Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Effect of granulometric characteristics of the filtration medium in pre-filtration systems for domestic use purposes in isolated rural communities

Efeito das características granulométricas do meio filtrante em sistemas de pré-filtração para uso doméstico em comunidades rurais isoladas

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ABSTRACT

Decentralized water treatment systems have limitations when raw water has high concentrations of impurities. This study evaluated the influence of different granulometric characteristics of the filter medium on the clogging in pre-filtration systems for domestic use in isolated rural communities, to minimize the impact of impurities in fresh raw water on final treatment. Three pre-filters, filled with filtration material with effective diameters of 0.20, 0.40, and 0.60 mm, and low uniformity coefficient (1.6), were operated continuously for 116 days. At a depth of 5–20 cm, 87, 57, and 41% of the total head loss were concentrated in the granulometries of 0.20, 0.40, and 0.60 mm effective diameters, respectively. Except for apparent color, no statistical difference was identified in water quality parameters between the different granulometries used in the study. The pre-filters showed an average turbidity removal efficiency of 65%. True and apparent colors presented an average removal of 32 and 39%, respectively. Total coliforms were found up to 15 cm deep in the filtration medium. Heterotrophic bacteria were observed throughout the depth of the filtration medium, with more than 1,000 bacterial colonies found. The use of filter media with a larger effective diameter can bring operational benefits, as it shows cleaning frequencies two to three times lower than filter media with smaller granulometry, besides presenting longer filtration runs, minimizing the impact of system operation errors by the owner.

Keywords: safe water; decentralized water treatment; pre-treatment; filtering material; grain size distribution.

RESUMO

Sistemas descentralizados de tratamento de água apresentam limitações quando a água bruta possui altas concentrações de impurezas. Este estudo avaliou a influência de diferentes características granulométricas do meio filtrante no processo de colmatação de sistemas de pré-filtração para uso doméstico em comunidades rurais isoladas, visando minimizar o impacto das impurezas da água fresca bruta no tratamento final. Três pré-filtros, preenchidos com material filtrante de diâmetros efetivos de 0,20, 0,40 e 0,60 mm, e baixo coeficiente de uniformidade (1,6), foram operados continuamente por 116 dias. A uma profundidade de 5–20 cm, 87, 57 e 41% da perda de carga total foram concentradas nas granulometrias de 0,20, 0,40 e 0,60 mm de diâmetros efetivos, respectivamente. Com exceção da cor aparente, não foi observada diferença estatística nos parâmetros de qualidade da água entre as diferentes granulometrias utilizadas no estudo. Os pré-filtros apresentaram uma eficiência média de remoção de turbidez de 65%. A cor verdadeira e a cor aparente apresentaram uma remoção média de 32 e 39%, respectivamente. Coliformes totais estavam presentes até uma profundidade de 15 cm no meio filtrante. Bactérias heterotróficas foram observadas ao longo da profundidade do meio filtrante, com mais de 1.000 colônias bacterianas encontradas. O uso de meio filtrante com um diâmetro efetivo maior pode trazer benefícios operacionais, pois mostrou frequências de limpeza de duas a três vezes menores do que o meio filtrante com granulometria menor, além de apresentar carreiras de filtração mais longas, minimizando o impacto de erros de operação do sistema pelo proprietário.

Palavras-chave: água segura; tratamento de água descentralizado; pré-tratamento; material filtrante; distribuição granulométrica.

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Conflicts of interest: the authors declare no conflicts of interest.

Funding: none.

Received on: 07/04/2024. Accepted on: 05/15/2025.

https://doi.org/10.5327/Z2176-94782180

Introduction

Significant demand for water quality and quantity is one of the major social challenges faced today, according to the World Health Organization (WHO, 2024). This scenario includes isolated communities in rural areas, which are often severely affected either by water availability or quality for consumption (Freitas and Sabogal-Paz, 2019). This situation becomes increasingly critical in the face of population growth and climate change (Chan et al., 2020; Souza and Pizella, 2021).

The United Nations (UN) endorses the use of decentralized water treatment systems for situations such as this, aligning with objective 6 (Clean water and sanitation) and target 6.1 (Achieve universal and equitable access to safe and affordable drinking-water for all.) of the United Nations' Sustainable Development Goals, as stipulated in the 2030 Agenda decreed by the WHO (ONU, 2015). Such technologies are typically designed to be operated without major difficulties, while ensuring the quality of water for consumption. The technologies used include conventional continuous slow sand filtration (Freitas et al., 2023), intermittent conventional sand filtration (Puhl et al., 2023), and backwashed slow sand filtration (De Souza et al., 2021a; De Souza et al., 2021b).

However, these systems have shown limitations at high levels of turbidity (max. 10 NTU) and other characteristics of raw water (Freitas et al., 2021). Consequently, they are susceptible to high concentrations of organic and inorganic solids, causing not only clogging of the filtration medium but also the potential compromise of the quality of the filtered water (Abdiyev et al., 2023).

Proper pre-treatment, such as through a pre-filtration system, enables the reduction of impurities in raw water before it reaches its final treatment (Abdiyev et al., 2023). Thus, filtration units, especially those without a coagulation step, can be shielded from natural fluctuations in raw water quality (Lunardi et al., 2022). As a result, the quality of filtered water is guaranteed, and filtration runs tend to extend due to reduced clogging of the filtration medium.

Filtration theory demonstrates that the physical properties of filtering materials, such as specific mass, specific surface area (grain shape), and arrangement of intragranular voids, play an essential role in the filtration process (Trussell and Chang, 1999). Grain shape is directly related to its sphericity coefficient and the arrangement of intragranular voids, quantified by the porosity parameter (Cescon and Jiang, 2020).

The retention of impurities is influenced by filtration mechanisms that depend directly on the characteristics of raw water, filtering material, and the hydraulic operation mode of the system (Cescon and Jiang, 2020). The mechanisms that stand out in the particle removal process are transport, adherence, and detachment (Amirtharajah, 1988). This set of mechanisms, resulting in the filling of the porous space of the filtration medium, is known as clogging (Soares, 2015). Clogging can occur through four different processes: physical (Tang et al., 2020; Dubuis and De Cesare, 2023), chemical (Wang et al., 2020), biological (Baveye et al., 1998; Puhl et al., 2023), and mechanical (Princ et al., 2020).

The granulometric distribution of suspended material and filtering material determines whether the clogging process will develop on the surface (external clogging) or in the porous space inside the filtering material (internal clogging) (Hägg and Pott, 2022; Lunardi et al., 2022; Dubuis and De Cesare, 2023). This process also depends on fluid properties (pore velocity, viscosity, and density) (Herzig et al., 1970). The clogging process increases the hydraulic resistance of the fluid in the porous medium, causing a progressive increase in the system's head loss (Agbo et al., 2021), which can influence the quality of filtered water (Lunardi et al., 2022).

The literature does not provide clear guidance on the exact physical characteristics of the filter media to be used in pre-treatment systems. It merely recommends the use of gravel and sand—which may vary in granulometry—to mitigate the impact of fluctuations in raw water quality on slow sand filters, regardless of their type (intermittent, conventional, or backwashable) (Lunardi et al., 2022). However, studies have demonstrated that pre-treatment systems, even with similar granulometry to that used in this study, are of great importance for the performance of slow filtration treatment systems. For instance, pre-treatment systems prior to slow filtration systems, removed about 84 and 72% of turbidity in the studies of Lunardi et al. (2022) and Freitas et al. (2023), respectively. However, the performance analysis of such systems, considering other technical aspects, may not have been sufficiently explored yet.

Therefore, this study aimed to evaluate the influence of the physical characteristics of the filtration medium in domestic pre-filtration systems, using sand with different granulometries, on clogging. The effects on the system's hydraulics and potential interference with the quality of pre-filtered water were also assessed.

Methodology

Study site and experimental design

The experiment was conducted in the municipality of Frederico Westphalen, Rio Grande do Sul state, Brazil, from June to November 2022. Fresh raw water was pumped from a dam with an approximate surface area of 264 m^2 and a depth of 2 m to the laboratory. In the laboratory, it was stored in a 200 L reservoir and maintained at a constant level. The raw water inflow was introduced at the bottom of the reservoir to induce a turbulent flow and prevent particle sedimentation. Without altering the suction manometric height, metering pumps (Exatta-EX2-20) were used to transport water from the reservoir to constant-level chambers, carefully sized to control the feed flow to three pre-filtration systems.

The three units of pre-filtration (PF1, PF2, and PF3) were constructed with fittings and 100 mm PVC pipes with a height of 1.3 m (Figure 1). The outlet of pre-filtered water occurred through fittings and 20 mm PVC pipes. The pre-filtered water outlet was located 10 cm above the surface of the filtration medium. The maximum hydraulic head established was 60 cm above the pre-filtered water outlet pipe, defined through an overflow at the top of the system.

Preparation of the filtration medium

Sand was utilized as the filtration medium, with 40 cm height, following recommendations from the National Health Foundation (Fundação Nacional de Saúde [FUNASA], 2019) and De Souza et al. (2021a) and our previous experience with the study raw water (Lunardi et al., 2022). The authors reported achieving good removal of suspended solids with this thickness of filter media layer. Thus, the pre-filtration systems PF1, PF2, and PF3 were filled with sand of three different effective diameters (d_{10}) (0.2, 0.4, and 0.6 mm). In all cases, the uniformity coefficient was 1.6. The materials were prepared in the laboratory through a sieving analysis, following the DIN 18123/1983 standard (DIN, 1983), to achieve the desired granulometric characteristics. The procedure utilized an electromagnetic sieve shaker (Bertel) and a digital scale (Toledo Prix 9094 Plus). Total porosity was estimated in the pilot system, using the volumetric method (Manger, 1963). The theoretical hydraulic conductivity (K) was determined by Hazen's equation (Carrier, 2003). The material densities were obtained by dividing their mass by the filter volume. The characteristics of each pre-filter with the defined granulometries are presented in Table 1.

Support layer was the same for the three PFs and was composed of a 1.5 cm layer of fine gravel (2.0–4.8 mm), a 1.0 cm layer of medium gravel (4.8–9.0 mm), and a 2.5 cm layer of coarse gravel (9.5–19.0 mm). The preparation of the support layer also followed the DIN 18123/1983 standard (Normenausschuss, 1983).

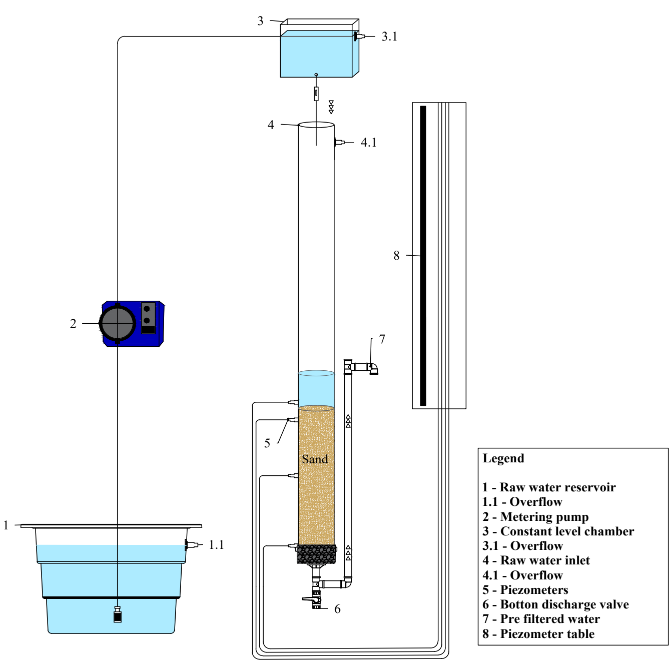

Figure 1 – Layout of the pre-filtration systems.

System operation

Raw water was pumped continuously and daily from a dam with an approximate surface area of 264 m^2 and a depth of 2 m to the laboratory, using a centrifugal pump Schneider BCR-2010V. The system was filled continually, 24 hours per day for 116 days. Filtration occurred in descending flow, variable head loss, and constant filtration rate of 4.0 $m.d^{-1}$, based on studies using the same raw water (Martins et al., 2021; Lunardi et al., 2022; Puhl et al., 2023). Filtration runs were concluded when reaching the pre-established maximum hydraulic head (60 cm).

At the end of each filtration run, the raw water inlet was stopped, and the filter bed was slowly drained until the surface layer was exposed. The top 5 cm of the filtration medium were removed by scraping—a method commonly used in decentralized systems (De Souza et al., 2021b; Puhl et al., 2023). The removed material was washed with potable current tap water and carefully placed back into the pre-filtration system.

The control of the system's head loss was carried out by installing four piezometers in each pre-filtration system (Figure 1). The first piezometer was installed just above the filtration medium. The others were installed at 5, 20, and 40 cm below the surface of the filtration medium.

Water quality monitoring

The analysis of water quality parameters followed the Standard Methods for Examination of Water and Wastewater (APHA, 2017). Although being a pre-treatment system, it was considered the minimum potability parameters established by Brazilian regulations (Brasil, 2021) and the WHO (2024) guidelines to evaluate the performance of the system. Daily samples were collected and analyzed for the parameters of pH (Hach HQ40d; pHC 101), dissolved oxygen (Hach HQ40d; LDO 101), temperature (Hach HQ40d; pHC 101), electrical conductivity (Hach HQ40d; CDC 401), turbidity (Hach 2100P), and apparent and true colors (every 48 hours) (Hach DR900). Data followed a normal distribution, so the statistical treatment of water quality data was performed through analysis of variance (one-way ANOVA) and Tukey's test.

Table 1 – Characteristics of filtering materials.

Filter material characteristic	PF1	PF2	PF3
d_{10} (mm)	0.20	0.40	0.60
Curvature coefficient (Cc)	0.90	0.92	1.05
Uniformity coefficient (Cu)	1.6	1.6	1.6
K ($m.s^{-1}$)	0.46×10^{-3}	1.86×10^{-3}	4.18×10^{-3}
Density ($kg.m^{-3}$)	1720.1	1562.3	1466.8
Total porosity (%)	34.0	37.0	39.0

PF: pre-filter.

Filtration medium sampling and microbiological analysis

At the end of 116 days of system operation, a microbiological analysis, in triplicate, was conducted to identify the presence of microorganisms in different layers of the pre-filtration system. The aim was to evaluate how the different filter media functioned as a barrier for microorganism removal in the pre-treatment system. The identification of total coliforms and *Escherichia coli* was performed by the pour plate method in Chromocult Coliform® Agar, and incubation of the plates at 37 standard deviation (±) 24 hours. The detection of heterotrophic bacteria was conducted by a spread plate assay on Plate Count Agar®, and incubation of the plates at 35±1°C for 48 hours. The assays were carried out following the guidelines of the Standard Methods for Examination of Water and Wastewater (APHA, 2017).

To collect the filtration material, the systems were slowly drained to prevent alteration of the clogging structure. Then the material was removed layer by layer at the following depths: 0–2, 2–4, 4–6, 6–8, 8–10 cm, and at 15, 20, 30, and 40 cm. At each layer change, the filtration medium removal device was cleaned with potable running water and sterilized with alcohol to avoid cross-contamination. The collected material was deposited in sterilized plastic bags with zip-lock closures. The samples were identified and immediately placed in the refrigerator (5°C) to preserve compositional characteristics. Sample preparation and analysis started a few hours after the end of the experiment (day 117).

Results and Discussion

Effect of granulometric characteristics on the hydraulic performance of the system

Figure 2 demonstrates all the results regarding hydraulic performance for each configuration of the pre-filter media. The pre-filter, composed of sand with an effective diameter of 0.20 mm (PF1) completed six filtration runs, that can be observed in Figures 2A and 2B. The first layer of the filtration medium (0–5 cm) was primarily responsible for particle removal, especially in the first filtration run. That was responsible for 49% of the total head loss. Over time, this layer lost prominence and reduced to 9% of the total head loss in the last filtration run.

The second monitored layer (5–20 cm) represented only 19% of the total head loss in the first filtration run. However, by the end of the monitoring period (6th filtration run), it accounted for 87% of the total head loss, becoming the most relevant among the three layers. The third monitored layer also showed variation in total head loss, contributing 3% to the first filtration run. By the end of the monitoring period, it contributed only 4% of the total head loss.

Figures 2C and 2D depict the behavior of head loss in PF2. This pre-filter exhibited three complete filtration runs and one incomplete run. The first layer (0–5 cm) played a significant role in the total head loss of the system in the first two filtration runs, contributing above 56% of the total head loss. This prominence diminished to 14% over the monitoring period. Then, the second layer (5–20 cm) became more relevant in the particle capture process, ending with 57% of the total head loss in the fourth, albeit incomplete, filtration run.

Figures 2E and 2F demonstrate the graphical results of PF3. It can be observed that 68% of the total head loss in the first and only complete filtration run is located in the first monitored layer (0–5 cm). In the second and incomplete filtration run, a balance is noted between the monitored layers. Thus, 23, 41, and 35% of the total head loss were distributed among the first (0–5 cm), second (5–20 cm), and third (20–40 cm) monitored layers, respectively.

In all PFs, changes in head loss readings could be caused by declogging processes. Factors such as temperature variation, affecting water viscosity, could also contribute.

In all pre-filters, the capture of suspended particles in the upper layer and sub-layers was caused by elementary mechanisms such as retention sites, retention forces, and capture processes (Herzig et al., 1970). In this process, the difficulty of fluid percolation in the available porous space was primarily and initially intensified in the first 5 cm of filtration medium. The surface serves as the primary receptor for solid particles and organic matter from the raw water, leading to an accumulation of these materials and resulting in higher head loss within this layer. This phenomenon was also reported by Lunardi et al. (2022) and Mohamed et al. (2023). The authors noted, through head loss readings and reduction in hydraulic conductivity, respectively, that the first 5 cm of filter material are primarily responsible for intercepting suspended material.

A considerable internal clogging of the filtration medium was observed throughout the pre-filters monitoring period. However, it appeared intensified in PF1, probably caused by the type and frequency of pre-filter cleaning. De Souza et al. (2021b), comparing two types of slow sand filter cleaning, also identified the progression of internal clogging. They attributed this phenomenon to the filter cleaning process, due to the reopening of the porous space. In this context, Song et al. (2020) explained that, in porous space, when the fluid approaches the particle surface, this can occur because the hydrodynamic torque surpasses the adhesive torque, causing particles to be dragged to greater depths.

The rounded grain shape conferred by the siliceous material also plays an important role in this scenario, as it influences the dynamics of capturing suspended particles. Waldschläger and Schüttrumpf (2020) demonstrated, through experiments with columns filled with glass spheres, the facilitated transport of particles through the filter medium for particles approaching a rounded shape. This occurs not only due to the shape of the filter medium grains but also because of the shape and granulometric characteristics of the suspended material (Herzig et al., 1970; Trussel and Chang, 1999).

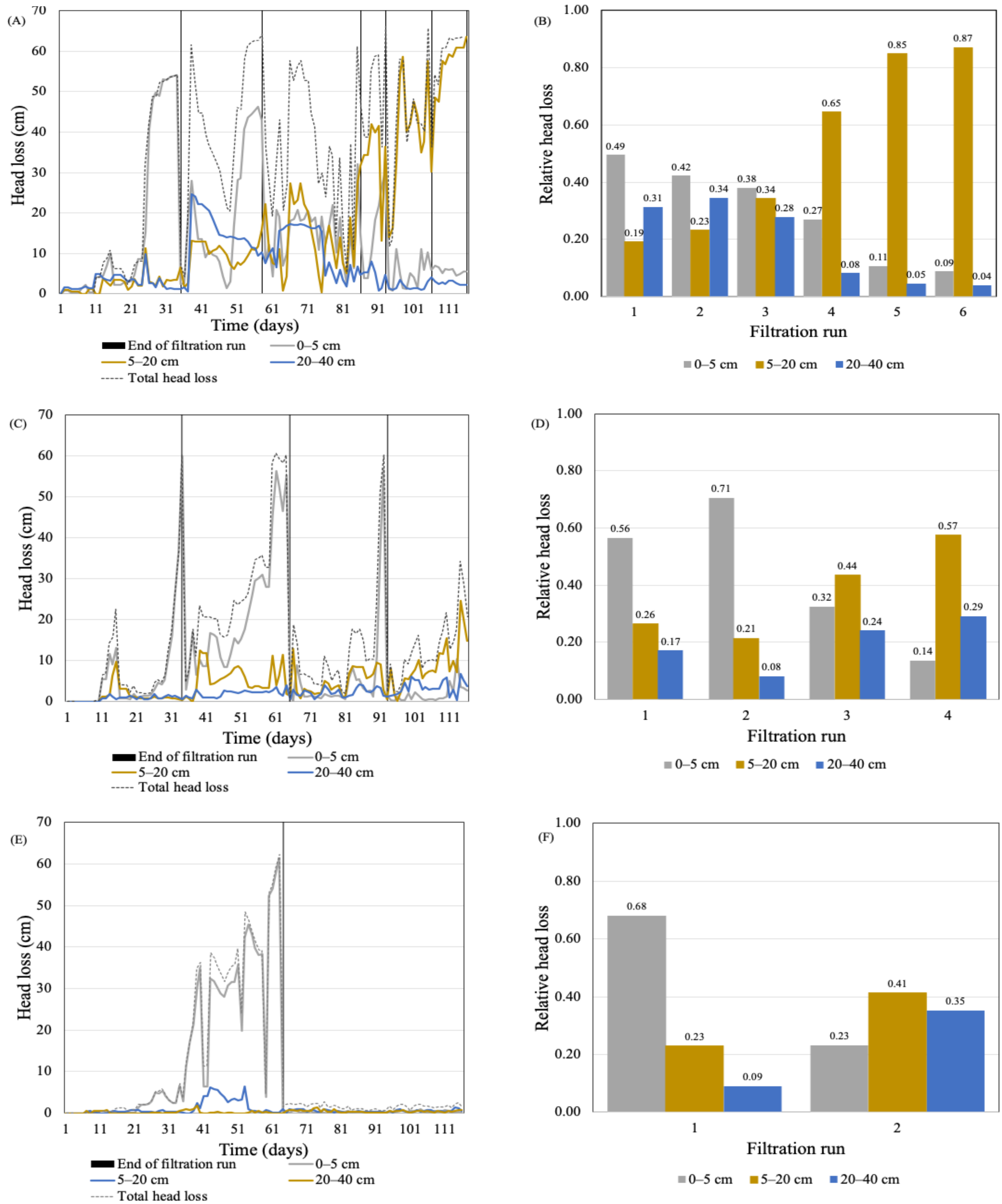

Figure 2 – Absolute and relative head loss of PF1 (A and B), PF2 (C and D), and PF3 (E and F).

Homogeneous and poorly graded filtration media utilized in the research may intensify clogging in depth, as there is less tortuosity between the grains. Thus, the probability of capturing suspended material by the porous medium is reduced, allowing the transport of particles to greater depths, as pointed out by Waldschläger and Schüttrumpf (2020) and also by Bennacer et al. (2022), who used homogeneous and poorly graded filtration media. Both studies realized the facilitated transport of suspended particles through the filtration medium.

Thus, the superior hydraulic performance obtained by PF3 considered the entire theoretical framework mentioned, including the mechanisms of particle capture and detachment, as well as the hydraulic forces promoted during filtration. All of this is aligned with the grain shape used in this study, along with other physical characteristics of the filter media.

Effect of granulometric characteristics on water quality

Table 2 demonstrates the average behavior of the monitored water quality parameters. A statistical analysis of the monitored water quality data ($p<0.05$) shows the relevance of the obtained data. Except for the dissolved oxygen, no statistical difference was observed between the diverse granulometries used for the studied parameters.

Regarding turbidity, apparent color, and true color, although they underwent significant fluctuations in raw water throughout the monitoring period, the different filtration media used generally exhibited a very similar particle removal dynamic. The fluctuations in the mentioned parameters in raw water coincide with periods of precipitation.

Considering the overall average values of the three filtration media used, the turbidity of the pre-filtered water had values of approximately 4.31 NTU. This indicates an average removal of approximately 63% of this water characteristic. Regarding apparent color, the average value among the three studied granulometries was 84.16 Hu, the average removal was 39%, and true color's average was 44.71 Hu in the studied granulometries, and a removal of 32% was achieved.

In comparison, Lunardi et al. (2022) identified removals of 84.5% for turbidity, 47.6% for apparent color, and 21.7% for true color, through pre-filters with the same cleaning system. Puhl et al. (2023), using intermittent filters and also the same raw water, observed slightly higher removals in the order of 80% for turbidity, 73% for apparent color, and 46% for true color. The studies used filtration media with an effective diameter ranging from 0.16 to 0.46 mm in their granulometric distribution, similar to the filtration media used in this study. Freitas and Sabogal (2019) chose a different raw water quality and achieved a removal efficiency of 79% for turbidity, 47% for apparent color, and 30% for true color, also very similar to the removals obtained in this study.

No significant difference was found between the means of global removals for the different filter media for the parameters of turbidity and true color. However, in the case of apparent color, PF2 showed a significant difference between the means of global removals when compared to the other filter media, although this difference was not detected in their overall values. This disparity may have been caused by the natural process of capturing and releasing suspended particles adhered to the filter media.

The low removal of apparent and true color characteristics was expected since systems that do not use physicochemical processes in treatment have low removal of humic substances (Freitas and Sabogal-Paz, 2019). According to Liu et al. (2023), the death of microorganisms in the filtration medium can cause the release of compounds and enzymes, also influencing the increase in turbidity and color in the filtered water. Additionally, hydraulic aspects, such as the applied filtration rate, can also influence the process of particle capture and detachment. In the same study, when the filtration rate was increased from 0.1 to 0.2 $m.h^{-1}$, very similar to this study (0.17 $m.h^{-1}$), no difference in organic matter removal was observed between the different granulometries studied (0.5–1.0 mm).

Observing the removal efficiency between filtration runs, the first run allowed for a greater passage of suspended material. Consequently, the parameters turbidity, apparent color, and true color in the first filtration run were higher.

As also noticed by Waldschläger and Schüttrumpf (2020) and Bennacer et al. (2022), the high uniformity of grains in the different types of filtration media, corroborating this study, was considered to have facilitated the transport of particles along the medium, where some accumulated diffusely. The authors identified, experimentally and using a mathematical model, respectively, the transport of physical particles reaching a depth of 30 cm in a filtration medium with a low uniformity coefficient. This is in line with the results collected from the loss of loads expressed by internal clogging (Figure 2). Regarding the effects on water quality in the first filtration run, the larger porous space and lower intragranular tortuosity in the clean filtration medium allowed the breakthrough of particulate material (Soares, 2015). As the maturity of the filtration medium advances, the efficiency of capturing suspended material increases substantially. Studies have shown that, although dependent on the quality of the raw water, a maturation period of 60 to 80 days can substantially improve treatment efficiency (Andreoli and Sabogal-Paz, 2020; Puhl et al., 2023). Thus, although this study was carried out for about 120 days, it is expected that pre-treatment efficiency will improve over time.

The observed inconsistency and occasional dependency in the results are explained by the declogging phenomenon, which can cause detachment of particles during the filtration process. Potential occasional fluctuations in hydraulic load and degradation of organic matter deposited in the intragranular space can also contribute to the reopening of pores and, consequently, the transport of particles through the filtration medium (Martins et al., 2021; Liu et al., 2023).

Turbidity, apparent color, and true color were above potability standards according to Brazilian legislation (Brasil, 2021) and the WHO (2024) (<1 NTU and <15 Hu), respectively. However, these characteristics will likely be further reduced when subjected to the final water treatment for consumption, which in this case should be slow filtration. The other parameters met national and international regulations.

Table 2 – Monitored pre-filtered water quality parameters (average values and standard deviation).

Parameter	Sample Type	Filtration run							
		1	2	3	4	5	6	Global value	Global Removal (%)
Turb (NTU) (M±SD)	RW	10.99 ±12.75	10.93 ±11.86	14.54 ±35.89	41.98 ±57.74	6.99 ±5.01	3.14 ±0.78	12.30 ±24.34	-
	PF1	7.64 ±10.1-1	4.50 ±9.39	1.62 ±2.09	3.74 ±4.02	1.67 ±0.70	1.03 ±0.28	4.03a ±7.45	64a
	PF2	6.57 ±7.64	4.27 ±8.60	5.08 ±11.97	2.82* ±4.02	-	-	4.65a ±8.25	64a
	PF3	5.40 ±6.79	3.24* ±5.31					4.26a ±6.12	61a
App. color (Hu) (M±SD)	RW	134.61 ±79.65	124.04 ±98.83	110.39 ±69.59	307.67 ±162.11	139.83 ±52.79	106.18 ±19.48	133.35 ±90.82	-
	PF1	101.48 ±72.59	72.96 ±79.36	54.39 ±17.46	108.83 ±51.81	67.17 ±24.69	64.73 ±22.45	77.14a ±58.77	42a
	PF2	111.14 ±58.53	90.27 ±76.32	97.29 ±85.01	77.68* ±48.70	-	-	93.83a ±67.29	34b
	PF3	83.50 49.99	80.11* 66.02	-	-	-	-	81.52a ±58.83	41a
True color (Hu) (M±SD)	RW	59.00 ±19.50	52.47 ±41.78	62.93 ±21.46	112.75 ±55.67	84.67 ±28.00	51.67 ±13.03	62.66 ±30.77	-
	PF1	47.48 ±18.41	30.53 ±10.45	34.00 ±16.02	47.50 ±28.58	36.50 ±24.92	25.67 ±9.42	39.28a ±18.69	34a
	PF2	56.29 ±18.41	42.72 ±12.75	45.64 ±25.83	43.71* ±38.92	-	-	48.82a ±29.39	31a
	PF3	46.33 ±24.65	45.58* ±38.83	-	-	-	-	46.02a ±31.38	31a
DO (mg/L) (M±SD)	RW	7.51 ±0.57	7.81 ±0.65	9.91 ±1.12	7.68 ±0.76	6.80 ±1.04	6.18 ±0.79	7.97 ±1.46	-
	PF1	6.92 ±0.53	7.39 ±0.46	8.69 ±0.57	7.88 ±0.41	7.35 ±0.51	7.84 ±0.50	7.64a ±0.84	-
	PF2	6.43 ±0.60	6.65 ±1.23	8.13 ±1.07	7.66* ±0.57			7.22b 1.10	-
	PF3	7.10 ±0.85	8.04* ±0.85					7.60ac ±0.97	-
EC (µm/cm) (M±SD)	RW	93.36 ±55.26	89.42 ±13.14	86.46 ±27.20	67.70 ±42.42	67.61 ±7.42	74.72 ±6.39	85.79 ±35.23	-
	PF1	71.76 ±9.44	80.98 ±10.52	79.41 ±7.82	75.15 ±11.79	69.79 ±2.62	71.38 ±5.64	75.64a ±9.57	-
	PF2	77.72 ±25.42	79.57 ±9.01	82.32 ±13.94	68.51* ±9.13			76.23a ±16.81	-
	PF3	77.56 ±16.01	73.53* ±12.76					75.43a ±14.47	-
pH (M±SD)	RW	6.69 ±0.50	7.19 ±0.61	7.19 ±0.21	6.85 ±0.12	6.77 ±0.12	6.73 ±0.08	7.01 ±0.43	-
	PF1	7.00 ±0.31	6.99 ±0.09	7.13 ±0.20	6.73 ±0.25	6.89 ±0.18	6.83 ±0.19	6.99a ±0.24	-
	PF2	6.86 ±0.56	7.01 ±0.12	7.04 ±0.22	6.86* ±0.13			6.93a 0.33	-
	PF3	6.90 ±0.56	6.91* ±0.37					6.91a ±0.40	-
Temp (°C) (M±SD)	RW	16.96 ±1.80	15.27 ±2.22	18.43 ±1.28	20.68 ±1.07	20.50 ±1.64	24.05 ±2.09	17.62 ±2.79	-
	PF1	16.36 ±2.55	14.57 ±3.04	17.52 ±1.59	20.32 ±0.97	19.89 ±2.08	22.35 ±1.64	16.84a ±3.19	-
	PF2	16.29 ±2.42	14.86 ±2.76	16.76 ±1.74	19.52* ±2.58			17.01a ±2.96	
	PF3	15.72 ±2.78	18.02* ±2.68					16.94a ±2.95	

*incomplete filtration run; RW: raw water; NTU.: nephelometric turbidity unit; PF1: 0.2 mm; PF2: 0.4 mm; PF3: 0.6 mm; SD: standard deviation; M: average value; Turb: turbidity, App: apparent, DO: dissolved oxygen; EC: electrical conductivity, pH: potential hydrogen; Temp: temperature; PF1: n=114; PF2: n=116); PF3: n=116; True color: n=57 (PF1), n=58 (PF2), n=58 (PF3). Average and global removal values followed by the same horizontal letters do not differ significantly from each other ($p \geq 0.05$). Average and global removal values with different letters differ significantly from each other ($p < 0.05$).

As for the difference in dissolved oxygen consumption across different filtration media, it was found that the effective size of 0.40 mm showed lower concentration or higher consumption.

That can be attributed to higher microbial activity in PF2. Despite the tendency for the biofilm to accumulate and present greater thickness in the low-flow velocity filter as seen in PF3, PF2 might have provided greater biofilm viability by producing a thinner and more stable biofilm at higher velocities. Hence, with more nutrients and oxygen diffusing through the biofilm, there is an increased oxygen consumption through aerobic metabolism (Lin et al., 2016).

Parameters such as pH, electrical conductivity, and temperature are commonly used to monitor processes such as precipitation, leaching of natural compounds, dilution, and organic activity, whether anthropogenic or natural, in raw and pre-filtered water. Sudden changes in these parameters can alter the hydraulic behavior of the system through clogging or declogging of the filtration medium. In this study, no significant abrupt changes were encountered in these parameters in raw or pre-filtered water that could compromise the pretreatment, except for the temperature, which presented seasonal variations due to natural climatic fluctuations.

Effect of granulometric characteristics on microbiological presence along the filtration medium

Figure 3A shows the number of colonies of total coliforms per gram of filtering material. Figure 3B illustrates the number of colonies formed by heterotrophic bacteria, also per gram of filtering material. The presence of *E. coli* was not detected in the analyzed samples. Total coliforms, *E. coli*, and heterotrophic bacteria serve as indicators of water quality and may suggest the presence of potentially pathogenic bacteria. Their presence along the filtration medium indicates the retention of these microorganisms from raw water, the development of biological clogging, and the potential risk of pre-filtered water contamination. Simultaneously, the presence of such microorganisms indicates the filling of the porous medium with biofilm, which is crucial in water treatment systems that do not utilize chemical coagulation.

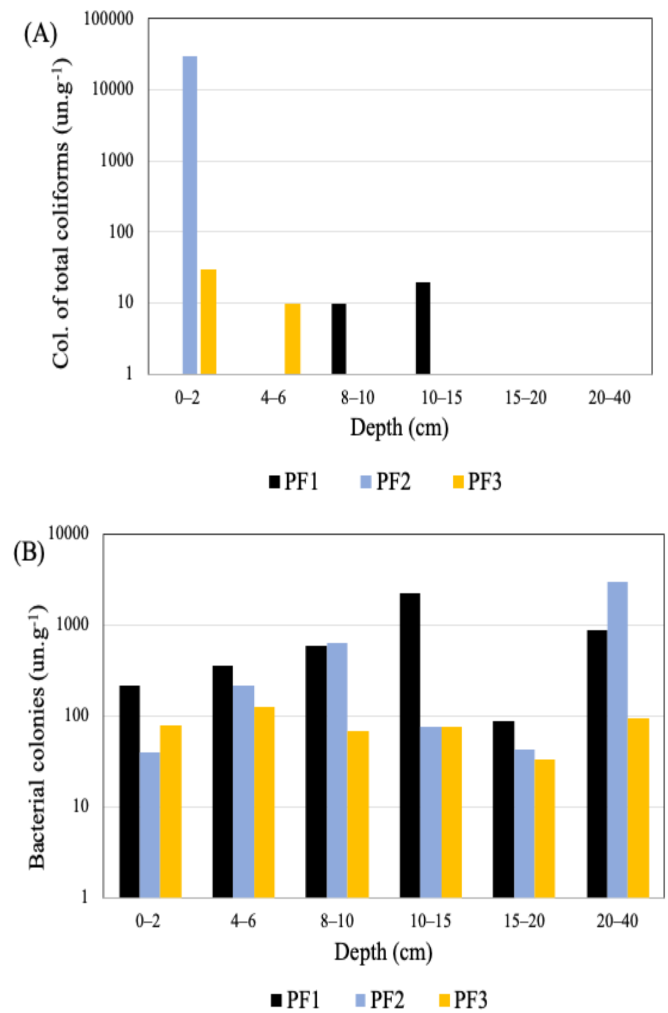

Figure 3 – Colonies of total coliforms (A) and heterotrophic bacteria (B) along the depth of the filtering media.

In PF1, total coliforms were found at a depth of 8–15 cm. In the other filtering media (PF2 and PF3), the presence of these microorganisms was limited to a depth of up to 6 cm. Normally, the scraping process, by itself, affects the distribution of microorganisms in the surface layer (De Souza et al., 2021b). Then, the higher frequency of cleaning the filtering medium of PF1 and the consequent reopening of the porous space in the upper layer possibly promoted the transport of these microorganisms to greater depths.

Regarding the number of colonies of heterotrophic bacteria, the intrusion of microorganisms was observed throughout the depth of the filtration medium for all the studied granulometries. PF1 and PF2 generally exhibited an increasing number of colonies up to a depth of 15 cm, when compared to PF3. This is potentially attributed to a higher frequency of cleaning of the upper layer of the filtering medium between filtration cycles. The filtering medium with larger granulometry and lower cleaning frequency (PF3) demonstrated greater stability in terms of the number of bacterial colonies throughout the depth of the filtering medium.

The presence of certain groups of microorganisms is directly related to the characteristics of the raw water. Freitas et al. (2021), in an experiment using a filtration medium with granulometry similar to that of this study, demonstrated that the most effective zone for the removal of coliforms was the top 5 cm of the filtration medium; however, their presence was located up to 55 cm in depth, also similar to the depth found in this study. Although it was not evident in this study, Andreoli and Sabogal-Paz (2020) demonstrated that typically the most significant proliferation of microorganisms, including the bacterial community, in a filter with a low filtration rate is localized within the upper strata of the filter medium, indicating consumption by the biological layer. Chen et al. (2021) demonstrated that the upper layer of the filtration medium (up to 10 cm deep) is primarily responsible for the capture and development of biomass, which rapidly decreases beyond this depth. The decrease in these organisms at other depths may be due to the reduced availability of dissolved oxygen transported during the filtration process. In comparison, Liu et al. (2023) observed the influence of the filtration rate on the transport and formation of bacterial community diversity along the filtration medium, in biofilters up to 120 cm in depth.

In general, in this study, the cleaning frequency of the upper layer of the filtering medium and the consequent reopening of the porous space in this layer seemingly promoted greater percolation of organic material to greater depths and, consequently, of microorganisms.

This process is intensified by the intragranular velocity in turbulent flow during the filtration process (Herzig et al., 1970), leading to internal clogging of the filtering medium and contributing to the end of filtration runs. The high grain uniformity and low tortuosity of the filtering materials can also enhance the transport of suspended material into the columns, as described in the studies by Soares (2015) and Puhl et al. (2023).

The pre-filtration system employed seemingly limited the risk of contamination of the pre-filtered water, considering the presence of total coliforms. However, the same was not observed when the presence of heterotrophic bacteria in the media was considered. It is expected that water treatment systems utilizing low filtration rates, as in this study, do not achieve complete removal of microorganisms (Pizzolatti et al., 2014). Therefore, a disinfection step before water consumption might be necessary to achieve complete microorganism removal, but also mandatory to keep water safe, according to national regulations.

Conclusions

The use of a smaller effective diameter for granulometry in pre-filtration systems results in more frequent cleaning of the filtering medium and a higher number of filtration runs. The superficial layer of the filtering medium plays a crucial role in the removal of suspended particles, especially in the first filtration cycle, considering the operational method employed in head losses reading.

It was observed that the cleaning operation, commonly used in decentralized systems, facilitated the development of internal clogging of the filtering medium. This occurred due to the reopening of the porous space in the first layer, along with the hydraulic forces generated by the filtration process, and possibly enhanced by the low uniformity coefficient of the filtering medium.

For the three studied granulometries, no significant differences were found in the evaluated water quality parameters in the pre-filtered water. Thus, considering the water under study, the use of larger effective diameter granulometry may bring operational benefits to this type of decentralized pre-treatment unit, such as a lower frequency of cleaning the filtering medium and longer filtration cycles. This also minimizes the impact of system operation errors by the owner.

The pre-filtration system was shown to be a significant barrier to the removal of microorganisms, as indicated by the reduction in total coliform indicators, potentially facilitating the final filtration system's performance. However, the same was not observed concerning the presence of heterotrophic bacteria.

As with many studies involving water treatment systems, the results obtained in this study heavily depend on the characteristics of the raw water. Therefore, these findings should not be generalized to other situations, although they may serve as a decision-making support tool for future studies.

Authors' Contributions

Poncio, T.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft. **Lunardi**, S.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, validation, visualization, writing – review & editing; **Decezaro**, S.T.: conceptualization, formal analysis, methodology, project administration, validation, visualization, writing – review & editing.; **Romero-Esquivel**, L.G.: formal analysis, validation, visualization, writing – review & editing.; **Medeiros**, R.C.: conceptualization, formal analysis, methodology, project administration, validation, visualization, writing – review & editing. **Aguiar**, L.: conceptualization, formal analysis, methodology, validation, visualization, writing – review & editing. **Soares**, M.: conceptualization, formal analysis, methodology, project administration, resources, supervision, writing – review & editing.

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