Ávila
garcia10f@hotmail.com
Full list of author information is available at the end of the article

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Graphical abstract

1 Introduction

The sixth goal of the 2030 Agenda for Sustainable Development establishes universal access to water, sanitation, and hygiene; however, more than two billion people did not have access to safe drinking water in 2017 (Gwenzi et al. 2017; Hegarty et al. 2021). These statistics are striking if one takes into account the great technological advances and the strong globalization process that has been experienced in recent decades; however, around the world, it has not been possible to guarantee access to water sources for all the population (Gwenzi et al. 2017; García et al. 2023).

The economic and technical limitations of this sector of society, together with the high costs of construction, operation, and maintenance inherent to a conventional drinking water treatment plant make it difficult for communities in rural areas to implement an entire purification system, reaching in the best of cases to implement only slow filtration systems preceded by a prefiltration system with gravel (García-Ávila et al. 2021; Machado et al. 2019). Slow filtration systems typically use sand as the filter medium, while fast filtration systems use sand and/or a combination of sand and anthracite as the filter medium (Cescon and Jiang 2020). These filter media are difficult to acquire for the majority of these communities due to their high costs; therefore, biochar is an alternative material for the emplacement of these systems.

Although the studies related to the application of biochar have been focused mostly on its efficiency as a soil improver or remediator, from an analysis of the increase in carbon retention capacity and the reduction of greenhouse gas emissions (Gwenzi et al. 2017; Wang et al. 2023), this material has also proven to be an alternative solution within the filtration processes for wastewater treatment systems, because it is a sustainably produced and easily accessible adsorbent, which can be manufactured with materials available in any medium; additionally, it has also been proven that it has the ability to inhibit the development of pathogenic microorganisms (Pooi and Ng 2018; Bolster 2019). Its production and application have also been developed within rural communities as part of drinking water treatment, although without sufficient efficiency for obtaining a quality resource (Kearns 2012). For this reason, the use of biochar as filter materials in rapid filters for the provision of drinking water in rural communities was experimentally evaluated in the present study.

Valdiviezo et al. (2021) recommended to study different types of technologies for obtaining drinking water, such as: (a) sand filtration, (b) biochar filtration, (c) ceramic filter, (d) photocatalysis or disinfection with sodium, (e) tubular flocculation, and (f) sedimentation (p. 33), in their scientometric study on technologies for drinking water treatment. As can be seen, one of the emerging applications of biochar is the treatment of water

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for human consumption and wastewater. Ahmad et al. (2014) explained that biochar has a large surface area and large pore volume, a rich organic carbon content and mineral composition, and great quantity of diverse functional groups, which allows it to have a strong adsorption capacity for organic pollutants and inorganics to remove water (Wang et al. 2020).

Biochar's potential to remove different types of contaminants in water has been tested on a laboratory scale; however, it is necessary to take this type of study towards pilot treatment systems and even on an industrial scale (Gwenzi et al. 2017). Additionally, the inclusion of other filter media such as anthracite is suggested to compare the performance of this emerging material with materials typically used in the filtration process (Kaetzl et al. 2020; Enaime et al. 2020). Biochar is a carbon-rich solid material, which is obtained by heating biomass in a closed reactor under certain temperature and ambient conditions; that is, at a temperature above 250 °C, in the absence or with a limited oxygen content [a process called carbonization or pyrolysis] (Lehmann and Joseph 2015). Furthermore, Valdiviezo et al. (2023) indicated that the use of biochar as chelants and desorbents allows the immobilization of inorganic pollutants and potentially toxic elements (PTEs), while natural and synthetic surfactants mobilize persistent organic pollutants (p. 3).

Pyrolysis is the thermochemical process in which the reaction atmosphere is inert or with a reduced amount of stoichiometric oxygen; in which biomass is thermally degraded into its chemical constituents (Tripathi et al. 2016). Pyrolysis has two stages: primary and secondary pyrolysis. The biomass is devolatilized by the action of heat through decarboxylation, dehydration, and dehydrogenation during primary pyrolysis; that is, its organic compounds decompose, releasing a vapor phase, where the high molecular weight compounds condense, forming a liquid phase called bio-oil; while low molecular weight compounds remain as gases (H_2, CO_2, CO, and CH_4) (Ochnio et al. 2020). In secondary pyrolysis, the breakdown of heavy compounds that converts the biomass into carbon occurs and the release of gases also occurs (Lee et al., 2019a; Tripathi et al. 2016). This entire process can be summarized by chemical reaction in the Eq. 1; in which the first part of the products corresponds to the liquid phase, the next is the gas phase, and finally the solid phase (biochar) is given (Raza et al. 2021):

$$(C_6H_6O_6)_n \xrightarrow{\text{Heat}} (H_2 + CO + CH_4 + \ldots + C_5H_{12}) + (H_2O + CH_3OH + CH_3COOH + \ldots) + C \quad (1)$$
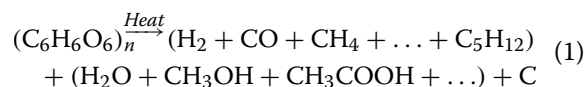
Depending on the operating parameters such as: residence time, temperature and heating rate, pyrolysis can generally be classified as fast and slow, producing biochar with different yields (Mohan et al. 2014; Tomczyk et al. 2020; Tripathi et al. 2016). These parameters are summarized in Table 1.

Fast pyrolysis occurs at temperatures between 400 °C and 600 °C, in a short residence time (seconds) and is characterized by its fast heating rate of 10 to 200 °C s^{-1}, parameters that allow greater bio-oil production and low yield in biochar production (Tripathi et al. 2016; Raza et al. 2021). This process occurs at a lower temperature, from 350 °C to 800 °C, at a longer residence time that varies from 30 min to more than an hour, and at a slower heating rate (5–7 °C min^{-1}), obtaining a higher yield in biochar production (Lee et al., 2019b).

The amount and yield of biochar depend on multiple factors, such as: biomass, temperature, pressure, heating rate, residence time, particle size, feedstock composition, moisture content, and reactor configuration (Rathnayake et al. 2021). The characteristics of biochar vary according to the type of biomass, residence time in the reactor, heating speed, and particularly the pyrolysis temperature, because it defines its chemical and physical structure, as well as its stability (Chen et al. 2016). The most important physicochemical characteristics of biochar are: (a) true, bulk, and relative density, (b) porosity, (c) surface area, (d) point zero charge (PZC), and (e) elemental composition (Breton et al. al., 2021; Leng et al. 2021).

Biochar's pyrolysis temperature has several effects on its structure; thus, as the pyrolysis temperature increases, the biochar structure tends to become more porous, due to the thermal decomposition of the organic components of the biomass, which results in the formation of pores in the biochar (Tomczyk et al., 2020). The pyrolysis temperature influences the surface area of biochar. At higher temperatures, biochar can experience further reduction in its surface area due to

Table 1 Types of pyrolysis: operating parameters and products proportion

Pyrolysis type	Temperature (°C)	Residence time	Heat rate	Products (%)		
				Biochar	**Bio oil**	**Gas**
Fast	400–600	0.5–10 s	10–200 °C s^{-1}	15–35	60–75 (25% $_{water}$)	10–20
Low	350–800	30 – >60 min	5–7 °C min^{-1}	35–50	30 (70% $_{water}$)	35

Adapted of the studies of Daful et al. (2020), Tomczyk et al. (2020), and Lee et al. (2019)

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the degradation of organic compounds and loss of surface structures (Chatterjee et al. 2020).

Biochar produced at higher temperatures tends to have greater thermal stability. It means that it is less prone to breakdown or thermal degradation when it is exposed to high temperatures in subsequent applications (Wystalska and Kwarciak-Kozłowska 2021). The pyrolysis temperature affects the chemical composition of the biochar; thus, at higher temperatures, the organic compounds present in the biomass decompose more completely, which can result in a biochar with a lower organic carbon content and a higher proportion of inorganic carbon, such as ash (Almutairi et al. 2023).

The pyrolysis temperature influences the physical properties of the biochar, such as its bulk density and mechanical resistance. In general, it is observed that biochar produced at higher temperatures tends to have a higher density and resistance due to the greater compaction of the structure (Riva et al. 2021). The pyrolysis temperature influences the carbon content of the biochar. Thus, at higher temperatures, greater removal of volatile components occurs, resulting in a biochar withhigher carbon content (Tomczyk et al. 2020).

Biochar has different granulometries, being associated with the origin and size of the biomass used for its production, which allows the obtention of high porosity with a wide variety of pore shapes and sizes (Liu et al. 2017). The macropores (internal diameter > 50 nm) come from the own spaces of biomass and the micropores (internal diameter < 2 nm) are generated during the biochar production process. It should be noted that these pores are associated with the adsorption of liquid, solid, and gaseous compounds (Amalina et al. 2022). Due to these and other additional characteristics, such as the surface area and functional groups present in biochar, it becomes a viable alternative material for use in the removal of contaminants present in wastewater (Tan et al. 2015; Yang et al. 2023).

Although this study did not focus on the biochar structure, it is important to note that the morphology of the biochar is an important factor in the filtration process. Using scanning electron microscopy (SEM), it has been determined that for bamboo biochar, produced at temperatures between 450 and 500 °C, the material preserves its original honeycomb-like pore structure, showing some new pores generated during the pyrolysis process (Li et al. 2023; Sahoo et al. 2021).

Biochar has been used primarily for soil remediation and amendment; however, biochar is being used for the removal of polluting substances present in water in recent years, largely due to its profitability and sustainability (Choudhary et al. 2020). The main purpose of this research was to evaluate the application of biochar from the combustion of residual biomass in the filtration as part of the purification process experimentally. Due to the aforementioned, the use of alternative filter media such as biochar for the treatment of drinking water would allow the implementation of a sustainable strategy for obtaining economic benefits. Finally, the possible uses or the appropriate final disposal that biochar must have in order to contribute to the circular economy strategy are indicated.

2 Materials and methods

2.1 Biochar production

The production process of the biochars generated in this study was divided into three parts: (1) pre-processing: the necessary materials (both for raw material and fuel) were collected and prepared for use; (2) thermochemical decomposition (pyrolysis): constitutes the manufacture of the carbon itself; and (3) post-processing: the obtained carbons were characterized and prepared for their use within the filtration tests. Figure 1 presents a general scheme of this production process.

2.1.1 Obtention and preparation of initial biomass

Two types of biomasses were used as raw materials for biochar production: (a) eucalyptus of the Eucalyptus globulus species and (b) bamboo of the *Guadua angustifolia* species. Eucalyptus (E) was obtained from parts of
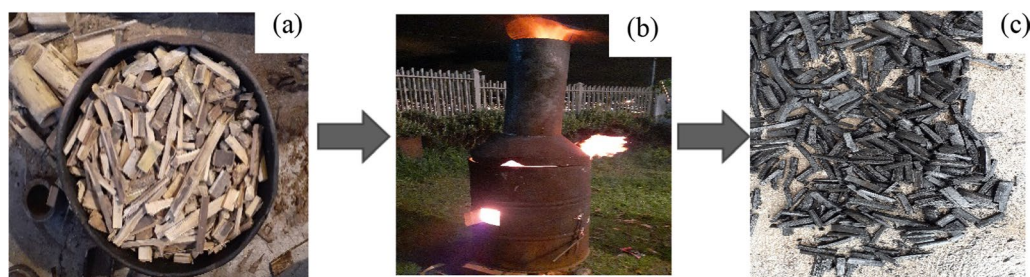
Fig. 1 **a** Obtention and preparation of initial biomass, **b** Biomass pyrolysis, **c** Post processing

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felled trees found lying on the ground in wooded areas. Eucalyptus branches were the raw materials for charcoal production and eucalyptus logs were used as an energy source for the pyrolysis process. Branches with a diameter between 10 and 40 mm were chosen and divided into segments of between 5 and 10 mm in length to occupy the largest amount of space inside the reactor at the time of charring and thus limit the amount of oxygen inside the reactor for ensuring the success of the pyrolysis process. Green softwood of low maturity was discarded.

Bamboo (B) was collected from a forest plantation of *Guadua angustifolia* species. The obtained material was only collected from the ground. The rigid part of the trunk was used, which is the most voluminous and resistant part of the whole plant, as well as showing great porosity in its structure. Similarly, these trunks were also segmented into smaller parts (pieces between 5 and 15 cm^2), taking into account the same considerations as described above for the preparation of the eucalyptus. Only advanced maturity bamboo was collected.

2.1.2 Pyrolysis process
The design used for the construction of the artisanal reactor for pyrolysis was based on the design proposed by Iglesias-Abad et al. (2020). This design was adapted and built from recycled materials in order to present a design that can be reproduced and that the production of biochar can be carried out in an artisanal way.

Brewer and Brown (2012) and Pandey et al. (2020) defined slow pyrolysis as the process to follow when the objective is to prioritize the production of biochar over the other products generated during the thermochemical decomposition of biomass. The carbonization of each biomass (eucalyptus and bamboo) was carried out applying two slow pyrolysis processes that are distinguished from each other based on the process temperature and residence time. Lee et al. (2019) and Pandey et al. (2020) indicated values of 300 and 350 °C, as the minimum temperatures to carry out a slow pyrolysis process.

A first pyrolysis process "Process a" was carried out, trying to maintain an average temperature of 400 °C, in order to shorten the residence time. The second pyrolysis process "Process b" was carried out at an average temperature of 300 °C and consequently, a longer residence time was obtained, as well as a lower heating rate compared to "Process a".

The biomass was placed in the internal chamber until it occupied the greatest amount of space in order to limit the oxygen content inside. The fuel was placed inside the (external) combustion chamber. Subsequently, the necessary activation energy was supplied to start the combustion of the fuel. The temperature was monitored using the TENMARS model TM-301 digital infrared thermometer.

The measurement of the temperature inside the internal chamber was carried out every 2 min, pointing the thermometer towards the upper hole of this chamber, placed precisely for this purpose. The pyrolysis process was terminated when the emission of gases from the internal chamber ceased, indicating that the thermochemical decomposition of the biomass had concluded.

2.1.3 Post-processing
The biochar was moistened in order to avoid its combustion when it came into contact with oxygen from the ambient air, after having been extracted from the internal chamber. Subsequently, this moisture was removed to facilitate the cutting and sieving processes, for which the biochar was allowed to dry in ambient air for at least 48 h. Subsequently, the biochar was cut in order to increase the surface area, which allowed a greater retention of impurities during filtration. In the first instance, sieving was carried out with thick coals, a Gilson model SS-14D shaker and four sieves of 4.75, 10, 14, and 20 mm, respectively of the ISO 3310/1 series of the same brand were used.

Subsequently, an Endecotts 9520 brand shaker and seven ASTM sieves of the following numbers were used: 4 (4.75 mm), 6 (3.35 mm), 8 (2.36 mm), 12 (1.70 mm), 16 (1.18 mm), 20 (0.85 mm), and 30 (0.6 mm), for finer granulometry coals. All the material was sieved in portions of approximately 500 g for periods of 10 min for each one. The material retained on each sieve was weighed and stored in different containers for later use in filtration, for each sieving process. The granulometric analysis was carried out as indicated by Chapuis (2021) and Aluvihara et al. (2021).

The CHN628 LECO brand version $1.3\times$ equipment was used for the elemental analysis of biochar, which determined the percentage of carbon, hydrogen, and nitrogen. The true density was determined by the pycnometer method adopted by Hidnert and Peffer (1950). The bulk density was determined based on the method adopted by Sahoo et al. (2021). The porosity of the material was achieved by what was recommended by Berger (2012). The PZC is a parameter that indicates the pH value required for the net surface charge of the biochar to be zero, which was determined by the pH derivation method (Liu et al. 2012).

2.2 Experimental phase: filtration tests
2.2.1 Implementation of filtration columns
The experimental filtration system implemented for this study consisted of a group of individual columns with granular media prepared for high-rate filtration. The described system worked by gravity and when the filters were saturated, the filter medium was cleaned by means

of a pressure backwash. In Fig. 2a the filtration columns appear, that were acrylic tubes of 1.8 m high with an outer diameter of 10 cm. The filter bed of all the columns consisted of 30 cm of gravel as a mechanical support, on which the different filter media tested during this study were placed. The height for each bed was estimated at 60 cm, which gave each filter a maximum head loss of 90 cm. On the other hand, the pipes and accessories used both for the filtered water drainage system and for washing the filters were made of ½" diameter polyvinyl chloride (PVC) material. This system was implemented in the drinking water treatment plant (DWTP) Bayas from the city of Azogues, Ecuador.

2.2.2 Operation of the biochar filter

The efficiency of each biochar to remove suspended solids was tested, for which the removal of turbidity and colour of the filtered water was determined. For this purpose, the filtration system operated with different tributaries, such as: raw water, flocculated water, and settled water, which were obtained from the entrance to the rapid mixer, the flocculator outlet, and the settler outlet, respectively, from the DWTP Bayas where this study was performed (Fig. 2b).

Subsequently, the removal efficiency of chemical parameters such as: copper, iron, aluminium, and nitrates were evaluated; for which, water with content of the mentioned chemical parameters was used. Finally, for the evaluation of biological parameters such as total and fecal coliforms, the raw water that was at the entrance of the treatment plant was used as a tributary. Different filtration rates were also tested, for which a valve was installed at the inlet of each filter in order to regulate the influent flow based on the different filtration rates experienced. The filters were open to the atmosphere, so the flow of water through the bed was driven by gravity. The effluent was collected in the lower part of the column through a valve that constituted the sampling point for each of the filters.

2.2.3 Filtration system maintenance

The beds were cleaned by means of a backwash system, after finishing the filtration. Said system used potable water from an elevated water storage tank. The valve at the outlet of each filter made it possible to regulate the washing flow.

2.2.4 Filtration tests

The filtration tests were divided into three stages. The first stage was to determine the type of biochar with the greatest potential as a filter medium according to its material. Four types of biochars were prepared: two biomasses with process "a" and two biomasses with process "b". In each column, a height of 30 cm was used for each material that was between 10 and 14 mm in diameter and 30 cm in height with materials between 4.75 and 10 mm in diameter. Table 2 shows the symbols assigned to each of the four filter beds.

During this stage 1, filtration tests were carried out with a filtration rate of 120 $m^3/m^2/d$ (fast filtration rate) for the removal of the physical parameters (colour and turbidity) and copper removal. These tests were carried out for 45 days. The filter washing process was carried out using a washing rate five times higher than that of in
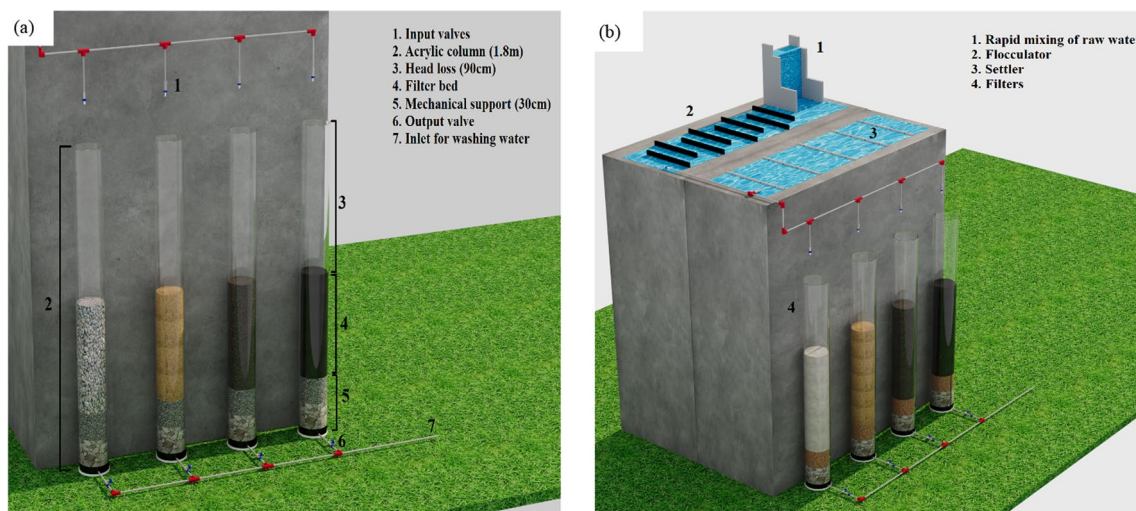
Fig. 2 **a** Filtration columns of acrylic material is 1.8 m in height, 10 cm in diameter, with each bed of 60 cm. **b** Supply of the different tributaries to the filtration system: raw water, flocculated water and settled water, which were obtained from the entrance to the rapid mixer, exit from the flocculator and exit from the decanter, respectively

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Table 2 Filter beds (stage 1)

Filter material		Simbology
Biomass	Pyrolysis process	
Bamboo	a (> temperature, < residence time)	Ba
	b (< temperature, > residence time)	Bb
Eucalyptus	a (> temperature, < residence time)	Ea
	b (< temperature, > residence time)	Eb

Table 3 Categorization of inputs of turbidities (stage 3)

Affluent water	Turbidity range (NTU)	Sampling frequency (min)	
		120 m³/m²/d	240 m³/m²/d
Raw	0–20	60	60
	20–50	60	30
	50–100	30	15
	> 100	15	15
Flocculated	0–15	60	60
	15–30	60	60
	> 30	30	30
Settled	< 3	60	60

this stage 1 (600 m³/m²/d). The washing process lasted for 15 min and was carried out after the filter medium was saturated.

In stage 2, a comparison was made between different granulometries of the biochar with the best performance found in stage 1. In this stage, the influence of biochar granulometry in the filtration process was evaluated. Three filter media were configured with the same material, but with different particle size distributions. The granulometries were assigned based on the thirty and sixty percentiles of the general distribution of all the biochar produced for this stage. To evaluate the granulometry, the same physicochemical parameters measured in stage 1 were analyzed. The same filtration and washing rates of stage 1 were used.

In stage 3, the efficiency of the biochar selected according to stages 1 and 2 was evaluated against materials commonly used as filter media, such as: gravel (Gr), sand (Ar), and (Ca). For this evaluation, simple beds were used (a single filter material in a column); later, mixed beds were used (different materials in the same column). The filtration tests were categorized by ranges according to the turbidity of the influent using simple beds, as indicated in Table 3. Filtration rates of 120 and 240 m³/m²/d were used, which are framed under the operating conditions for fast filters. The tests were carried out in duplicate for each one of the turbidity ranges; that is, a total of 16 filtration runs were carried out using raw water as

influent, 12 tests using flocculated water as influent, and four tests using settled water as influent. Filtered water samples were taken 15 and 30 min after the process started, time within which the system begins to regularize its functions. After that, the following measurements were made at different times that depended on the variability of the process, the duration of the filtration run, its turbidity range, and the filtration rate. This information is detailed in Table 3.

In stage 3, using simple beds, in addition to the evaluation of the removal of physical parameters (turbidity and apparent colour), the removal of various chemical parameters (Cu, Fe, Al, and NO_3^-) was evaluated, as well as the removal of biological parameters (fecal and total coliforms). For obtaining affluents with Cu, Fe, Al, and NO_3^-, solutions were prepared using copper sulfate, ferric chloride, aluminium sulfate, and potassium nitrate, respectively. Tests with each of these solutions were carried out in duplicate at a single rate of 180 m³/m²/d.

At the same time that the filtered water sample was taken for evaluating the removal of the physicochemical and microbiological parameters, the pressure loss experienced by each filter medium over time was also determined. The filtration run was terminated when the filter bed was clogged, which was evidenced by the decrease in the flow rate and the quality of the effluent. The filtration run was finished after 24 h in certain tests, even though the filters were still in operating condition.

The washing rate was determined experimentally based on the expansion that was obtained in each of the filter media, for which the flow rate of the washing water was gradually increased until reaching a correct expansion. The reference expansion was calculated through Eq. 2, proposed by Kawamura (1999). The time required for washing was also established experimentally, fixing the optimal washing time at the instant in which the quality of the washing water was less than 5 NTU and the removal efficiencies with respect to the initial turbidity were greater than 99%. In addition, these data allowed us to calculate the volume of water necessary for the washing process in each one of the beds.

$$Optimum\ Expansion\ Rate = \frac{0.6 - e}{0.4} \qquad (2)$$

where e represents the porosity of the medium before expansion.

In stage 3 using mixed beds, colour and turbidity removal was evaluated using four multimedia bed configurations, using sand, anthracite and biochar, whose characteristics are detailed in Table 4. For each configuration, the filter material was placed first, with the highest density and the one with the lowest density on the top of it, in order to facilitate the expansion of the filter medium and the

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Table 4 Filter beds for stage 3

Filter	Simbology	Filter bed	
		Material	**Height (cm)**
1	M1	Sand	30
		Anthracite	30
2	M2	Sand	30
		Biochar	30
3	M3	Anthracite	30
		Biochar	30
4	M4	Sand	20
		Anthracite	20
		Biochar	20

partial mixture between materials, optimizing the washing process. For each one of the configurations, the removal of the same physical parameters of the previous stage was analyzed, using the same filtration rates and with sampling within the previously stipulated times. In the same way, the washing process was executed in accordance with what was indicated in the preceding instance.

Turbidity was measured with a HACH 2100Q turbidimeter. The colour was measured with the HACH DR890 colorimeter. The presence of aluminium, copper, iron, and nitrates was determined with the HACH DR 2500 spectrophotometer. The existence of fecal and total coliforms was measured with the general method of counting in liquid medium by the determination of the most probable number (MPN). All water samples were analyzed according to the standard methods for the analysis of drinking water (APHA 2005).

2.3 Calculations and statistical analysis

The removal efficiency of the different physicochemical and microbiological parameters was calculated through Eq. 3 (Crittenden et al. 2012).

$$R = 1 - \frac{C_e}{C_i} * 100 \qquad (3)$$

where R is the removal in percentage (%), C_e is the concentration in the effluent, and C_i is the concentration in the effluent.

The Turbidity Robustness Index (TRI) was applied in order to know the distribution of the effluent turbidities of each filter during its test period. The formula of TRI applied by Upton et al. (2017) and García-Ávila et al. (2021) is in the Eq. 4.

$$TRI_{95} = 0.5 \left(\frac{T_{95}}{T_{50}} + \frac{T_{50}}{T_{obj}} \right) \qquad (4)$$

where TRI_{95} is the index calculated for the 95th percentile. T_{95} and T_{50} correspond to the 95th and 50th percentiles of the turbidity distribution, respectively. T_{obj} represents the target turbidity to be achieved at the outlet of the system. The target turbidity was estimated at 5 NTU, being the maximum limit allowed in water for human consumption (WHO 2017). If the resulting TRI95 value is closer to 1; then, the robustness of the analyzed system will be higher (Hartshorn et al. 2015).

The comparison between beds for each stage was made through the analysis of variance, which was developed based on the colour and turbidity removal efficiencies for each of the influent waters to the filters. The null hypothesis proposed for each of the tests would be equivalent to the existence of a statistically insignificant difference between the average efficiencies of each one of the beds. On the other hand, as a prerequisite for this analysis, the normality of the data was evaluated through the graphic analysis of its residuals, for which the Shapiro–Wilk test was used (Kozak and Piepho 2018).

For a better understanding of the similarities and differences between the subgroups identified within the analysis of variance, it was decided to apply a pairwise test, also known as post-hoc analysis as McHugh (2011) suggested. In this case, the HSD (Honestly Significant Difference) test developed by Tukey was applied, whose purpose is to identify those subgroups that statistically come from the same sample population (Williams and Abdi 2010).

For analyzing the influence of two factors on the removal means, the ANOVA test of two factors was used. In the cases in which the data did not demonstrate normality in the analysis of residuals, an equivalent non-parametric analysis was applied: Kruskal–Wallis for ANOVA of one factor (Gooch 2011) and the t2way function of the WRS2 package of the R programming language for ANOVA of two factors, the same one that applies a robust test for the analysis of variance (Feys 2016).

3 Results and discussion

The results of the characterization of the biochar, filtration tests, analysis of filtration runs, and analysis of the washing process are in this section jointly with the discussion of the results of this research versus the results of previous studies.

3.1 Biochar characterization

Table 5 shows the characteristics of the filter materials according to the stage in which they were determined and according to the development of the study. In stage 1, the value of the PZC oscillated around 7.55; therefore, the pH of the feed water to the filter must be above the PZC for the biochar to behave as an anion, so that adsorption occurs by electrostatic attraction between the biochar and the ions of the contaminants that are absorbed and wanted for their

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Table 5 Characteristics of biochars and filter materials

	Characteristic	Unit	Filter material			
			Ba	Bb	Ea	Eb
Stage 1	Diameter	mm	4.75–14	4.75–14	4.75–14	4.75–14
	Carbon	%	50.46 ± 9.76	55.49 ± 6.24	57.46 ± 2.99	53.07 ± 12.28
	Nitrogen	%	0.52 ± 0.14	1.24 ± 0.57	0.95 ± 0.38	0.22 ± 0.06
	Hydrogen	%	3.69 ± 0.86	3.49 ± 0.17	2.72 ± 0.29	3.9 ± 0.69
	H/C	–	0.07	0.06	0.05	0.07
	PZC	–	7.77	7.53	7.75	7.13
			G1*	G2*	G3*	
Stage 2	Diameter	mm	3.35–4.75	1.18–3.35	0.6–1.18	
			Gravel**	Sand	Anthracite	Biochar*
Stage 3	D_{10} (mm)	mm	3	0.61	0.95	0.65
	D_{60} (mm)	mm	6.7	0.98	1.5	0.92
	CU	–	2.23	1.61	1.58	1.41
	True density	g cm^{-3}	–	2.68	1.67	0.68
	Bulk density	g cm^{-3}	–	1.41	0.84	0.3
	Relative density	g cm^{-3}	–	2.68	1.67	1.1
	Porosity	–	–	0.475	0.498	0.559

Values are given as means ± standard deviation

* Filter Material: bamboo biochar manufactured under the b process

** The gravel is the control bed for the experiment and only acts as a support medium for the filter media

removal (Liu et al. 2012), because this value indicates the net total surface charge of the particles (Lu et al. 2013). It can be evidenced in the filtration results of chemical parameters, due to that the metal removal efficiency confirms that the pH of the inlet water was above the PZC and therefore the surface charge of biochar is negative.

In stage 2, the particle size distribution of the biochars ranged between 0.6 and 4.75 mm, in such a way that three ranges were established: (a) 3.35–4.75 mm as coarse granulometry (G1); (b) 1.18–3.35 mm as intermediate granulometry (G2); and (c) 0.6–1.18 mm as fine granulometry (G3). In stage 3, a filter bed must have a coefficient of uniformity (CU) between 1.7 and 2.5 and an effective size (D10) between 0.7 and 1 mm (Arboleda-Valencia 1992). The produced biochar had values of 1.41 and 0.65 mm for CU and D10, respectively, complying with the specifications as well as the anthracite and the sand used in this stage (Table 5).

3.2 Filtration test stage 1: evaluation of different biomasses

3.2.1 Removal of physical parameters
Although the removal percentages (Table 6) indicate that Bb was the most efficient material in removing colour and turbidity, this advantage is statistically significant ($p < 0.05$) only with respect to Ba and Ea for the treatment of settled water. Kazemi et al. (2020) and Kumar et al.

(2020) pointed out that the resulting biochars will have a reduced surface area when applying the fast pyrolysis process (higher temperature and shorter residence time). As process "a" had a higher temperature and shorter residence time and process "b" had a lower temperature and longer residence time, the resulting biochars presented differences regarding their surface area (b > a). A greater surface area represents a greater capacity of biochar as a filter medium for adsorbing or for retaining the impurities present in the water (Perez-Mercado et al. 2018). The average turbidity efficiencies were similar for the raw water and somewhat more differentiated for the flocculated and settled waters (Table 6), for which it is possible to explain the superior performance presented by the coals manufactured through process "b", with respect to those produced by process "a".

3.2.2 Copper removal
Water with a concentration of 56.1 µgL^{-1} of copper was used as affluent, obtaining removal efficiencies of $75.67 \pm 3.65\%$, $72.91 \pm 8.02\%$, $71.12 \pm 3.03\%$, and $70.59 \pm 3.74\%$ in the following order: Bb > Eb > Ea > Ba. As in the previous analysis (turbidity and colour), the biochar and the process with the most efficient results were Bb and "b", respectively. Aran et al. (2016) reached a very similar efficiency (75.7%) in the removal of copper with

Table 6 Removal efficiencies for physical parameters (Stage 1)

Filter bed	Turbidity removal (%)			Colour Removal (%)		
	Raw	Flocculated	Settled	Raw	Flocculated	Settled
Ba	25.66 ± 13.47 [A]	43.28 ± 16.11 [A]	49.34 ± 20.85 [A]	22.26 ± 13.69 [A]	41.49 ± 24.11 [A]	37.54 ± 30.44 [A]
Bb	29.82 ± 12.91 [A]	54.14 ± 14.71 [AB]	59.56 ± 24.58 [B]	23.99 ± 14.77 [A]	55.89 ± 20.93 [AB]	51.64 ± 30.07 [A]
Ea	24.77 ± 13.31 [A]	44.10 ± 12.99 [A]	51.04 ± 21.44 [A]	21.15 ± 14.91 [A]	42.83 ± 21.20 [A]	43.21 ± 25.96 [A]
Eb	26.20 ± 11.88 [A]	47.37 ± 14.84 [B]	60.78 ± 16.25 [B]	21.37 ± 12.72 [A]	50.48 ± 23.51 [B]	46.43 ± 26.86 [A]
p value						
Effect of biomass	0.112	0.134	0.963	0.407	0.531	0.549
Effect of process	0.051	0.004 *	0.003 *	0.584	< 0.001 *	0.025 *
Effect of biomass × process	0.338	0.081	0.528	0.792	0.299	0.290

Values are given as mean ± standard deviation

[A B] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

* Significant effect (*p < 0.05*)

eucalyptus biochar, determining that the removal efficiency was associated with the organic matter present in the used solution.

3.3 Filtration tests stage 2: evaluation of biochar with different particle sizes

3.3.1 Removal of physical parameters

The efficiencies presented in Table 7 indicate that the yield of G3 (fine granulometry) was significantly higher than those of the other beds (p < 0.05), with the exception of the sedimented water treatment.

These results agree with the results obtained by Khiari et al. (2020), in whose study, when comparing the turbidity removal efficiencies for biochars with different particle sizes within the treatment of wastewater from an aquaponic system, it was found that the biochar with the highest efficiency was the biochar with the smallest particle size. This fact is attributed to the lower total porosity in the filter bed and the greater surface area that is achieved by reducing the particle size. The average turbidity removal efficiencies obtained by Khiari et al. (2020) were 60.47% for the thick material (3–5 mm) and 80.66%

for the fine material (1–3 mm), which were higher values than those presented in the results of the present study (48–56.29%). However, it should be taken into account that the filtration rates of the study in comparison were only 5, 10, and 15 m^3/m^2/d, all corresponding to slow filtration, while the rate applied at this point in the present study was 120 m3/m2/d, value corresponding to a fast filtration rate.

Perez-Mercado et al. (2018) compared organic matter removal efficiencies in terms of chemical oxygen demand (COD) for municipal wastewater, using biochars produced from a mixture of pine and fir, with effective sizes (d10) of 0.7, 1.4, and 2.8 mm. Perez-Mercado et al. (2018) found that the 94% efficiency achieved by the largest biochar (2.8 mm) was significantly lower than the 99% obtained by the other two sizes (0.7 and 1.4 mm), specifying that increasing particle size increases also the volume of voids in the bed and with it, the risk that the influent water passes through the filter without having much contact with the filter medium. Similarly, Jin et al. (2022) found that the adsorption of trichlorethylene was higher for the material with a particle diameter between

Table 7 Removal efficiencies for physical parameters (stage 2)

Filter bed	Turbidity removal (%)			Colour removal (%)		
	Raw	Flocculated	Settled	Raw	Flocculated	Settled
G1	48.00 ± 15.52 [A]	87.70 ± 7.59 [A]	63.91 ± 21.09 [A]	35.62 ± 15.77 [A]	79.87 ± 11.91 [A]	36.42 ± 27.70 [A]
G2	49.96 ± 13.37 [A]	90.91 ± 13.02 [B]	66.57 ± 22.20 [A]	36.16 ± 15.12 [A]	83.46 ± 14.58 [A]	39.89 ± 30.91 [A]
G3	56.29 ± 13.82 [B]	95.95 ± 5.72 [C]	65.72 ± 18.95 [A]	43.31 ± 16.26 [B]	89.92 ± 8.83 [B]	39.63 ± 32.55 [A]
P value Effect of granulometry	0.003 *	< 0.001 *	0.576	< 0.001 *	< 0.001 *	0.844

Values are given as mean ± standard deviation

[A B C] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

*Significant effect (*p < 0.05*)

0 and 75 µm, compared to those with diameters between 75 and 150 µm, and between 150 and 250 µm, for biochar produced from peanut shells at 900 °C.

3.3.2 Removal of chemical parameters

Water with a concentration of 3.97 mg L^{-1} of copper was used as affluent, obtaining efficiencies G3 > G2 > G1 with values corresponding to $99.62 \pm 0.13\%$, $98.99 \pm 0.76\%$, and $97.23 \pm 0.5\%$. As for turbidity and colour removal, the efficiency of the process increases as the particle size in the bed decreases. These results coincide with those obtained by Mahdi et al. (2018), in which a date seed-based biochar presented a copper removal efficiency of 93% with a particle size between 0.6 and 1.4 mm, higher than with a size greater than 2 mm in which the efficiency decreased to 78%. When comparing these results with those of the previous stage, it is also shown that the higher concentration of the contaminant in the influent implies the higher percentage of removal, which is achieved during filtration, although it does not necessarily imply lower concentration values for the effluent.

3.4 Filtration tests stage 3: evaluation of biochar vs other filter media using individual beds

3.4.1 Removal of physical parameters

The general results (Table 8) indicate that Bc had greater efficiency in removing turbidity and colour; furthermore, this difference with respect to the other three filter media was always significant, except for the removal of colour in the treatment of settled water. Leng et al. (2021) pointed to the porosity of biochar as the characteristic responsible for giving the material its surface area, especially that known as microporosity, which increases the capacity of the material to retain impurities.

Studies conducted by Kaetzl et al. (2018) for slow filtration in the direct treatment of municipal wastewater could be used as a point of comparison for the results obtained by Bc in the treatment of raw water. Within the first investigation, Kaetzl et al. (2018) used a commercial type biochar produced from softwoods and obtained an average percentage of turbidity removal of 93%, far exceeding that achieved during this study, which can be attributed to the very low filtration rate of 1.2 $m^3/m^2/d$ (among other operating conditions), barely 1% of the lowest rate applied in the present study (120 $m^3/m^2/d$) and corresponds to a fast filtration rate. In addition, it was shown that this efficiency was significantly higher ($p < 0.05$) than those presented by the gravel and wood chip filters, because the retention time was lower than that of biochar, so is the efficiency in the first case.

In the second case, when dealing with materials with similar retention times and porosities, the logical explanation would be to attribute the effect to the greater specific surface area that was presented by the biochar. For the second case study, Kaetzl et al. (2020) used a commercial biochar produced from Miscanthus, a type of herbaceous plant, under the same filtration rate (1.2 $m^3/m^2/d$); obtaining an average removal efficiency just above 31%; that is, less than half the efficiency achieved by the biochar produced and tested in the present investigation (64.37%).

Regarding the effect of the filtration rate, the results for raw water (Table 9) indicate the following: (a) for the same bed, efficiency generally increases at a low rate, although they do not show significant differences (p > 0.05); (b) the effect of the rate loses significance with the increase of the influent turbidity; and (c) the filter material is always the significant variable ($p < 0.05$). Regarding the treatment of flocculated water (Additional file 1: Table S1), the effect of the filtration rate is significant only when the turbidity of the water at the entrance of the system is high ($p < 0.05$) and the same occurs within the treatment of raw water, although the effect of

Table 8 Removal efficiencies for physical parameters (stage 3)

Filter bed	Turbidity removal (%)			Colour removal (%)		
	Raw	Flocculated	Settled	Raw	Flocculated	Settled
Ar	41.67 ± 27.72 [B]	84.35 ± 23.47 [C]	71.78 ± 16.74 [B]	28.07 ± 22.31 [B]	81.42 ± 23.06 [B]	62.76 ± 30.20 [B]
Bc	64.37 ± 13.13 [D]	93.90 ± 5.14 [D]	80.79 ± 12.18 [C]	45.08 ± 15.95 [D]	90.75 ± 7.63 [C]	69.03 ± 27.77 [B]
Ca	52.01 ± 14.29 [C]	82.96 ± 11.22 [B]	70.08 ± 18.53 [B]	33.81 ± 15.10 [C]	79.92 ± 12.90 [B]	59.65 ± 32.64 [B]
Gr	25.32 ± 13.30 [A]	42.52 ± 20.44 [A]	16.59 ± 17.52 [A]	16.14 ± 13.28 [A]	44.14 ± 17.78 [A]	23.09 ± 28.64 [A]
p value						
Effect of filter bed	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001*	< 0.001*	< 0.001 *

Values are given as mean ± standard deviation

[A B C D] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

* Significant effect (*p < 0.05*)

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Table 9 Effect of the filtration rate on the removal of physical parameters for raw water (stage 3)

Filter bed	Loading rate (m³/m²/d)	Influent turbidity			
		Low (< 20 NTU)	Low intermediate (20–50 NTU)	High intermediate (50–100 NTU)	High (> 100 NTU)
Turbidity removal (%)					
Ar	120	42.40 ± 17.50 [C D]	56.78 ± 23.96 [C D E]	38.62 ± 32.76 [B C]	38.57 ± 38.06 [A B]
	240	29.68 ± 22.62 [B C]	40.56 ± 25.17 [B]	48.83 ± 25.55 [C]	38.36 ± 34.42 [A B]
Bc	120	53.67 ± 5.18 [E]	65.23 ± 6.59 [E]	67.85 ± 11.31 [D E]	81.81 ± 7.61 [D]
	240	50.95 ± 8.60 [D E]	61.93 ± 11.48 [D E]	75.55 ± 8.68 [E]	70.49 ± 13.23 [C D]
Ca	120	43.28 ± 8.05 [C]	55.98 ± 5.57 [B C D]	58.21 ± 12.85 [C D]	70.56 ± 16.36 [C D]
	240	42.83 ± 10.20 [C]	46.84 ± 9.65 [B C]	46.92 ± 12.09 [B C]	57.55 ± 19.22 [B C]
Gr	120	32.52 ± 10.62 [B]	24.29 ± 12.81 [A]	29.50 ± 15.52 [A B]	39.59 ± 8.04 [A B]
	240	10.56 ± 7.11 [A]	22.04 ± 6.32 [A]	18.61 ± 7.10 [A]	27.26 ± 13.23 [A]
p value					
Effect of filter bed		< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
Effect of loading rate		< 0.001 *	0.005 *	0.724	0.156
Effect of bed x rate		< 0.001 *	0.379	0.011 *	0.943
Colour removal (%)					
Ar	120	24.27 ± 15.50 [C D]	39.48 ± 26.05 [B C]	27.54 ± 23.76 [A B]	27.22 ± 27.71 [A B]
	240	14.74 ± 11.93 [B]	26.91 ± 18.59 [B]	39.72 ± 21.43 [B C]	30.03 ± 27.42 [A B]
Bc	120	34.36 ± 10.89 [E]	40.20 ± 6.31 [C]	50.05 ± 10.25 [C D]	64.22 ± 13.88 [D]
	240	29.66 ± 6.72 [D E]	41.26 ± 13.39 [C]	64.69 ± 12.40 [D]	53.49 ± 14.83 [C D]
Ca	120	25.05 ± 13.51 [C D E]	32.26 ± 5.62 [B C]	40.82 ± 9.62 [B C]	53.81 ± 17.17 [C D]
	240	21.65 ± 6.12 [B C]	29.11 ± 10.23 [B]	37.79 ± 14.08 [B C]	40.55 ± 20.22 [B C]
Gr	120	20.19 ± 15.27 [B C]	14.15 ± 7.07 [A]	19.02 ± 10.88 [A]	25.55 ± 9.50 [A B]
	240	4.09 ± 4.88 [A]	13.50 ± 4.04 [A]	21.20 ± 26.63 [A]	15.52 ± 11.75 [A]
p value					
Effect of filter bed		< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
Effect of loading rate		< 0.001 *	0.140	0.023 *	0.169
Efecto bed × rate		0.059	0.710	0.013 *	0.812

Values are given as mean ± standard deviation

[A B C D E] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

* Significant effect (*p < 0.05*)

the filter material prevails in all cases here too ($p < 0.05$). In addition, the results of the sedimented water treatment (Additional file 1: Table S2) indicate that the effect generated by the filtration rate proves to be significant for the removal of turbidity and for the removal of colour ($p < 0.05$).

Regarding the turbidity effect of the influent (to see Additional file 1: Table S3), it is possible to identify significant differences between the turbidity ranges ($p < 0.05$) for the same bed, within the raw water treatment. In this case, both the effect of the filter material and the influent turbidity are significant in the removal of turbidity and colour for the two filtration rates applied in this study ($p < 0.05$). For the treatment of flocculated water (to see Table 10), the significant differences ($p < 0.05$) between the influent turbidity ranges for the same bed appear only between the low and high turbidities for the Ar, Bc, and Ca beds when the rate of filtration is 120 m³/m²/d and the comparison parameter is the percentage of turbidity removed. However, the effect presented by the filtering bed and the influent turbidity continue to be significant ($p < 0.05$) for the removal of turbidity and colour regardless of the rate with which one is working.

3.4.2 Removal of chemical parameters

Based on the results shown in Table 11, Bc presented a higher efficiency in the removal of metals (Fe, Al, and Cu), compared to other filter beds. However, Ca presented higher nitrate removal efficiency, although this difference was not statistically different between the beds ($p > 0.05$). These results suggest that the PZC for Bc and Ar are lower compared to Ca and Gr, for which the first group presented a higher affinity for cation retention

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Table 10 Effect of influent turbidity on the removal of physical parameters for flocculated water (stage 3)

Filter bed	Influent turbidity	Turbidity removal (%)		Colour removal (%)	
		$120\ m^3/m^2/d$	$240\ m^3/m^2/d$	$120\ m^3/m^2/d$	$240\ m^3/m^2/d$
Ar	Low	84.68±21.47 [BC]	86.6±11.71 [CDE]	84.30±22.52 [BCD]	85.06±13.74 [CD]
	Intermediate	86.56±25.16 [CD]	81.45±31.39 [CDE]	79.48±23.42 [BCD]	78.87±29.94 [CD]
	High	95.48±3.80 [DE]	68.37±34.69 [BC]	91.05±3.03 [DE]	66.11±33.67 [BC]
Bc	Low	92.23±4.54 [CD]	91.59±6.07 [DE]	91.25±9.19 [DE]	90.51±11.82 [D]
	Intermediate	95.36±2.23 [DE]	96.21±1.30 [E]	88.73±4.35 [CDE]	91.96±2.32 [D]
	High	98.08±1.61 [E]	91.27±7.80 [DE]	94.46±2.32 [E]	87.77±7.38 [CD]
Ca	Low	80.67±11.16 [B]	81.81±8.64 [C]	79.07±12.00 [BC]	81.03±16.88 [CD]
	Intermediate	85.63±10.18 [BC]	83.55±8.01 [CD]	79.31±10.53 [B]	79.97±8.26 [CD]
	High	91.43±5.53 [CD]	75.03±16.25 [C]	88.09±4.91 [BCDE]	71.73±16.83 [BC]
Gr	Low	41.50±23.22 [A]	34.67±17.04 [A]	49.06±16.28 [A]	38.94±18.69 [A]
	Inteemediate	50.34±21.32 [A]	45.27±20.84 [AB]	48.52±20.49 [A]	48.20±11.69 [AB]
	High	55.80±11.57 [A]	27.50±14.07 [A]	51.88±10.88 [A]	25.36±12.72 [A]
p value					
Effect of filter bed		< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
Effect of influent turbidity		0.002 *	0.004 *	0.016 *	< 0.001 *
Effect of bed × turbidity		0.837	0.514	0.727	0.347

Low turbiity (< 15 NTU), intermediate (15–30 NTU), high (> 30 NTU)

Values are given as mean±standard deviation

[ABCDE] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

*Significant effect (*p < 0.05*)

(Fe, Al, and Cu); while the second does it for the anions (NO_3^-).

Several studies have demonstrated the ability of biochar to remove metals, as in the case of copper, in which it was shown that the sorption of this metal is due to the organic functional groups of carbon at the pH of 6 and 7 (Ahmad et al. 2014; Dias et al. 2019), which corresponds to the PZC of the biochar evaluated in this study. The removal of metals from water is an aspect that must be taken into account in water treatment, due to its effects on health and the environment. Activated carbon has been the commonly used material for this purpose, but its cost is high; therefore, the use of biochar as an adsorbent is a viable option, because efficiencies that are comparable to the efficiencies of activated carbon were obtained. In addition, organic waste was used for its production (Mohan et al. 2014).

The low capacity of biochar for nitrate removal has already been evidenced in other studies, regardless of the type of biomass and without having been treated or modified. According to Zhang et al. (2020), this low efficiency is due to the electrostatic repulsion between the surface of biochar and nitrate, due to their similar negative charge; the same that is evidenced by the PZC of biochar.

Table 11 Removal efficiencies for chemical parameters (stage 3)

Filter bed	Removal (%)			
	Iron (Fe)	Aluminium (Al)	Copper (Cu)	Nitrates (NO_3^-)
Ar	92.01±6.61 [B]	85.56±7.15 [B]	65.82±8.89 [BC]	10.40±9.75 [A]
Bc	95.70±3.93 [B]	90.72±6.58 [B]	75.90±9.30 [C]	10.90±9.60 [A]
Ca	87.54±5.54 [B]	84.81±5.09 [B]	53.15±10.48 [B]	18.86±10.38 [A]
Gr	43.76±14.69 [A]	46.00±9.05 [A]	36.05±9.65 [A]	12.17±11.67 [A]
p value				
Effect of filter bed	< 0,001 *	< 0,001 *	< 0.001 *	0.349

Values are given as mean±standard deviation

[ABC] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

* Significant effect (*p < 0.05*)

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However, there are studies that show that bamboo biochar slightly increases nitrate absorption by increasing the pyrolysis temperature to more than 600 °C, because a greater surface area and porosity are obtained, always taking pH into consideration (Zhang et al. 2020). In relation to the PZC obtained for the different biochars and in relation to the results obtained with the removal of chemical contaminants, it is concluded that the surface charge of the biochars is negative; therefore, the removal of metals (cations) is very efficient.

3.4.3 Removal of biological parameters

The removal efficiency of total coliforms for raw water presented by Bc was the highest among all the filter beds ($94.3 \pm 5.6\%$); while the performance of Bc ($88.9 \pm 11.4\%$) was similar to that of Ca ($89.8 \pm 12.5\%$) for fecal coliforms. However, these removal efficiencies were not enough to reach the maximum allowed limit (> 1.1 NMP /100 ml) established by INEN (2020), as shown in Fig. 3. According to the review carried out by Palansooriya et al. (2020), the efficiency of the removal of E. coli (fecal coliform) with biochar as filter material is between 85.21 and 99.98%, depending on both the type of biochar and the type of filtration system in which it is applied. Within this review, the case with the greatest similarity to the one presented in the present study is for a column filter of a commercial softwood biochar without any type of activation and configured by three layers of 50 cm of material, each one at a different temperature. granulometry; obtaining a removal efficiency of 89.77%; that is, just 0.87% more than Bc, considering that the bed in comparison was 2.5 times higher (150 cm) than the one used in the present study (60 cm).

3.5 Filtration tests stage 3: evaluation of biochar in mixed beds

3.5.1 Removal of physical parameters

The general results for this stage (Table 12) indicate that for the treatment of raw water, M2 (sand + biochar) was the bed with the highest efficiency in removing turbidity and colour, without presenting in the first case a significant difference with none of the other beds ($p > 0.05$). For the flocculated water, there was a significant difference only with respect to M1 (sand + anthracite) ($p < 0.05$). Those beds that had biochar within their configuration M2, M3 (anthracite + biochar), and M4 (sand + anthracite + biochar) for settled water are significantly ($p < 0.05$) more efficient for turbidity and colour removal than those that were not configured with this material (M1). The effects of the filter bed and the presence of biochar within the configuration of those beds within the resulting removal means proved to be significant only for flocculated and settled water ($p < 0.05$).

Regarding the effect of the filtration rate (to see Table 13), in the case of raw water treatment, although the filter beds with Bc presented efficiencies higher than M1, there is no significant contrast between beds ($p > 0.05$). For colour removal, the effect of the filtration rate is shown to be significant for intermediate turbidities ($p < 0.05$); while the effect of the filter bed for low intermediate turbidity ($p < 0.05$).

For the treatment of flocculated water (Additional file 1: Table S4), although the efficiency is higher at a low rate, the effect produced by the filtration rate is significant only when the influent turbidity is high ($p < 0.05$). Although the efficiencies presented by M2, M3, and M4 are higher than those of M1, they do not show a significant contrast in any of the cases ($p > 0.05$).
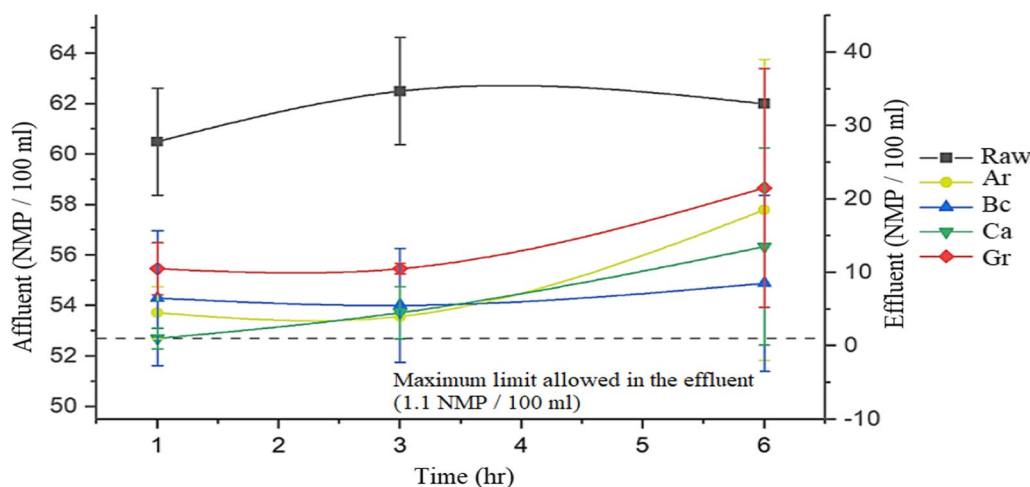

Fig. 3 Fecal Coliform Removal for Simple Filter Beds (stage 3)

Table 12 Removal efficiencies for physical parameters (stage 3)

Filter bed	Turbidity removal (%)			Colour removal (%)		
	Raw	Flocculated	Settled	Raw	Flocculated	Settled
M1	70.65±14.79 [A]	82.53±13.69 [A]	73.05±7.10 [A]	50.35±20.51 [A]	77.59±19.05 [A]	69.50±22.04 [A]
M2 [Bc]	71.29±18.01 [A]	89.07±9.58 [B]	79.95±5.98 [B]	52.42±20.94 [A]	85.67±12.37 [B]	83.29±19.03 [BC]
M3 [Bc]	71.10±17.52 [A]	86.60±10.35 [AB]	77.46±6.43 [B]	52.29±20.35 [A]	83.35±13.16 [AB]	79.48±18.02 [B]
M4 [Bc]	70.90±17.57 [A]	87.69±9.24 [B]	79.95±6.20 [B]	52.32±20.33 [A]	84.60±12.51 [B]	85.93±15.37 [C]
p value						
Effect of filter bed	0.290	0.006 *	< 0.001 *	0.282	0.013 *	< 0.001 *
Effect of biochar	0.057	0.002 *	< 0.001 *	0.051	0.002 *	< 0.001 *

[Bc] Filter bed with biochar

Values are given as mean±standard deviation

[A B C] Means of each column grouped with the same letter are not significantly different ($p > 0.05$)

*Significant effect ($p < 0.05$)

Table 13 Effect of the filtration rate on the removal of physical parameters for raw water (stage 3)

Filter bed	Loading rate (m³/m²/d)	Influent turbidity			
		Low (< 20 NTU)	Low intermediate (20–50 NTU)	High intermediate (50–100 NTU)	High (> 100 NTU)
Turbidity removal (%)					
M1	120	60.18±9.68 [A]	66.46±7.07 [A]	70.98±13.30 [A]	89.29±11.17 [A]
	240	59.91±5.13 [A]	68.95±9.10 [A]	70.87±6.90 [A]	85.32±18.62 [A]
M2 [Bc]	120	62.13±10.49 [A]	69.57±6.36 [A]	76.81±9.72 [A]	73.53±37.70 [A]
	240	63.51±4.22 [A]	72.93±8.44 [A]	73.10±8.82 [A]	88.12±16.78 [A]
M3 [Bc]	120	63.12±6.54 [A]	71.54±5.40 [A]	75.29±9.37 [A]	73.07±37.68 [A]
	240	62.37±4.16 [A]	72.66±8.00 [A]	74.13±5.94 [A]	85.14±20.97 [A]
M4 [Bc]	120	64.17±6.27 [A]	70.33±7.18 [A]	74.42±10.13 [A]	72.43±37.65 [A]
	240	61.61±4.32 [A]	72.27±8.07 [A]	73.55±5.87 [A]	86.09±20.62 [A]
p value					
Effect of filter bed		0.293	0.075	0.607	0.962
Effect of loading rate		0.502	0.902	0.625	0.315
Effect of bed x rate		0.811	0.888	0.980	0.883
Colour removal (%)					
M1	120	36.88±9.82 [A]	43.33±7.44 [A]	54.49±14.98 [A]	77.25±15.77 [A]
	240	34.14±11.01 [A]	41.37±16.34 [A]	48.58±8.44 [A]	74.16±21.94 [A]
M2 [Bc]	120	39.48±8.90 [A]	46.15±10.11 [A]	60.34±11.96 [A]	64.56±35.10 [A]
	240	42.28±7.80 [A]	46.79±15.47 [A]	51.50±11.44 [A]	78.41±20.40 [A]
M3 [Bc]	120	40.89±7.64 [A]	49.03±8.36 [A]	58.46±12.69 [A]	64.38±35.39 [A]
	240	40.60±6.89 [A]	46.27±15.17 [A]	51.80±8.10 [A]	75.68±22.80 [A]
M4 [Bc]	120	43.81±7.87 [A]	48.13±9.37 [A]	56.62±13.25 [A]	63.48±35.60 [A]
	240	40.02±7.25 [A]	46.85±14.72 [A]	49.92±9.51 [A]	76.14±23.79 [A]
p value					
Effect of filter bed		0.186	0.020 *	0.789	0.975
Effect of loading rate		0.324	0.005 *	0.013 *	0.234
Effect of bed x rate		0.608	0.898	0.988	0.848

[Bc] Filter bed with biochar

Values are given as mean±standard deviation

[A B] Means of each column grouped with the same letter are not significantly different ($p > 0.05$)

* Significánt effect ($p < 0.05$)

Regarding the treatment of settled water (to see Additional file 1: Table S5), the effects of both the filter bed and the filtration rate prove to be significant in the removal of turbidity and colour ($p < 0.05$). On the other hand, for the same bed, the efficiencies obtained for each rate do not prove to be significantly different ($p > 0.05$). In addition, the analysis of each rate separately shows that the difference between the configurations composed of Bc (except M3) are significantly higher than M1 in the removal of these physical parameters ($p < 0.05$).

Regarding the effect of the turbidity of the influent, the analysis of the effect of the inlet turbidity in the system for the treatment of raw water (to see Additional file 1: Table S6) reveals that when the inlet turbidity increases its value, the efficiencies of the filtering increases too. It can be corroborated by comparing the removal means for each one of the beds, where it is possible to distinguish that there is always a significant difference between the low and high turbidity ranges ($p < 0.05$), regardless of the filtration rate or the measured parameter. Likewise, by dividing the analysis by turbidity ranges, it is possible to establish that although the efficiencies of the filter media that contain Bc are higher in all cases than the one that does not have this material (M1), the differences between the efficiencies were not significant ($p > 0.05$).

Higher filtration rates can affect the efficiency of removing contaminants from the water. At higher filtration rates, water can pass through the filter media more quickly, which can reduce the contact time between the water and the contaminants present in it. It can result in lower contaminant removal efficiency compared to lower filtration rates, where there is more time for contaminant adsorption and retention to occur on the filter media. As the filtration rate increases, the head drop across the filter can also increase. It can influence filter performance and life, as well as contaminant removal efficiency.

It is important to consider that the type of feed water (raw, flocculated, and settled) interacted with the filtration rates for influencing the results obtained in the study. The filtration rate influenced the efficiency according to the conformation of the filter medium; thus, when simple beds were used, the decrease in efficiency when increasing the rate from 120 to 240 m^3/m^2d was greater than when mixed beds were used. In the latter case, a notable decrease in removal efficiency was not observed when increasing the rate of filtration.

The initial turbidity in the flocculated water treatment (Table 14) shows a significant effect for the removal of turbidity and colour only when the filters work with a low rate ($p < 0.05$). That is why when analyzing the individual performance of each one of the beds at this rate, the existence of significant differences between the turbidity ranges is observed in all cases ($p < 0.05$); mainly, between low and high turbidities. For the aforementioned rate, if the ranges are analyzed in a differentiated way, then it is possible to notice that the highest efficiencies belong in the same way to the beds made up of Bc; however, the only significant difference with respect to M1 appears in the removal of turbidity by M2 ($p < 0.05$).

3.5.2 Comparison of mixed beds with simple beds

Within the treatment of raw water, the removal efficiencies achieved by the mixed beds prove to be significantly higher than those corresponding to simple beds ($p < 0.05$). Regarding the robustness index, it is observed that Bc working at a rate of 120 $m^3/m^2/d$ is the most robust treatment system for this case (Table 15).

For the removal of turbidity in flocculated water, the efficiencies achieved by Bc with both rates prove to be significantly higher than all the others ($p < 0.05$) (to see Table 16). Bc working at a low rate was the most robust system and the only bed for achieving mean turbidity below 1 NTU regardless of its filtration rate.

For settled water, the target turbidity in the effluent was set at 0.5 NTU, considered an appropriate value to guarantee the effectiveness of a hypothetical subsequent disinfection process (García-Ávila et al. 2021). Bc at low rate was the most efficient system for turbidity removal (to see Additional file 1: Table S7). For this case, M4 working at a low rate was the most robust system.

3.6 Analysis of filtration runs

As indicated in Fig. 4, filtration runs decrease with the increase of influent turbidity and filtration rate for raw and flocculated water treatment. The Bc filtration run is higher than that of Ar in some specific cases, although in general all the beds present similar filtration times. In the case of settled water, the filtration runs were maintained for more than 24 h regardless of the bed, the filtration rate, or the influent turbidity.

As indicated in Fig. 4, filtration runs decrease with increasing influent turbidity and filtration rate for raw and flocculated water treatment. In Fig. 4a it can be seen that, when raw water with low turbidities was used as influent, the filtration runs lasted between 5 and 10 h; meanwhile, for high turbidities of the raw water, the filtration runs lasted between 1 and 2 h. In all cases, biochar and anthracite had similar filtration paths. In Fig. 4b it can be seen that, when flocculated water was used as influent, the filtration runs lasted between 5 and 7 h; meanwhile, for high turbidities of the flocculated water, the filtration runs lasted between 2 and 4 h. For all filter media, the filtration runs were similar. In the case of settled water, the filtration runs were maintained for more than 24 h regardless of the bed, the filtration rate or the turbidity of the influent (Fig. 4 c).

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Table 14 Effect of influent turbidity on the removal of physical parameters for flocculated water (stage 3)

filter bed	Influent turbidity	Turbidity removal (%)		Colour removal (%)	
		120 m³/m²/d	240 m³/m²/d	120 m³/m²/d	240 m³/m²/d
M1	Low	80.56±13.69 [A]	76.08±17.59 [A]	76.26±16.15 [A]	65.5±29.96 [A]
	Intermediate	81.01±13.16 [A]	82.35±8.52 [A]	73.67±17.5 [A]	79.23±12.64 [A]
	High	92.4±5.29 [CDE]	83.1±14.85 [A]	90.89±6.61 [BC]	79.96±16.57 [A]
M2 [Bc]	Low	90.21±6.24 [BCD]	85.43±12.7 [A]	85.48±9.83 [AB]	81.58±15.44 [A]
	Intermediate	86.67±8.24 [ABC]	86.21±11.77 [A]	80.23±13.9 [A]	85.09±14.26 [A]
	High	96.18±2.66 [E]	88.72±10.58 [A]	95.34±3.66 [C]	86.03±11.16 [A]
M3 [Bc]	Low	87.27±7.15 [ABC]	82.79±13.27 [A]	82.34±10.85 [A]	83.75±12.58 [A]
	Intermediate	82.57±13.26 [AB]	84.05±6.91 [A]	74.88±17.89 [A]	81.41±12.01 [A]
	High	94.7±3.65 [DE]	87.11±10.4 [A]	94.2±3.47 [C]	83.26±12.6 [A]
M4 [Bc]	Low	87.86±7.86 [ABC]	83.66±11.79 [A]	84.76±10.83 [AB]	80.52±17.65 [A]
	Intermediate	87.32±7.39 [ABC]	85.41±7.37 [A]	80.77±13.51 [A]	84.52±7.63 [A]
	High	95.05±4.66 [E]	86.54±10.82 [A]	93.95±5.95 [C]	83.43±12.21 [A]
p value					
Effect of filter bed		0.026 *	0.075	0.142	0.168
Effect of influent turbidity		< 0.001 *	0.259	< 0.001 *	0.613
Effect of bed x turbidity		0.872	0.989	0.975	0.959

Low turbidity (< 15 NTU), intermediate (15–30 NTU), high (> 15 NTU)

[Bc] Filter bed with biochar

Values are given as mean ± standard deviation

[ABCDE] Means of each column grouped with the same letter are not significantly different (*p > 0.05*)

*Significant effect (*p < 0.05*)

Table 15 Turbidity removal and robustness index within raw water treatment

Filter bed	Loading rate (m³/m²/d)	Turbidity removal (%)	T_{50} (NTU)	T_{95} (NTU)	TRI_{95}
Ar	120	44.47±28.59 [BC]	19.15	151.95	5.88
	240	38.33±26.49 [B]	22	110	4.7
Bc	120	65.86±12.4 [DE]	13.05	41.47	2.89
	240	62.59±13.85 [D]	11.3	43.68	3.06
Ca	120	55.81±14.26 [C]	16.95	57.79	3.4
	240	47.47±13.06 [B]	21.1	59.86	3.53
Gr	120	30.89±13.13 [A]	36	140.7	5.55
	240	18.67±10.13 [A]	31.9	121	5.09
M1	120	70.55±15.17 [EF]	8.05	33.7	2.9
	240	70.81±14.39 [EF]	8.54	78.17	5.43
M2	120	69.37±20.41 [EF]	7.29	32.95	2.99
	240	74.02±13.66 [F]	6.76	71.53	5.97
M3	120	69.70±19.51 [EF]	7.04	36.47	3.3
	240	73.09±14.18 [F]	7.12	73.8	5.89
M4	120	69.49±19.45 [EF]	6.98	43.72	3.83
	240	72.88±14.46 [F]	7.28	75.08	5.89

Turbidity removal is given as mean ± standard deviation

[ABCDEF] Means grouped with the same letter are not significantly different (*p > 0.05*)

3.7 Analysis of the washing process

The results of the washing process (Table 17) indicate that for the beds configured totally or partially by Bc, the expansion measured during washing was well above the optimum. It occurred because the upward force generated by lower washing rates than those presented in each

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Table 16 Turbidity removal and robustness index within flocculated water treatment

Filter bed	Loading rate (m³/m²/d)	Turbidity removal (%)	T_{50} (NTU)	T_{95} (NTU)	TRI_{95}
Ar	120	88.22±19.95 [E F]	1.32	4.63	1.89
	240	79.34±26.85 [B C D]	2.38	36.36	7.89
Bc	120	94.82±4.02 [G]	0.76	2.15	1.5
	240	92.71±6.16 [F G]	0.95	7.1	3.85
Ca	120	85.18±10.39 [B C D]	2.42	6.65	1.62
	240	80.08±11.75 [B]	4.01	18.38	2.69
Gr	120	48.21±20.53 [A]	9.8	27.69	2.39
	240	35.16±18.09 [A]	14.2	42.75	2.93
M1	120	84.3±12.58 [B C D]	2.52	8.16	1.87
	240	80.64±14.7 [B C]	3.23	16.41	2.86
M2	120	90.95±7.13 [E F]	1.56	4.05	1.46
	240	87.06±11.4 [C D E]	1.62	11.49	3.71
M3	120	88.1±9.86 [D E F]	2.09	4.65	1.32
	240	84.99±10.72 [B C D]	2.15	12.01	3.01
M4	120	89.89±7.58 [D E F]	1.61	5.91	2
	240	85.34±10.31 [B C D]	2.2	12.57	3.08

Turbidity removal is given as mean±standard deviation

[A B C D E F G] Means grouped with the same letter are not significantly different ($p > 0.05$)

case was not enough to remove the particles retained between the bed during the filtering process, so it was necessary to opt for higher rates that ensure the cleaning of the bed, although they generate an expansion greater than theoretically necessary. On the other hand, it is also shown that Bc requires less water consumption for cleaning for simple beds and that the configuration of mixed beds contributes to reduce both the washing time and the consumption of water.

Then, although the low density of biochar facilitates its expansion even at relatively low rates, this characteristic also contributes to the fact that this material presents a greater amount of lost bed, after having concluded the operation of the filters; although as observed in the Table 23, the loss of bed is a normal process and the value corresponding to Bc is not very distant compared to the other materials. Likewise, the low density prevents the application of high washing rates inside this filter, due to that it would be exposed to the dragging of a greater amount of filtering material, also limiting the upward force of the washing water and its ability for removing the particles adhered to the filter bed, which results in the prolongation of the time required for the process and in remaining turbidity higher than the turbidities obtained from the other beds. However, the average turbidity for Bc at the end of the process was less than 5 NTU, a reference value proposed to corroborate the washing efficiency, which demanded a lower use of water than the uses required by the other simple beds.

3.8 Filtration mechanisms

Filtration is generally considered to be the result of two different but complementary mechanisms: transport and adhesion (Cescon and Jiang 2020). The most important transport filtration mechanisms are sifting, sedimentation, interception, diffusion, and inertial impact. Adherence is attributed to some types of phenomena that occur, such as the interaction between electrical forces and Van der Waals forces between the particles and the surface of the filter media granules, in this case biochar (Petean and Aguiar 2015; Cescon and Jiang 2020).

There is no doubt that not all of them necessarily have to act at the same time and that, in some cases, the contribution of one or more of them to retain the suspended material is perhaps trivial. But it must be taken into account that, given the complexity of the phenomenon, more than one mechanism must come into action to transport the different sizes of particles to the surface of the grains of the filter medium and adhere them (Arboleda 1992).

The occurrence of each mechanism depends on the particle size. If the size of the particles is greater than the size of the pores, it is a sifting; for smaller particles, sedimentation, interception, and diffusion are dominant. It is important to emphasize that the mechanisms act simultaneously, so that the effective transport of a particle cannot be attributed to just one, but to all of them. However, it must be considered that diffusion (erratic movement of particles smaller than one micron in size within the liquid
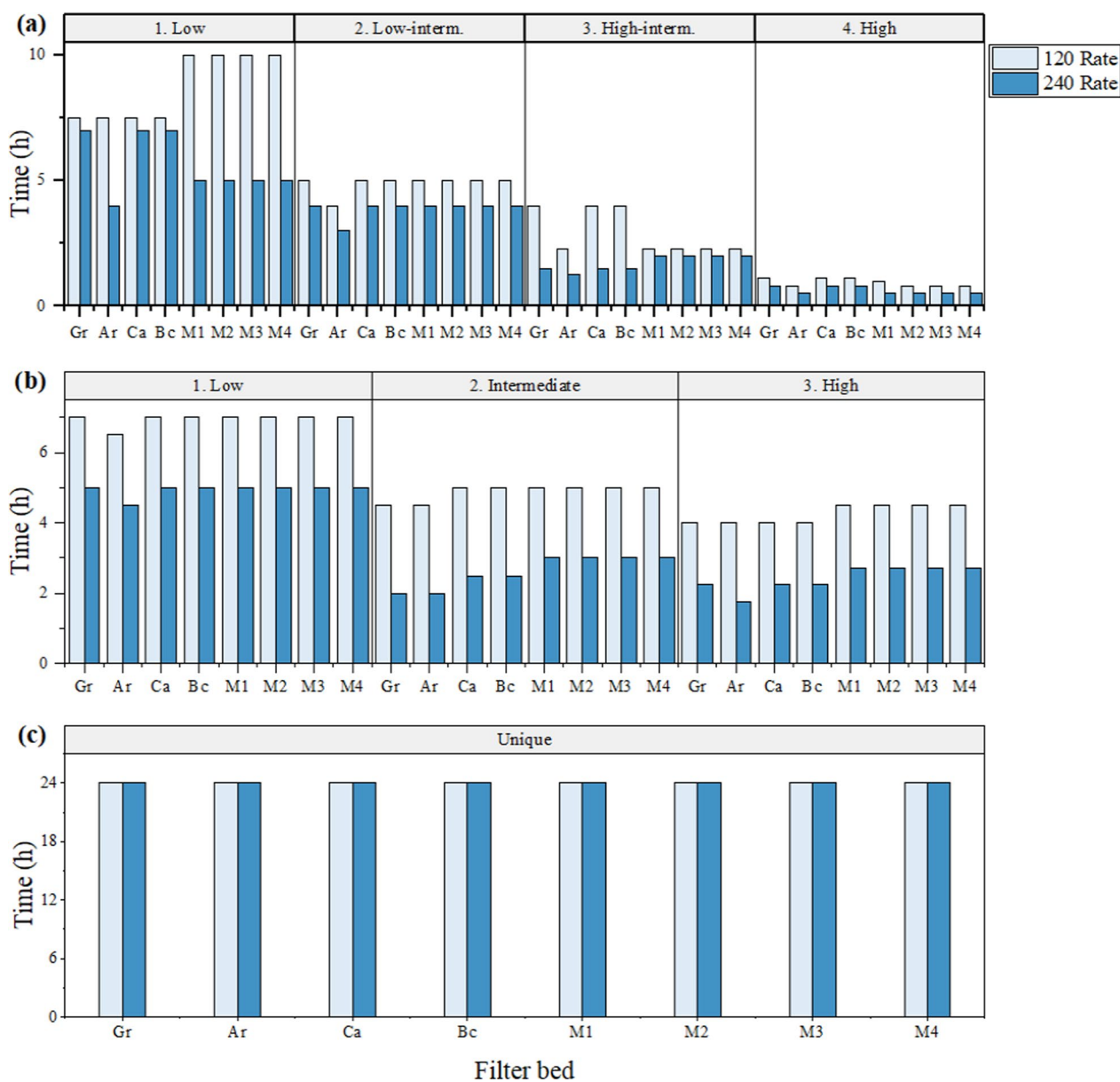
Fig. 4 Filtration runs for mixed and individual filter beds (stage 3). Figure 4. Filtration runs for mixed and individual filter beds (stage 3). **a** Variation of the filtration runs when raw water was used as influent. **b** Variation of the filtration runs when flocculated water was used as influent. **c** Variation of the filtration runs when settled water was used as influent

medium) is not very significant in rapid filtration, since chemical pretreatment favors the aggregation of smaller particles (O 'Melia 1985). Therefore, in this study when flocculated and settled water was used in biochar filtration, all transport mechanisms were presented except for diffusion; while, when raw water without coagulation was used, diffusion occurred.

While transport is primarily a physical phenomenon, adhesion is primarily chemical and requires prior destabilization (O'Melia and Ali 1978; Cescon and Jiang 2020).

Therefore, it can be considered that in this study, when flocculated and settled water was used in biochar filtration, both transport and adhesion mechanisms were presented; while, when raw water without coagulation was used, only the transport mechanism was presented.

3.9 Considerations regarding this study
The main purpose of this research was to evaluate the efficiency of biochar as a filter material to remove turbidity, colour, and other contaminants present in water,

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Table 17 Results of the washing process for single beds (stage 3 and stage 4)

Filter bed	Backwash rate (m³/m²/d)	Backwash time (min)	Used water (L)	Calculated bed expansion (%)	Real bed expansión (%)	Remainder turbidity (NTU)	Filter bed loss (cm)
Ar	1800	13.67 ± 2.27	118.88 ± 16.01	31.25	29.92 ± 5.13	1.15 ± 0.37	1.96
Bc	615	20.83 ± 4.28	61.85 ± 11.65	10.25	55.89 ± 9.92	2.60 ± 0.99	5.2
Ca	1350	12.83 ± 2.55	83.1 ± 14.31	25.5	27.96 ± 6.22	1.27 ± 0.45	3.96
Gr	3000	5.33 ± 0.65	80.0 ± 9.35	–	4.03 ± 4.09	0.64 ± 0.15	1
M1	1600	5.53 ± 1.22	43.82 ± 8.4	28.38	35 ± 4.67	1.45 ± 0.47	1.32
M2 $_{BC}$	1100	7.95 ± 2.66	41.51 ± 12.69	20.75	52.16 ± 16.4	2.35 ± 0.65	2.92
M3 $_{BC}$	985	7.84 ± 2.41	37.26 ± 10.98	17.88	48.74 ± 8.87	2.49 ± 0.84	2.57
M4 $_{BC}$	1100	7.95 ± 2.59	40.23 ± 10.83	22.33	44.97 ± 11.43	2.62 ± 0.92	2.59

$_{Bc}$ Filter Bed with Biochar

Means are given as mean ± standard deviation

Table 18 Previous studies that have characterized biochar and its surface properties

Biochar biomass	Temperature/heating rate	BET surface area (m²g⁻¹)	Sources
Bamboo	10 °C/min	64.78	Chen et al. (2014)
Bamboo	400 °C	63.52	Sahoo et al. (2021)
Bamboo	500 °C	225.33	Sahoo et al. (2021)
Bamboo	600 °C	307.10	Sahoo et al. (2021)
Bamboo	20 a 500 °C	174.67	Tulashie et al. (2022)
Bamboo	600 °C	181.05	Wang et al. (2018)
Eucalyptus wood	500 °C	48.4	Yusuff et al. (2022)
Eucalyptus wood	500 °C	253.25	Zeng et al. (2021)
Eucalyptus wood	700 °C	392	Fuentes et al. (2020)

and to provide practical information on the application of biochar in water treatment. For this reason, BET surface analysis was not performed. There are previous studies that have characterized biochar and its surface properties (Table 18).

4 Conclusions

The use of biochar obtained from residual eucalyptus and bamboo biomass in high-rate filters for purification can be a sustainable and environmentally friendly alternative. By taking advantage of the residual eucalyptus and bamboo biomass, the dependence on synthetic materials is reduced and the reuse of waste is promoted, thus contributing to the circular economy and helping to mitigate the problems associated with the management of agricultural and forestry waste.

Biochar can act alone or in conjunction with other typical materials such as sand and anthracite for retaining contaminants and improve water quality, presenting itself as a promising option for improving water quality and reduce dependence on conventional filter materials. This material presented porous properties and a large surface area, which gives it a high capacity for removing turbidity, colour, Cu, Fe, Al, NO3-, and coliforms. The granulometry is a factor to take into consideration; in general, the smaller the particle size, the greater its efficiency as a filter medium. The removal of metals was much greater than the removal of nitrates, thus concluding that the pH of the influent had a higher pH than PZC; therefore, the surface of the biochars was negatively charged.

When comparing the performance of biochar with other filter materials using single beds, it was found that biochar was the filter medium with the highest efficiency in removing turbidity and apparent colour for the treatment of raw, flocculated, and sedimented water, with similar filtration runs to those of anthracite and in many cases were higher than those presented by sand. In addition, its efficiencies in the removal of copper, iron, aluminium, and total coliforms were also the highest. The time required for washing the filters with biochar was somewhat greater than the time required by the other beds; however, the volume of water used for cleaning this filter was the lowest of all, which could well mean a lower maintenance cost compared to the other filter beds.

The application of the rapid filtration pilot system with biochar managed for obtaining removal efficiencies for turbidity, copper, and coliforms was very similar to those reported by other laboratory-scale systems and with slow filtration rates, which highlights the applicability of this material as a medium for filtering at larger scales. The application of biochar in mixed beds helps to substantially improve the apparent colour and turbidity removal efficiencies achieved by sand and anthracite beds alone. In addition, it was shown that these mixtures between filter materials help to significantly reduce the volume of water used during the filter washing process.

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The effects of the filtration rates and turbidities of the influent (raw, flocculated, and settled water) had a greater influence on the removal of turbidity and apparent colour using simple beds compared to mixed beds; in addition, between these two factors, the turbidity of the influent presented significant effects on the resulting removal yields with greater frequency. The biochar used for the treatment of flocculated and settled water made it possible to obtain turbidities at the outlet of the system not only below 5 NTU (WHO's reference value), but also below 1 NTU, ideal values to carry out a subsequent disinfection process efficiently. Biochar as a filter medium generated effluents with a low degree of dispersion in terms of turbidity values compared to the other materials used, so Bc was the most robust bed in the treatment of raw and flocculated water, while in the settled water treatment was M4 (a bed also configured with biochar).

For future research, it is recommended to carry out potabilization tests of water with biochars based on eucalyptus and bamboo, and also with other substances from rural areas of various countries, considering the areas affected by formal and informal mining exploitation, as well as oil exploitation. It is also recommended that seawater purification processes be developed, with biocarbons made from materials from dry forests, as well as organic waste from municipalities in coastal areas.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-023-00256-4.

Additional file 1: Table S1. Effect of the Filtration Rate on the Removal of Physical Parameters for Flocculated Water (Stage 3). **Table S2.** Effect of Filtration Rate on the Removal of Physical Parameters for Settled Water (stage 3). **Table S3.** Effect of Influent Turbidity on the Removal of Physical Parameters for Raw Water (stage 3). **Table S4.** Effect of the Filtration Rate on the Removal of Physical Parameters for Flocculated Water (stage 3) **Table S5.** Effect of Filtration Rate on the Removal of Physical Parameters for Settled Water (stage 3). **Table S6.** Effect of Influent Turbidity on the Removal of Physical Parameters for Raw Water (stage 3). **Table S7.** Turbidity Removal and Robustness Index within Settled Water Treatment.

Author contributions
All authors contributed to the study conception and design. Conceptualization, investigation, resources, methodology, data collection and analysis, writing—original draft preparation, validation, writing-reviewing and editing were performed by FG, AG and MB. Data curation was kept with EAAP. Visualization and formal analysis were performed by SI. Software was performed by AA. Writing-reviewing and editing were performed by FG and EAAP. All authors read and approved the final manuscript.

Availability of data and materials
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

Author details
[1]Carrera de Ingeniería Ambiental, Facultad de Ciencias Químicas, Universidad de Cuenca, Cuenca, Ecuador. [2]Departamento de Química Aplicada y Sistemas de Producción, Grupo de Evaluación de Riesgos Ambientales en Sistemas de Producción y Servicios (RISKEN), Cuenca, Ecuador. [3]Professional School of Systems Engineering, Research Institute of Science and Technology, Universidad César Vallejo, Lima, Peru. [4]Carrera de Ingeniería Ambiental, Universidad Católica de Cuenca, Cuenca, Ecuador.

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