

Article

Wastewater Treatment with Geotextile Filters: The Role in Permeability and Pollutant Control

Maria Vitoria Morais ^{1,*}, Leonardo Marchiori ^{1,*}, Josivaldo Sátiro ^{1,2}, Antonio Albuquerque ¹
and Victor Cavaleiro ¹

¹ GeoBioTec, Department of Civil Engineering and Architecture, University of Beira Interior, 6201-001 Covilhã, Portugal; josivaldo.satiro@ubi.pt (J.S.); antonio.albuquerque@ubi.pt (A.A.); victorc@ubi.pt (V.C.)

² FibEnTech, Department of Chemistry, University of Beira Interior, 6201-001 Covilhã, Portugal

* Correspondence: vitoria.morais@ubi.pt (M.V.M.); leonardo.marchiori@ubi.pt (L.M.)

Abstract: The application of geotextiles as filter materials in various systems, such as biofilters, wetlands, and wastewater treatment plants, has grown significantly in recent years. The ability of these materials to support biofilm growth makes them ideal for the removal of organic and inorganic contaminants present in wastewater. The objective of this research was to analyze clogging through variations in permeability, using column tests for 80 days with two types of nonwoven geotextiles with different grammages (GT120 and GT300), as well as to study the efficiency in the removal of organic matter. A synthetic wastewater was used, allowing the specific observation of biological clogging and the treatment carried out exclusively by microorganisms. The results indicated that bioclogging was not a significant factor within the experimental period. Through the mass test, a continuous increase in biofilm growth over time was observed for both geotextiles. For scanning electron microscopic (SEM) images, GT300 presented a larger biofilm area. A higher removal of COD (80%), N (52%), and P (36%) by microorganisms present in GT300 was found, which appears to be associated with its greater thickness and weight. The higher mesh density provides a larger area for the growth of microorganisms, allowing a greater amount of biomass to establish itself and contributing to the efficient removal of pollutants. These findings highlight the potential of using geotextile filters in wastewater treatment applications, where biofilm growth can positively contribute to contaminant removal without immediately compromising permeability.

Keywords: geotextile; bioclogging; synthetic wastewater; biofilm; column tests



Academic Editors: Maria Cristina Collivignarelli, Alessandro Abbà and Marco Carnevale Miino

Received: 10 December 2024

Revised: 30 December 2024

Accepted: 8 January 2025

Published: 10 January 2025

Citation: Morais, M.V.; Marchiori, L.; Sátiro, J.; Albuquerque, A.; Cavaleiro, V. Wastewater Treatment with Geotextile Filters: The Role in Permeability and Pollutant Control. *Appl. Sci.* **2025**, *15*, 626. <https://doi.org/10.3390/app15020626>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Geotextile-based systems offer several advantages over conventional wastewater treatment methods, particularly in terms of cost-effectiveness, efficiency, and spatial requirements [1]. Traditional treatment facilities often require substantial capital investment and occupy large land areas, which can be a constraint in densely populated or resource-limited regions [2,3]. In contrast, geotextile-based systems can be implemented with lower initial costs and require less space, making them suitable for decentralized or small-scale applications. Furthermore, the widespread use of geotextiles in systems such as wastewater treatment plants, stabilization ponds, and landfills underscores their versatility. This increasing adoption is driven by their superior technical and economic benefits, providing a viable alternative to traditional natural materials like gravel and sand [4]. However, issues

related to clogging (whether physical, chemical, or biological) remain a critical limitation, significantly affecting their efficiency and lifespan [5].

In environmental and geotechnical applications, especially in contact with water and sewage, geotextiles can develop biofilms on their surface due to microbial activity. The ability of these materials to support biofilm growth makes them ideal for the removal of organic and inorganic contaminants present in wastewater. In the context of wastewater treatment, several studies have explored the application of geotextiles under varying conditions [6–8]. Ref. [9] conducted laboratory-scale column experiments employing multiple layers of geotextiles to evaluate filtration performance, in addition to [10], which investigated the microbial community dynamics within similar apparatus where four pilot-scale stainless-steel bioreactors were evaluated with single- and double-layer geotextile fabrics. Furthermore, Ref. [11] implemented an in situ filtration system using geotextiles in a eutrophic lake, demonstrating their efficacy in attenuating suspended solids and suppressing algae. These works have contributed to the literature regarding wastewater treatment within geotextile layers, mainly analyzing the biological aspects.

Biological wastewater treatment processes utilize microorganisms through two primary mechanisms: suspended growth or attached growth systems. Early studies, such as [12], investigated microbial attachment to geotextiles for treatment, with subsequent research by [10,13,14] and others expanding on this concept. Biofilms, consisting of microbial communities embedded within a matrix of extracellular polymeric substances (EPS), form on geotextile surfaces under favorable conditions, including abundant organic matter, adequate pH levels, and dissolved oxygen concentrations exceeding 2 mg/L [15]. The biofilm formation process involves microbial adhesion, growth, and eventual detachment, with EPS production playing a pivotal role in establishing and maintaining the biofilm structure. Detachment, driven by hydrodynamic forces, pH variations, and the presence of inhibitory compounds, regulates biofilm thickness and accumulation, significantly influencing bioclogging. Biofilms on geotextile surfaces function as biological barriers, capturing particles and facilitating pollutant degradation through microbial activity [10]. However, the efficacy of this treatment approach is inherently dependent on the sustained permeability of the geotextile, which can be adversely affected by the progressive effects of biological clogging.

The permeability of geotextiles can be affected by clogging, which arises from processes such as bacterial proliferation, mineral deposits, and the movement of soil particles into the material's structure. This phenomenon is typically categorized into three mechanisms: blinding, internal clogging, and blocking. Blinding takes place when soil particles build up at the interface between the soil and the filter, forming a low-permeability layer. Blocking involves particles attaching to pore surfaces, obstructing water flow. Meanwhile, internal clogging happens when fine particles infiltrate the pores, disrupting the geotextile's ability to allow water passage [16–19].

Most studies addressing clogging primarily concentrate on permeability loss, while investigations into treatment efficiency focus on pollutant reduction, often overlooking the interconnection between these two aspects. Consequently, it is critical to elucidate the mechanisms driving geotextile clogging and to correlate these phenomena with their performance in contaminant removal. Integrating these perspectives is essential for advancing the optimization of geotextile applications in sustainable and efficient water treatment systems.

This study aims to evaluate the performance of two nonwoven geotextiles with distinct grammages as substrates for the formation of biofilms and their subsequent role in wastewater treatment. The research focuses on assessing the temporal variation in permeability and the efficiency of biofilm-enhanced geotextiles in removing organic matter, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$. Geotextiles were inoculated with lyophilized bacterial cultures derived from water

treatment plant (WTP) sludge, facilitating the direct incorporation of an active microbiota into the wastewater treatment residue and enhancing its functionality as a filtration aid. Synthetic effluent was utilized to isolate and observe the effects of biological clogging and the treatment processes mediated solely by microorganisms, excluding the influence of physical clogging. This methodology ensures that the findings exclusively reflect biological activity, offering a clearer understanding of the geotextiles' treatment potential and the influence of bioclogging on their structural and functional properties.

2. Materials and Methods

2.1. Experimental Setup

To evaluate the biological clogging of geotextile filters, permeability tests were carried out, as recommended in [20,21] and following [22]. The permeameters have already been tested in experimental tests by [6–8], shown in Figure 1. For the research, tests were carried out on two types of geotextiles, with the fabric immersed in wastewater for different times, as shown in Table 1. The cylinders were fed with synthetic domestic wastewater, whose composition will be described below, and were operated in vertical downward flow. The average load used was 25 cm.

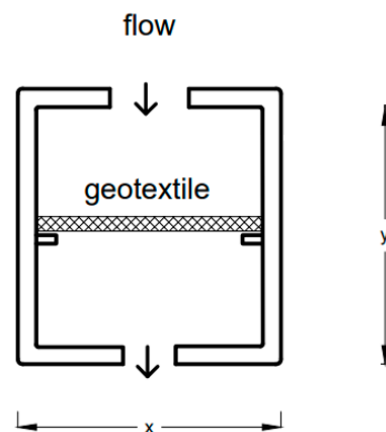


Figure 1. Setup permeameters used in the tests.

Table 1. Number of cycles tested by permeameters.

Tests (Unit)	Number of Cycles	Time in Days
Permeameter 1	5 cycles	20 days
Permeameter 2	10 cycles	40 days
Permeameter 3	15 cycles	60 days
Permeameter 4	20 cycles	80 days

2.2. Geotextile Characteristics

The experiments were conducted in permeameters with an internal diameter of 100 mm. Each permeameter had a 10 cm diameter of nonwoven geotextile with different characteristics (Table 2) which was composed of 100% polypropylene fiber.

Table 2. Characteristics of the geotextiles.

Tests (Unit)	Standard	GT120	GT300
Mass Per Unit Area (g/m ²)	[23]	120 (±5.00%)	300 (±10.00%)
Permeability (m/s)	[24]	6.3×10^{-2} (±10.00%)	6.3×10^{-2} (−0.019)
Thickness (2 kPa) (mm)	[25]	1.21 (±15.00%)	2.30 (±20.00%)
Tensile Strength Test MD (kN/m)	[26]	1.15 (±15.00%)	25.00 (±13.00%)
Tensile Strength Test CD (kN/m)	[26]	1.35 (±15.00%)	25.00 (±16.00%)
Characteristic Opening Size (µm)	[27]	100 (±10.00%)	58 (±17.0%)

2.3. Synthetic Effluent

The synthetic wastewater was prepared based on the following composition [15,28]: buffer solution (8.50 g KH_2PO_4 + 21.75 g K_2HPO_4 + 33.40 g $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$ + 1.70 g $\text{NH}_4\text{Cl/L}$), magnesium sulfate solution (22.50 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O/L}$), calcium chloride solution (36.43 g $\text{CaCl}_2 \cdot 2\text{H}_2\text{O/L}$), iron chloride solution (0.25 g $\text{FeCl}_3 \cdot 6\text{H}_2\text{O/L}$), oligoelement solution (0.04 g $\text{MnSO}_4 \cdot 4\text{H}_2\text{O}$ + 0.06 g H_3BO_3 + 0.04 g $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ + 0.032 g $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ + 0.0555 g EDTA ($\text{C}_{10}\text{H}_{14}\text{N}_2\text{Na}_2\text{O}_8 \cdot 3\text{H}_2\text{O}$) + 0.0445 g $\text{FeCl}_3 \cdot 6\text{H/L}$), sodium acetate solution (20.20 g $\text{C}_2\text{H}_3\text{O}_2\text{Na} \cdot 3\text{H}_2\text{O/L}$, organic source as acetate), ammonia chloride solution (20.30 g $\text{N-NH}_4\text{/L}$, nitrogen source), and potassium nitrate solution (13.7 g $\text{KNO}_3\text{/L}$, as phosphorous solution).

Geotextiles were inoculated with 2 mL of a biomass extracted from lyophilized sludge from the Boidobra wastewater treatment plant (WWTP) at Covilhã that was previously acclimatized during two weeks in a semi-continuous reactor, which contained 6.680 mg/L SSV, 8.420 mg/L TSS, 311.2 mg/L COD, 11.2 mg/L N-NH_4 , and a pH of 7.4. Experiments were performed with the synthetic wastewater (feeding solution) with initial average loads of 450 mg COD/L, 25 mg $\text{NH}_4\text{-N/L}$, and 19 mg $\text{PO}_4\text{-P/L}$. The average temperature during the tests was 20.8 °C.

2.4. Nutrient Removal Assessment

According to the experimental tests of [6,9], at the beginning of each cycle, permeability was measured, and synthetic wastewater samples were taken to determine pH, dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen ($\text{NH}_4\text{-N}$), and phosphorus phosphate ($\text{PO}_4\text{-P}$). At the end of each cycle, permeability was measured and samples of effluent water from the bottom of the permeameters (drained water) were taken for pH, DO, COD, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ analysis.

The measurements of DO, pH, and temperature were carried out through the probes Cellox 32 and SenTix 41 connected to a Multimeter 340i (WTW, Weilheim, Germany). COD, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ were determined by a colorimetric method using a RFID model DR3900 UV photometer (Hach, Loveland, CO, USA) and the cuvette tests LCK 114, LCK 303, and LCK 350, respectively. Removal efficiencies were calculated through Equation (1), where ΔC = removal efficiency for parameter C (%); C_i = concentration of parameter C in the feeding solution (influent) (mg/L); and C_e = concentration of parameter C in the drained samples (effluent) (mg/L).

$$\Delta C = \left(\frac{C_i - C_e}{C_i} \right) \times 100 \quad (1)$$

2.5. Scanning Electron Microscopy (SEM)

At the end of each cycle presented in Table 1, SEM images were taken using the Tescan VEGA equipment (TESCAN, Brno, Czech) to observe the biofilm arrangement on the geotextile mesh, and Energy Dispersive X-ray Spectroscopy (EDS) was performed to evaluate the chemical composition of the biofilms.

The samples were fixed using a buffer solution and glutaraldehyde for a period of 24 h. Subsequently, the samples were dehydrated in alcohol and initially immersed in a 50% alcoholic solution (half the volume in water and half in alcohol). The geotextiles were then immersed in concentrations ranging from 50 to 100% with progressive increases of 10%, a methodology used by [19]. After dehydration, the samples were fixed to the drying racks. Each geotextile sample tested was evaluated in three regions: the central part of the sample, the middle part, and the edge. In addition, a cross-section of each of these regions was performed.

3. Results and Discussion

3.1. Permeability

The permeability test results graphs are presented in Figures 2 and 3 for the GT120 and GT300 results, respectively. To interpret the graphs, it is necessary to know that “S” was used for the sample and “T” for the reading trial. Therefore, S1-T1 is the permeability of sample 1 (S1) and first test (T1); since the tests were very fast, they were performed in triplicate, resulting in T1, T2 and T3 for all samples.

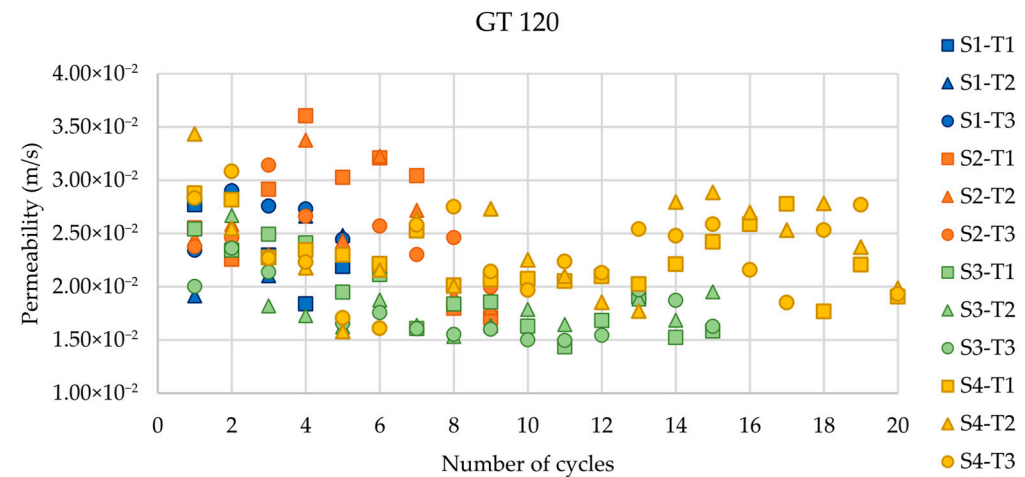


Figure 2. Permeability variation for GT120.

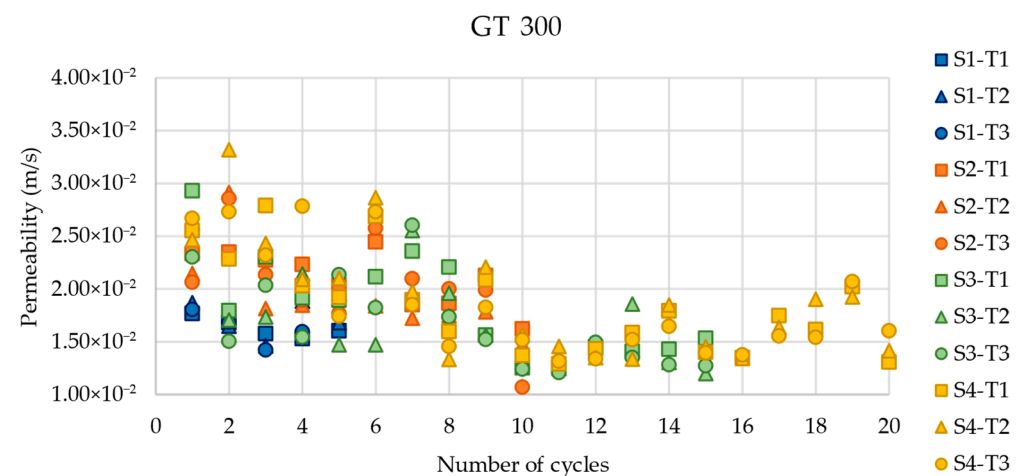


Figure 3. Permeability variation for GT300.

Figure 2 shows a small increase in permeability in the first cycles, followed by a reduction until cycle 12. After cycle 12, the curve starts to rise again, finding stability. The average permeability of the first cycle for all permeameters was 2.58×10^{-2} m/s, while the average of the last cycle was 1.94×10^{-2} m/s. Ref. [17] found similar permeability reduction values, from 5.8×10^{-2} to 5.0×10^{-2} m/s for the 80-day period with leachate. These reductions, in general, can be considered very small. Ref. [19] found reductions of 10^{-3} to 10^{-9} m/s over a 35-day period, and the results presented by these authors suggest the occurrence of biological clogging; however, it is possible that there was also physical clogging, considering that the material used in the research was pure leachate, which could contain physical substances capable of contributing to the observed clogging. This observation reinforces the complexity of clogging mechanisms and the importance of considering both biological and physical aspects when evaluating the permeability of geotextiles in contact with wastewater.

The increased variability in permeability during the initial 10 cycles could be attributed to the early stages of biofilm formation, which likely impacted the flow dynamics within the material's structure. The increase in permeability observed between cycles 10 and 20 can be explained by the detachment of some fractions of the biofilm that were not well-adhered to the geotextile mesh, possibly due to the lower thickness of GT120 since the GT300 presented more stable results for the same period of time, which will be discussed below.

A very similar behavior is observed in the GT300 experiment (Figure 3). Both tested samples experience an increase in permeability, followed by a period of stabilization, and then the permeability decreases again. Overall, the permeability of both types of geotextiles remained virtually unchanged throughout the 20 cycles, indicating that bioclogging was negligible during the approximately 80-day operating period, which contrasts with the results of [16–18] who found clogging in the order of 10^{-4} to 10^{-9} . This suggests that, within this time interval, the ability of the geotextiles to allow water flow was not compromised by biofilm formation or other biological clogging processes.

Some analytical methods have been developed to predict clogging using permeability; however, ref. [29] observed that the predictions differ considerably from the experimental data. This is mainly because these models cannot capture the complexity of the biofilm microstructure due to criteria such as biofilm growth and because they consider the morphology of the biofilm in porous media and detachment due to shear. All these criteria depend on both the culture medium and the microorganisms that will develop there, making the modeling different from the experimental data.

3.2. Physical–Chemical Parameters

This section will present the results obtained for the physical–chemical parameters of the synthetic wastewater tested during the permeability test. It is important to highlight that by using the geotextile as a bed material, or as a substrate for biofilm growth, the biofilm + geotextile system works as an integrated unit, functioning as a single system. The geotextile, on its own, serves only as a filter and is not capable of “treating” the effluents, as it is made of polypropylene fabric. The treatment of the effluents occurs through the action of bacteria adhered to the filter, which are responsible for the degradation of pollutants.

Figures 4–6 illustrate the progression of COD (ΔCOD), $\text{NH}_4\text{-N}$ ($\Delta\text{NH}_4\text{-N}$), and $\text{PO}_4\text{-P}$ ($\Delta\text{PO}_4\text{-P}$) removal in the eight permeameters. It was observed that COD, nitrogen, and phosphorus removal increased over time in all permeameters equipped with both types of geotextiles, starting after the first cycle. The highest removal rates were recorded for the heavier-weight geotextile (GT300), indicating a superior filtration and treatment efficiency of contaminants compared to the lighter-weight geotextiles.

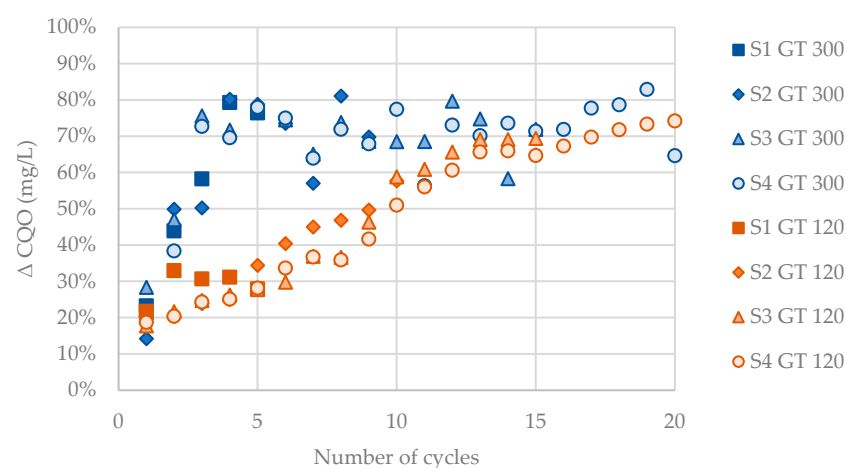


Figure 4. Variation in COD removal in permeameters with GT120 and GT300.

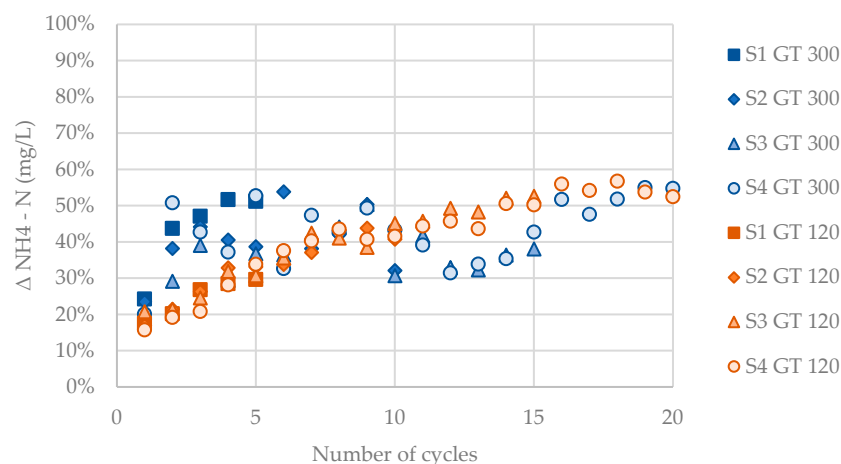


Figure 5. Variation in $\text{NH}_4\text{-N}$ removal in permeameters with GT120 and GT300.

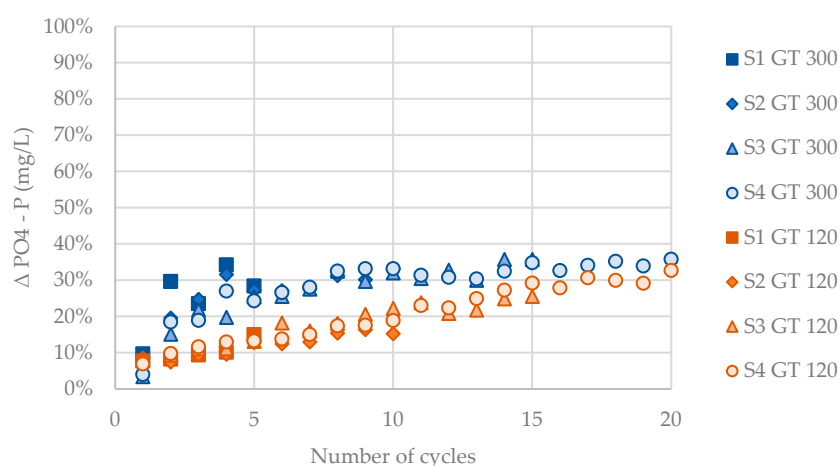


Figure 6. Variation in $\text{PO}_4\text{-P}$ removal in permeameters with GT120 and GT300.

In the first five cycles (approximately 20 days of operation), COD removal increased significantly, reaching up to 79% in GT300 and approximately 34% in GT120. Stabilization in COD removal for GT300, indicating steady-state conditions, was observed only after the tenth cycle. Between the fifth cycle (20 days of operation) and the twentieth cycle (52 days of operation), the average COD removal efficiency for the GT300 was 72%.

For the GT120, the average COD removal efficiency stabilized around the thirteenth cycle (52 days of operation), ranging from 65% to 75%. This demonstrates that, although both geotextiles eventually reach stable performance, the GT300 reaches higher levels of COD removal more quickly and maintains a higher average efficiency over time. Removal values of 63% in leachate were found by [19] at the end of 35 days, and removal values of 80% were found by [21] at the end of 90 days.

Regarding the removal of nitrogen in the form of ammonia (Figure 5), the removal efficiency in GT300 varied from approximately 22% to 40% in the first two cycles (8 days of operation) and stabilized after the third cycle (12 days of operation). For GT120, equilibrium conditions were reached around the tenth cycle (40 days of operation), presenting a greater variation in efficiency between the fourth and tenth cycles (16 to 40 days of operation). Despite this difference in time to stabilization, the final average removal efficiencies for both geotextiles were similar, at around 40%. This indicates that, although GT300 reaches a stable efficiency more quickly, both colonized materials are equally effective in removing ammonia–nitrogen in the long term.

The average phosphorus removal (Figure 6) started at 16% in the first three cycles (12 days) and stabilized at approximately 31% from the fourth to the tenth cycle for GT300.

The behavior of microorganisms in GT120 was more linear, reaching stabilization around the fifteenth cycle. This suggests that, while the heavier-weight geotextile (GT300) reaches a relatively fast phosphorus removal efficiency, GT120 requires a longer period to reach a similar stability. The difference in the stabilization rate can be attributed to variations in the interaction of microorganisms with the geotextile materials, influencing the phosphorus removal efficiency over time.

In general, the greater removal of COD, N, and P by the microorganisms arranged in the GT300 appears to be associated with its greater thickness and weight, which would have allowed greater biofilm development. The greater density of the mesh offers a larger area for the growth of microorganisms, allowing a greater amount of biomass to establish itself and contribute to the efficient removal of pollutants.

This behavior corroborates with that observed by [30–32], who highlight the influence of nutrients on bioclogging in a fundamental way. The concentration of biodegradable substrates in the feed water is a determining factor in the growth and greater resistance of this biofilm. In summary, a higher concentration of substrate in the feed water causes more biofilm growth and greater resistance to the biofilm. Nutrients can be considered as potential biomass. Thus, with a larger biofilm, higher values of nutrient absorption can be obtained, leading to the “treatment” of this wastewater.

Other parameters were measured, such as pH, conductivity ($\mu\text{S}/\text{cm}$), dissolved oxygen (mg/L), and temperature ($^{\circ}\text{C}$), as shown in Figure 7. Measuring these parameters is essential to better understand the environmental conditions in which microorganisms are operating, as they can significantly influence the efficiency of the biological and chemical processes involved in contaminant removal.

Variations in pH can affect microbial activity and the solubility of certain nutrients, while conductivity provides information about the concentration of ions in the medium. Dissolved oxygen is essential for the respiration of aerobic microorganisms, and temperature can impact biological and chemical reaction rates. Therefore, monitoring these parameters helps to fully assess the performance of the microorganisms’ attachment to the geotextile bed and optimize operating conditions to maximize pollutant removal.

Regarding pH, more stable values between 7 and 8 were found in GT300 (Figure 7b). This was expected, since the nutrient removal results indicated a faster biomass growth in this geotextile compared to GT120 (Figure 7a). The pH values for wastewater are between 7 and 9 [21,33–35]. pH stability in this range is beneficial for the microbial activity present in these wastewaters, since most microorganisms involved in pollutant removal operate more efficiently in neutral to slightly alkaline conditions.

The same behavior was observed for the conductivity parameter. In GT300, the measured values ranged from 800 to 900 $\mu\text{S}/\text{cm}$, demonstrating greater stability (Figure 7d). In GT120, there was a wider variation, with values between 700 and 900 $\mu\text{S}/\text{cm}$ (Figure 7c). This difference in conductivity stability suggests that GT300 provides a more consistent environment in terms of ionic concentration, which can be attributed to its greater biofilm development and more uniform treatment capacity.

In the literature, electrical conductivity values ranging from 14 to 18 mS/cm have been reported in tests performed with pure leachate, presenting a chemical oxygen demand (COD) of 4.690 mgO_2/L [19]. These values are significantly higher than those found in this study, which was expected due to the lower organic load present in the synthetic wastewater used in the study. This difference highlights the influence of the effluent composition on electrical conductivity, reinforcing the need to contextualize the results according to the specific characteristics of the wastewater in question.

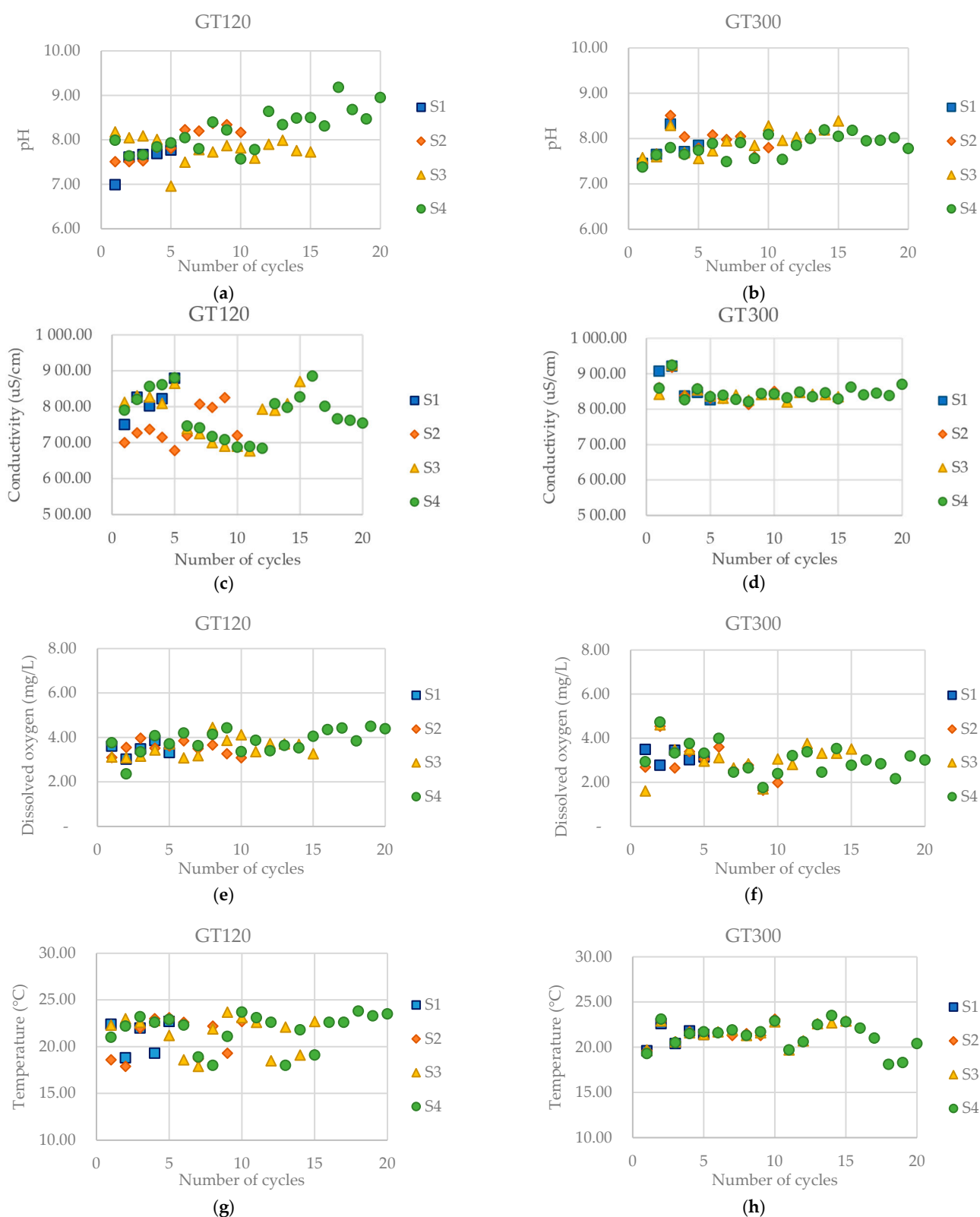


Figure 7. (a,b) pH, (c,d) conductivity, (e,f) dissolved oxygen, and (g,h) temperature parameters measured on the GT120 and GT300.

As for dissolved oxygen, values between 3 and 4 mg/L were found for both samples (Figure 7e,f). Values between 3 and 4 mg/L are generally considered sufficient for most biological treatment operations, ensuring that the microorganisms have the necessary oxygen to maintain their metabolic activities, since these were aerobic microorganisms [36,37].

Regarding temperature, both samples presented values between 18 and 24 °C (Figure 7g,h). Despite efforts to maintain a constant ambient temperature of 20 °C, variations were observed in the permeameters. These variations can be considered normal due to environmental and operational factors, since the tests were performed between spring and summer, when the temperature outside the laboratory reached 40 °C. Temperature is a critical parameter, as it influences the metabolic activity of microorganisms involved in pollutant removal. Variations within this range (18 to 24 °C) are generally acceptable and do not significantly compromise the efficiency of biological processes.

3.3. Measurement of Biomass Growth

Finally, at the end of each cycle, the filters were weighed to assess biomass growth (Figure 8). It is important to note that the geotextiles were initially weighed wet only with distilled water to ensure that the subsequent weight exclusively reflected the increase due to biomass growth. In the first five cycles, the GT300 showed an increase of 8 g, stabilizing at 15 g in the tenth cycle. In comparison, the GT120 had a mass increase of approximately 3 g in the first five cycles.

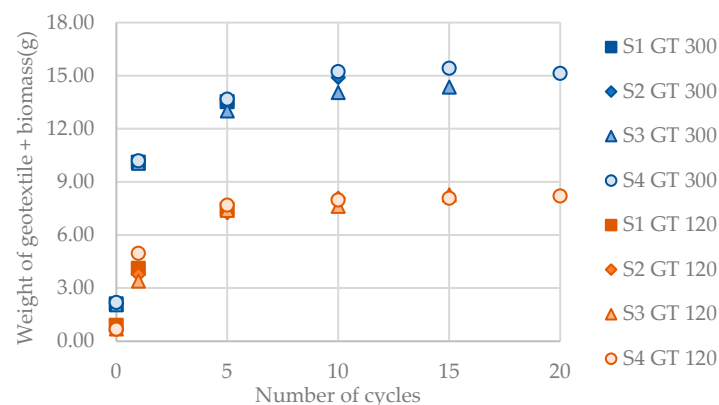


Figure 8. Results found for measuring biomass growth.

The ability of GT300 to support greater biomass is directly related to its greater grammage and density, which provides a more favorable environment for microbial colonization and activity, resulting in the more effective removal of COD, nitrogen, and phosphorus. Conversely, GT 120, which has a lower weight and mesh density compared to GT300, has slower growth.

3.4. Scanning Electron Microscopy

For the analysis of geotextile samples by SEM, samples were collected from three distinct regions: region I, called the “center”; region II, called the “middle”; and region III, called the “edge”, shown in Figure 9. Although the flow through the geotextile is designed to be uniform, there may be preferential flow conditions due to the structure of the geotextile mesh and the formation of biomass, consequently, which is expected of bioclogging.

Collecting samples from different regions allows a detailed evaluation of the characteristics and performance of the biofilm in various areas. The central region can provide information on the direct interaction of the main flow with the material, while the middle and edge regions can reveal variations in the distribution of biomass and possible zones of clogging or the accumulation of contaminants.

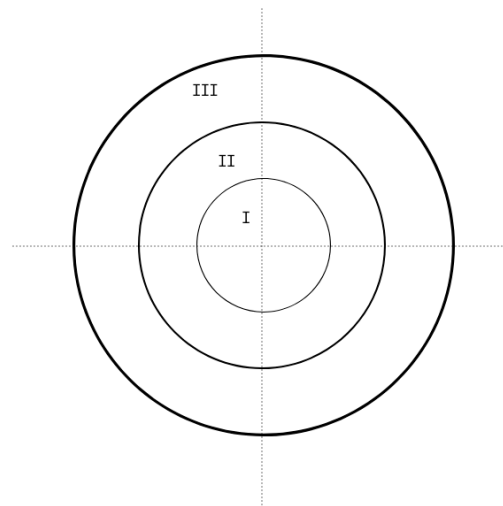


Figure 9. Layout used for SEM images.

The SEM analysis of these regions helps to identify the homogeneity of biofilm development and the distribution of particles retained in the mesh. Differences observed between these regions may indicate areas where the flow is more intense or where there is a greater deposition of material, influencing the overall efficiency of the treatment system. This information is essential to better understand the flow dynamics in the application of biofilms on geotextiles in filtration and water treatment systems.

In Figure 10, the images showed little biofilm formation in Figure 10c, which represents the edge of the geotextile mesh, with an initial distribution of microorganisms. The cross-section images reveal no changes, still indicating the possible beginning of microbial colonization. In Figure 11, there is a small growth of biofilm in the other regions (middle and center). In the cross-section, there is the appearance of a small biofilm, but still nothing that suggests any clogging.

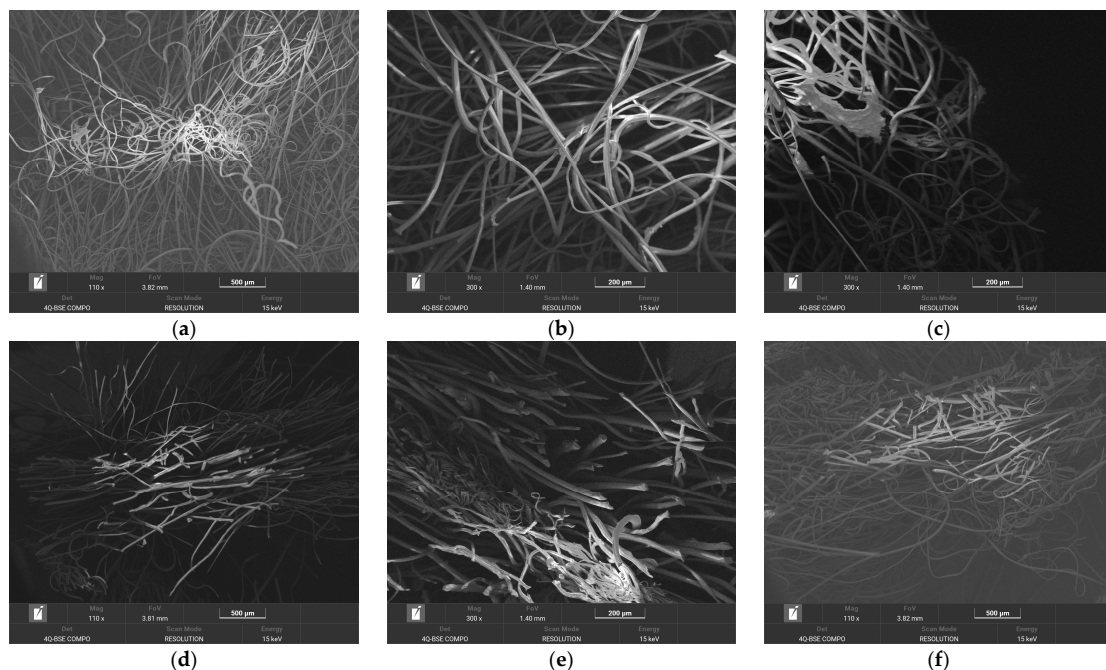


Figure 10. SEM images for the GT120—S1: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

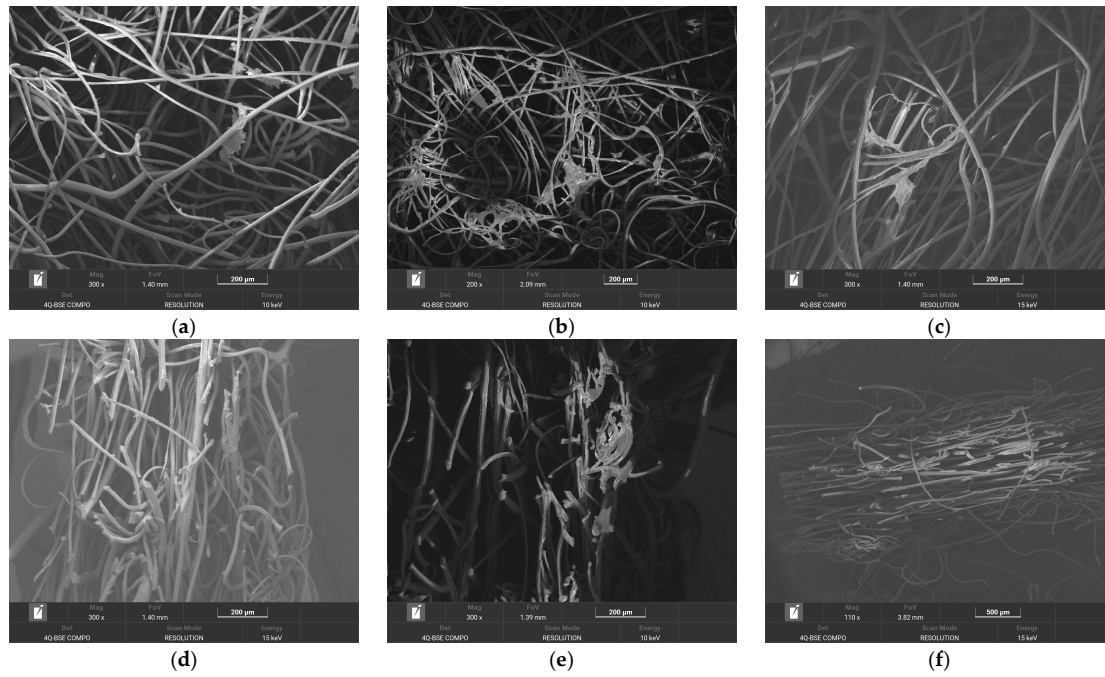


Figure 11. SEM images for the GT120—S2: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

In Figure 12, the top view of the central region (Figure 12a) shows the growth of some colonies. The cross-section shows some small agglomerations of microorganisms, but as expected, because the geotextile mesh is too thin, the biofilm is not able to develop over its entire length to ensure fixation.

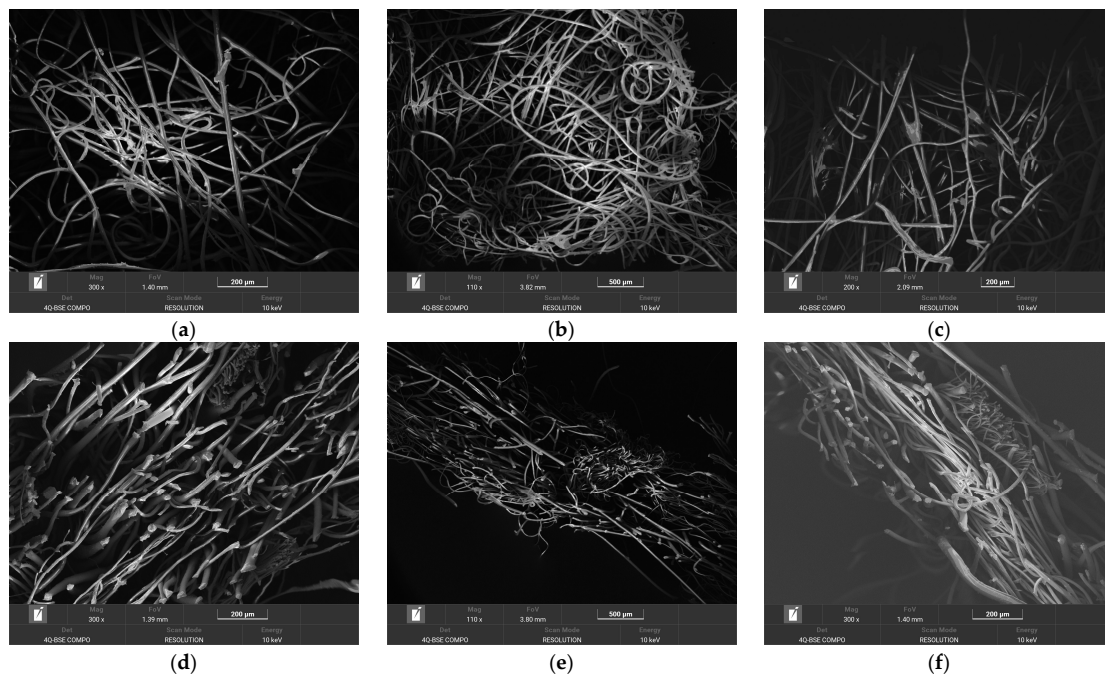


Figure 12. SEM images for the GT120—S3: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

In Figure 13, which shows the geotextile sample subjected to the test for a longer period, the biofilm covers almost the entire surface of the geotextile in all areas. Clogging is evident, especially in the middle and edge regions, where the biomass concentration is highest. The thickness of the biofilm reaches its peak during the period studied, indicating a significant filling of the geotextile mesh. This could be seen as the beginning of bioclogging; however, the biofilm structure is still too thin to ensure complete fixation. Furthermore, the results of the permeability test show that the biofilm is not yet capable of significantly compromising the effluent flow.

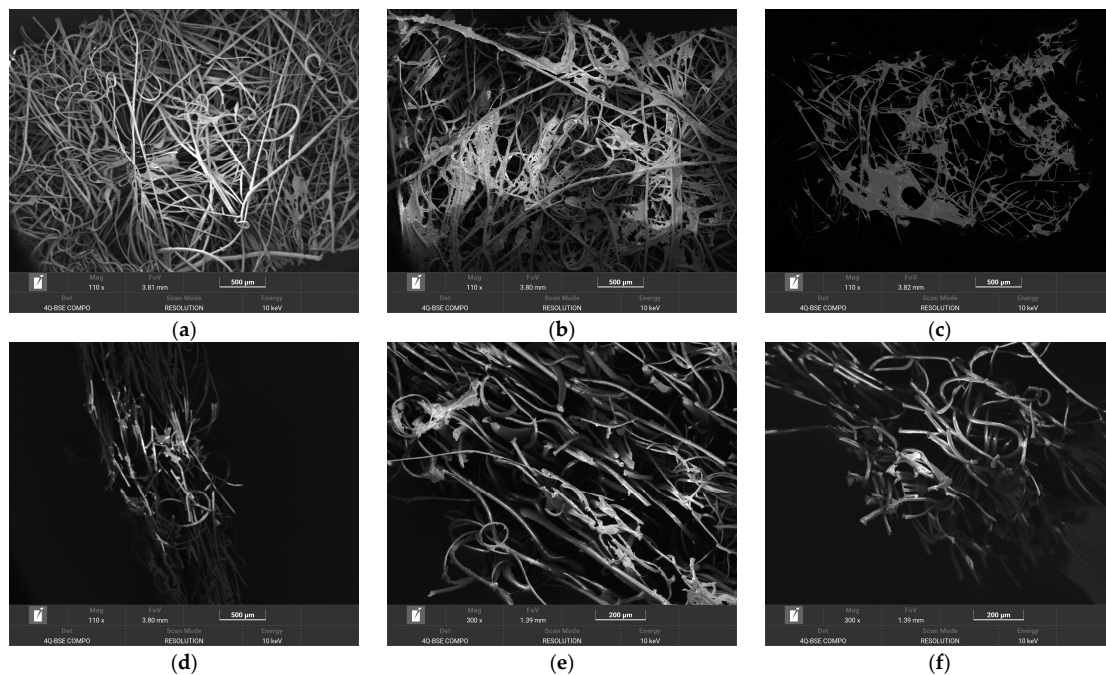


Figure 13. SEM images for the GT120—S4: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

The following figures show the results found for the GT300. In Figure 14, the top view (Figure 14a–c) shows an initial biofilm formation, with the presence of microorganisms dispersed throughout the surface of the geotextile, with greater accumulation in the middle and edge regions. The structure of the mesh is still visible and there are no significant signs of clogging. The cross-section reveals a thin layer of biomass, mainly in the edge region, indicating the beginning of microbial colonization. Comparing qualitatively, it can be said that, for the sample chosen for the SEM, the GT300 presents a higher concentration of microorganisms than the GT120 for the time tested.

In Figure 15, for the 40 days of operation, the growth of the biofilm is more evident in all regions, with a denser coverage of the mesh, mainly for the central region that did not previously present with the formation of biofilms. In the cross-section, it is also possible to observe some agglomerations, albeit small, within the geotextile mesh, which leads to the understanding that the biofilm formed by microorganisms is able to attach itself better to the GT300 than to the GT120 due to the density of the mesh.

In Figure 16, after 60 days of operation, the biofilm density continues to increase, covering a large part of the geotextile surface. The structure of the geotextile begins to be less visible due to the microbial coverage. In the cross-section, the distribution of microorganisms is more uniform. In Figure 17, after 80 days of operation, the biofilm almost completely covers the geotextile surface in all the regions that were tested. Qualitatively, clogging is

evident, especially in the middle and edge regions, where the biomass concentration is highest. A continuous increase in biofilm growth was observed over time, with the greatest accumulation occurring at 80 days, as expected.

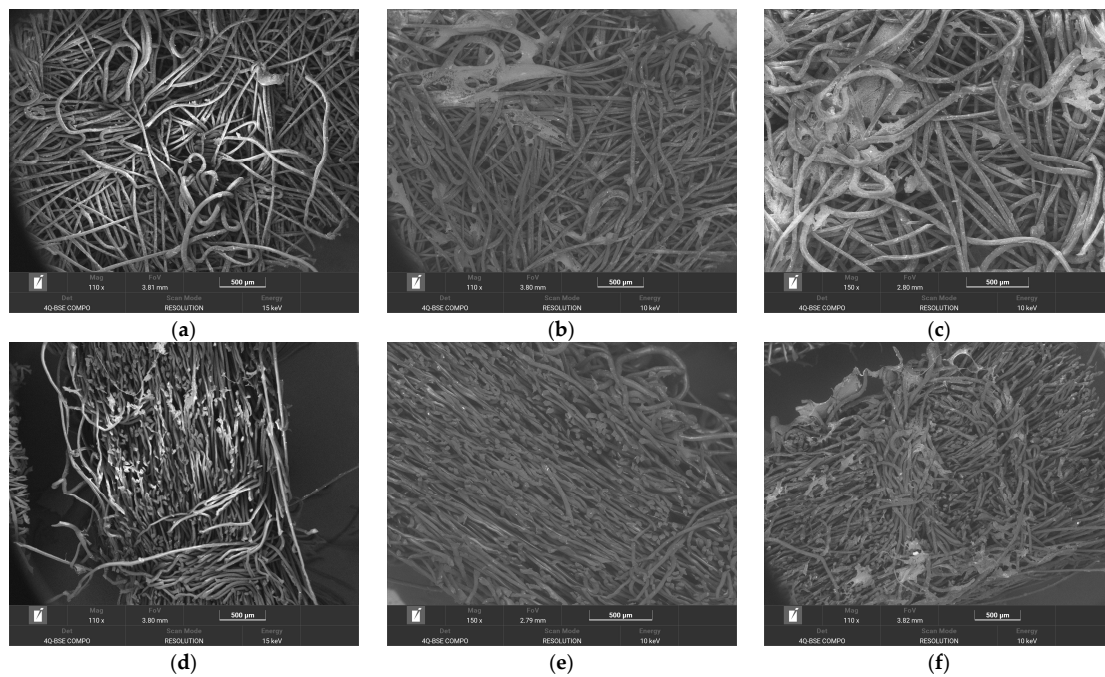


Figure 14. SEM images for the GT300—S1: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

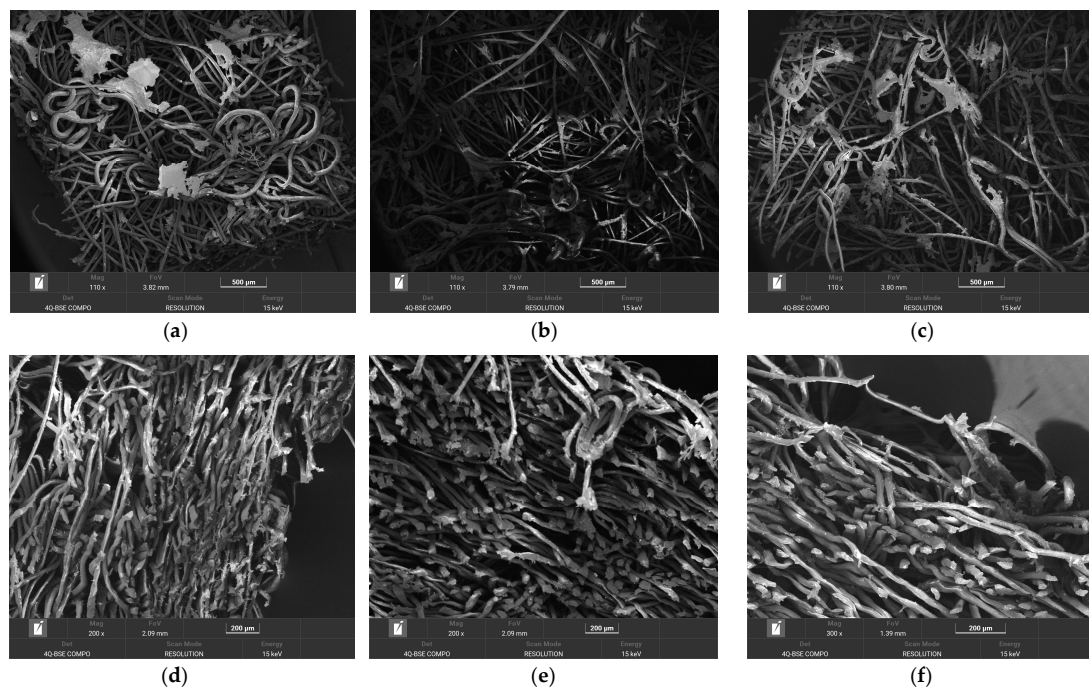


Figure 15. SEM images for the GT300—S2: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

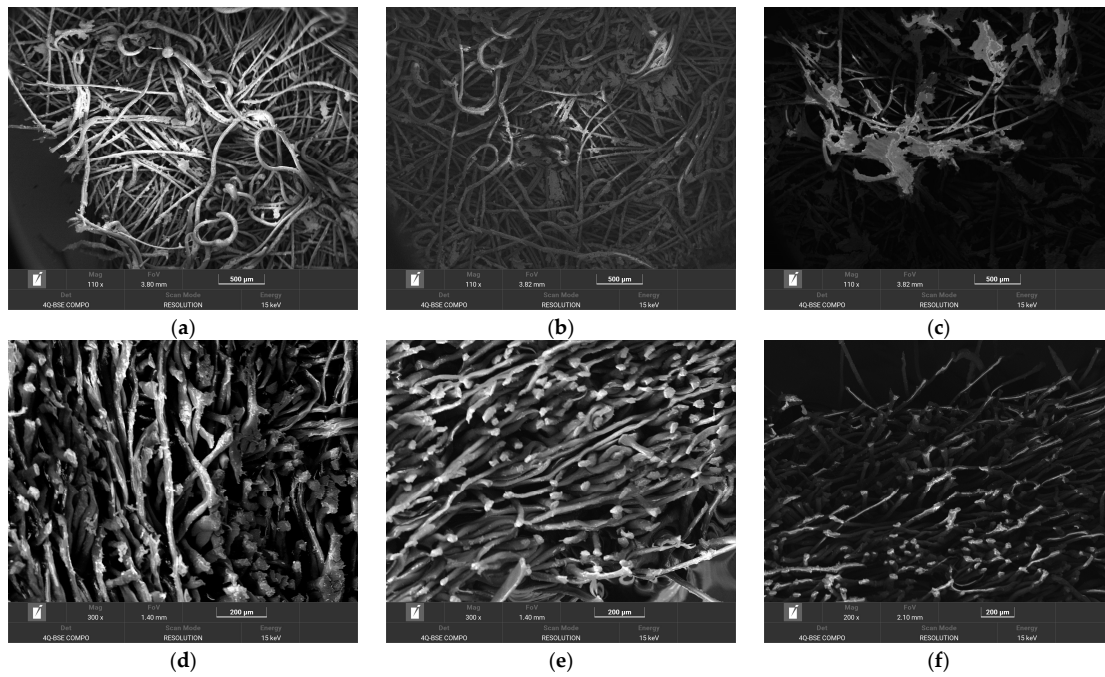


Figure 16. SEM images for the GT300—S3: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

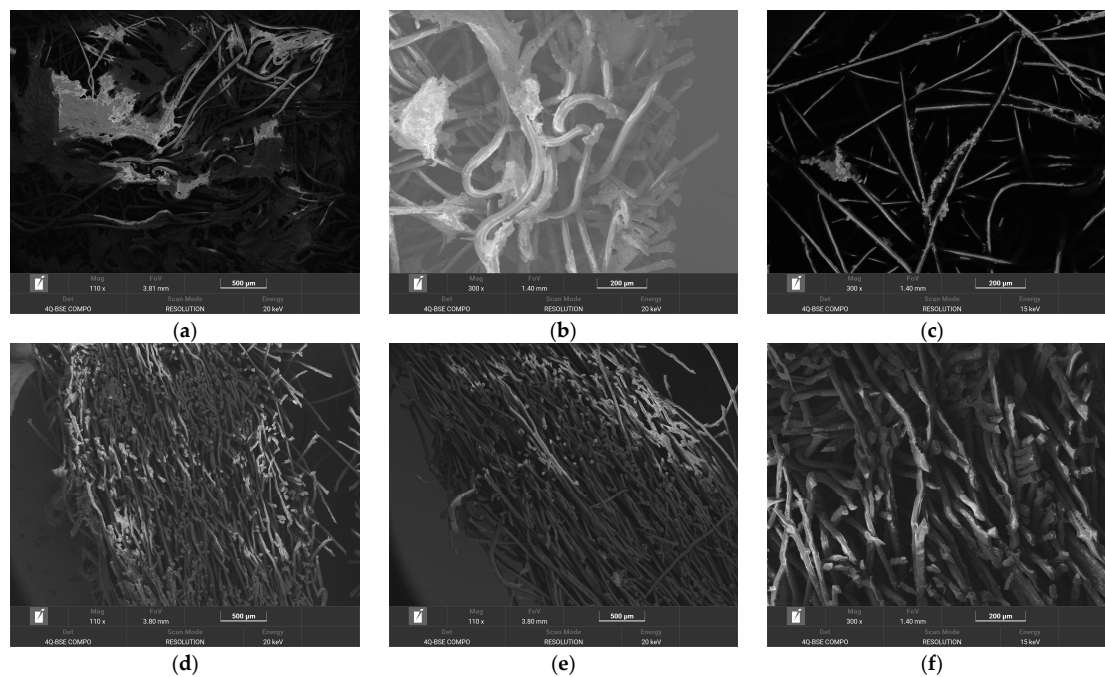


Figure 17. SEM images for the GT300—S4: (a) top view of the center, (b) top view of the middle, (c) top view of the edge, (d) cross-sectional view of the center, (e) cross-sectional view of the middle, (f) cross-sectional view of the edge.

In general, GT120 presents the first signs of clogging on the surface of the geotextile in S4, indicating that in the future, with a greater occurrence of flow and greater development of the geotextile, clogging by blinding may occur, which is the complete blockage of the surface pores. In the cross-section images, it was not possible to identify the presence of microorganisms infiltrated within the geotextile mesh, which suggests that internal clogging has not yet occurred, remaining restricted to the surface. This factor can be explained by the small thickness of the filter mesh.

On the other hand, in GT300, three distinct clogging mechanisms were observed: first, blinding on the surface, similar to that observed in GT120, which indicates an initial blockage of the external pores; second, the formation of biofilms between the geotextile fibers, which may compromise permeability over time; and third, the punctual formation of clogging, where the biofilm develops in specific areas, potentially creating zones with possible resistance to flow.

On the other hand, it was also observed that the biofilm, up to this point, was not able to resist the flow of water, mainly in the central region, which suggests that the biofilm has not yet reached sufficient thickness or density to cause a significant obstruction in the flow. Until this resistance is achieved, the biofilm remains functional and effective in the treatment of wastewater, promoting the removal of contaminants without compromising the permeability of the geotextile. This behavior indicates that the system is at a stage in which the biofilm offers benefits in the degradation of organic matter and nutrients present in the wastewater, without presenting the problems associated with severe clogging. This evidences a momentary equilibrium in which the biofilm contributes positively to the treatment process, while its influence on the permeability of the material is minimal.

4. Discussion

Geotextiles are an innovative solution for wastewater treatment, especially when integrated with biofilms to remove impurities. The ability of these materials to support the growth of microbial communities provides a hybrid approach that combines physical filtration with biological treatment [10,19]. This combination not only increases the efficiency of organic matter and nutrient removal, but also allows for the creation of more compact and adaptable systems compared to conventional technologies. This flexibility is especially relevant in urban and industrial applications, where space and operating costs are critical factors.

In Portugal, innovations in wastewater treatment have focused on the development of sustainable and efficient technologies, aligned with European guidelines for environmental management and circular economy. The country has invested in advanced treatment systems, such as constructed wetlands, membrane biological reactors (MBR), and resource recovery technologies, including nutrients and water for reuse [6–8,38]. The use of geotextiles in wastewater treatment has also gained attention, especially in constructed wetland systems and filtration applications for wastewater remediation in urban and rural areas.

The study presented demonstrates the significant potential of geotextiles in wastewater treatment systems. The results, in agreement with the existing literature, highlight the dual functionality of geotextiles: acting as a filter medium and support for the growth of biofilms capable of removing contaminants. The results show that the GT300 geotextile, characterized by greater grammage and density, outperformed GT120. Biofilm growth was more robust and consistent in GT300, resulting in higher pollutant removal efficiencies. These data corroborate studies such as those by [30,31], which emphasize that a larger surface area and substrate availability increase microbial colonization and activity. The higher mesh density of GT300 provided an optimized space for biofilm adhesion, allowing the establishment of a robust microbial community that is efficient in pollutant degradation.

The study controlled critical parameters, such as pH, temperature, and dissolved oxygen, to ensure optimal conditions for microbial activity. Stable pH values (7–8) and DO levels (3–4 mg/L) supported the aerobic metabolism of microorganisms, essential for the efficient removal of organic matter and nutrients. These findings corroborate studies by [14,28,33,36,37], which identified these parameters as determinants for microbial efficiency in biofilm systems.

This study represents the initial phase of a broader research project, focusing on evaluating the performance of nonwoven geotextiles as substrates for biofilm formation and their role in wastewater treatment. By isolating the phenomenon of biological clogging from other forms, such as physical or chemical clogging, this research provides an approach to understanding the interplay between biofilm development, permeability, and nutrient removal. Unlike previous studies that often treat clogging as a unified phenomenon, this investigation directly addresses the impact of biological clogging, highlighting its significant role in system functionality and treatment efficiency.

Future studies will delve deeper into the characterization of biofilms, including microbiological analyses, to identify microorganisms, assess their viability, and understand their specific contributions to treatment processes. Such analyses will complement the current findings, providing a more comprehensive understanding of the biological mechanisms and their implications for system design. Moreover, extending operational duration, testing geotextiles with varying compositions, and integrating advanced imaging techniques, such as tracer testing, will enhance the insights gained here. Together, these efforts aim to optimize geotextile-based filtration systems and further the field of environmental engineering by addressing critical gaps in the detailed analysis of biological clogging dynamics.

5. Conclusions

Regarding the behavior of microorganisms' fixation on geotextile filters for wastewater treatment, the main conclusions were as follows:

- Hydraulic Performance Stability: Over the 80-day experimental period, the GT120 and GT300 geotextiles exhibited minimal permeability fluctuations, indicating that biological clogging was negligible, thereby maintaining the hydraulic efficiency of the materials.
- Biofilm Growth Dynamics: The biofilm developed consistently and more robustly on the GT300 geotextile, attributed to its higher grammage and mesh density, which provided an optimized substrate for microbial adhesion and metabolic activity.
- Efficiency in Pollutant Removal: The GT300 demonstrated superior performance in removing contaminants, achieving removal rates of up to 80% for organic matter, 40% for ammoniacal nitrogen, and 31% for phosphorus. This enhanced efficiency was linked to its greater capacity to support biomass growth.
- System Stabilization: The GT300 achieved equilibrium in pollutant removal efficiency more rapidly (stabilizing after 10 cycles for COD and 3 cycles for NH₄-N), whereas the GT120 required an extended period to reach steady-state conditions.
- Impact of Biological Clogging: While early signs of clogging were observed, particularly in the GT300, these did not significantly affect permeability or the effectiveness of treatment, indicating a functional equilibrium between biofilm development and hydraulic performance.
- Environmental Suitability: Operating conditions, including pH (7–8), conductivity (800–900 μ S/cm), dissolved oxygen levels (3–4 mg/L), and temperature (18–24 °C), were conducive to microbial growth and the associated biological processes critical for contaminant removal.
- Clogging Mechanisms Identified: In the GT300, three distinct clogging processes were noted: surface occlusion (blinding), inter-fiber biofilm accumulation, and localized clogging. Despite these mechanisms, hydraulic flow remained largely unaffected, affirming the operational viability of the system. These observations indicate that GT300, due to its denser structure, may be more effective in processes that require a greater removal of contaminants and biofilm development, although bioclogging was not a limiting factor during the studied period.

- Long-term testing is needed to assess biofilm behavior in relation to wastewater treatment and clogging, allowing for a greater understanding of how biofilm evolves and stabilizes over time. These studies can reveal the ability of the biofilm to maintain its treatment efficiency over extended cycles and determine at what point clogging begins to negatively affect geotextile permeability. In addition, long-term testing can identify the durability of the system, and the frequency of maintenance required to ensure continued efficient wastewater treatment.

In general terms, the main distinction between these two materials lies in their structural properties, such as pore size, thickness, and surface area, which can significantly impact their performance in wastewater treatment systems. Understanding these differences allows for a more targeted approach in material selection based on the specific requirements of the wastewater treatment system, including factors such as the type of contaminants, required treatment efficiency, and flow rates. By selecting the appropriate geotextile, treatment processes can be optimized for microbial activity and hydraulic performance, ultimately improving the overall effectiveness of the treatment system.

Author Contributions: Conceptualization, M.V.M., A.A. and V.C.; methodology, M.V.M., L.M., J.S., A.A. and V.C.; software, M.V.M.; validation, M.V.M., A.A. and V.C.; formal analysis, M.V.M., A.A. and V.C.; investigation, M.V.M.; resources, A.A. and V.C.; data curation, M.V.M., L.M., J.S., A.A. and V.C.; writing—original draft preparation, M.V.M. and A.A.; writing—review and editing, M.V.M., L.M., J.S., A.A. and V.C.; visualization, M.V.M., L.M., J.S., A.A. and V.C.; supervision, A.A. and V.C.; project administration, M.V.M., A.A. and V.C.; funding acquisition, A.A. and V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This work was supported by the GeoBioTec Research Unit through the strategic projects UIDB/04035/2020 (<https://doi.org/10.54499/UIDB/04035/2020>) and UIDP/04035/2020 (<https://doi.org/10.54499/UIDP/04035/2020>), from Fundação para a Ciência e a Tecnologia (FCT), IP/MCTES through national funds (PIDDAC). The authors would like to thank the Geosciences Department of the University of Aveiro for the SEM images.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tanasa, F.; Nechifor, M.; Ignat, M.-E.; Teaca, C.-A. Geotextiles—A Versatile Tool for Environmental Sensitive Applications in Geotechnical Engineering. *Textiles* **2022**, *2*, 189–208. [[CrossRef](#)]
2. Mohamed, M.A.; Fouad, H.A.; Hefny, R.M. Rotating Biological Contactor Wastewater Treatment Using Geotextiles, Sugarcane Straw and Steel Cylinder for Green Areas Irrigation. *Egyptian J. Chem.* **2022**, *65*, 59–72. [[CrossRef](#)]
3. Ricau, M.; String, G.; Lantagne, D. Laboratory Efficacy of a Woven Geotextile, Nonwoven Geotextile, and Nylon Mesh in Dewatering and Filtering Simulant Fecal Sludge and Field Effectiveness of a Nonwoven Geotextile Geobag in Bangladesh. *J. Environ. Eng.* **2024**, *151*, 04024074. [[CrossRef](#)]
4. Lopes, M.G.; Barroso, M.; Neves, J. *Geossintéticos em Engenharia Civil*, 1st ed.; Comissão Portuguesa de Geossintéticos: Lisboa, Portugal, 2020; pp. 1–400. [[CrossRef](#)]
5. Fleming, I.R.; Rowe, R.K. Laboratory studies of clogging of landfill leachate collection and drainage systems. *Can. Geotech. J.* **2004**, *41*, 134–153. [[CrossRef](#)]
6. Morais, M.V.; Marchiori, L.; Albuquerque, A.; Cavaleiro, V. Analysis of permeability variation and biofilm growth in non-woven geotextiles filter barriers in contact with wastewater. In Proceedings of the 9th International Congress on Environmental Geotechnics, Chania, Greece, 25–28 June 2023. [[CrossRef](#)]

7. Morais, M.V.; Marchiori, L.; Albuquerque, A.; Cavaleiro, V. Physical Methods and Scanning Electron Microscopy for Evaluation of Bioclogging in Geotextiles. In *Testing and Experimentation in Civil Engineering*; Springer: Cham, Switzerland, 2023; Volume 4, pp. 203–211. [\[CrossRef\]](#)
8. Morais, M.V.; Marchiori, L.; Sátiro, J.; Albuquerque, A.; Cavaleiro, V. Evaluation of biofilm adhesion and development in nonwoven geotextile in contact with wastewater. In Proceedings of the 12th International Conference on Geosynthetics, Rome, Italy, 17–21 September 2023. [\[CrossRef\]](#)
9. Revathi, H.U.; Sadashiva, M. Treatment of Domestic Wastewater Using Geotextile as a Filter Media. *Int. Res. J. Eng. Technol.* **2016**, *3*, 1632–1637.
10. Yaman, C.; Rehman, S.; Ahmad, Y.; Kucukaga, Y.; Pala, B.; AlRushaid, N.; Hassan, S.; Yaman, A. Community Structure of Bacteria and Archaea Associated with Geotextile Filters in Anaerobic Bioreactor Landfills. *Processes* **2021**, *9*, 1377. [\[CrossRef\]](#)
11. Pereira, A.C.; Mulligan, C.N.; Veetil, D.P.; Bhat, S. An In-Situ Geotextile Filtration Method for Suspended Solids Attenuation and Algae Suppression in a Canadian Eutrophic Lake. *Water* **2023**, *15*, 441. [\[CrossRef\]](#)
12. Yaman, C.; Martin, J.P.; Korkut, E.N. Geotextile Biofilters for Wastewater Treatment. In Proceedings of the North American Geosynthetics Society, Las Vegas, NV, USA, 14–16 December 2005.
13. Yaman, C.; Aga, O. Multi-Layer Geotextile-Plastic Particle Water Treatment. Patent Application Publication U.S. 2021/0070640, 11 March 2021.
14. Yaman, C. Improvement of leachate quality and waste stabilization in pilot-scale bioreactor landfills containing geotextile filters and sewage sludge. *Desalination Water Treat.* **2019**, *158*, 41–58. [\[CrossRef\]](#)
15. Albuquerque, A. Contribuição Para o Estudo da Remoção de Residuais de Carbono em Filtros Biológicos de Leito Imerso e Fluxo Descendente. Ph.D. Thesis, University of Beira Interior, Covilhã, Portugal, 2003.
16. Palmeira, E. Fatores Condicionantes do Comportamento de Filtros Geotêxteis. In Proceedings of the 4º Simpósio Brasileiro de Geossintéticos, Porto Alegre, Brazil, 19–23 May 2003.
17. Vieira, J.L.; Abramento, M.; Campos, M.V.W. Experimental study of clogging in drainage systems. In Proceedings of the 9th International Conference on Geosynthetics, Guarujá, Brazil, 22–28 May 2010.
18. Miszkowska, A.; Lenart, S.; Koda, E. Laboratory tests of artificial clogging of nonwoven geotextiles. In Proceedings of the 6th European Geosynthetics Conference, Ljubljana, Slovenia, 25–28 September 2016.
19. Silva, J.L.V.; Lodi, P.C. Evaluation of Superficial and Internal Clogging of Geotextiles. *Int. J. Civ. Eng.* **2020**, *18*, 1125–1137. [\[CrossRef\]](#)
20. Remigio, A.F.N. Estudo da Colmatação Biológica de Sistemas Filtros-Drenantes Sintéticos de Obras de Disposição de Resíduos Domésticos Urbanos Sob Condições Anaeróbias. Ph.D. Thesis, University of Brasília, Distrito Federal, Brazil, 2006.
21. Palmeira, E.M.; Remigio, A.F.N.; Ramos, M.L.G.; Bernardes, R.S. A study on biological clogging of nonwoven geotextiles under leachate flow. *Geotext. Geomembr.* **2008**, *26*, 205–219. [\[CrossRef\]](#)
22. ASTM D-1987; Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters. ASTM International: West Conshohocken, PA, USA, 2018.
23. EN ISO 9864; Geosynthetics—Test Method for the Determination of Mass Per Unit Area of Geotextiles and Geotextile-Related Products. International Standard: Geneva, Switzerland, 2005.
24. EN ISO 12958; Geotextiles and Geotextile-Related Products—Determination of Water Flow Capacity in Their Plane. International Standard: Geneva, Switzerland, 2020.
25. EN ISO 9863-1; Geosynthetics—Determination of Thickness at Specified Pressures. Part 1: Single Layers. International Standard: Geneva, Switzerland, 2016.
26. EN ISO 10319; Geosynthetics—Wide-Width Tensile Test. International Standard: Geneva, Switzerland, 2015.
27. EN ISO 12956; Geotextiles and Geotextile-Related Products—Determination of the Characteristic Opening Size. International Standard: Geneva, Switzerland, 2019.
28. Albuquerque, A.; Gonzalez-Martínez, A.; Osorio, F. Effect of aeration on steady-state conditions in non- and partially aerated low-loaded biofilter. *Int. J. Environ. Sci. Technol.* **2012**, *9*, 395–408. [\[CrossRef\]](#)
29. Abbasi, B.; Ta, H.X.; Muhunthan, B.; Ramezani, S.; Abu-Lail, N.; Kwon, T.-H. Modeling of Permeability Reduction in Bioclogged Porous Sediments. *Geotech. Geoenviron. Eng.* **2018**, *144*, 04018016. [\[CrossRef\]](#)
30. Dreszer, C.; Vrouwenvelder, J.; Paulitsch-Fuchs, A.; Zwijnenburg, A.; Kruithof, J.; Flemming, H.-C. Hydraulic resistance of biofilms. *J. Membr. Sci.* **2013**, *429*, 436–447. [\[CrossRef\]](#)
31. Flemming, H.-C.; Wingender, J.; Szewzyk, U. *Biofilm Highlights*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2011; Volume 5, pp. 1–244. [\[CrossRef\]](#)
32. Vrouwenvelder, J.S.; Graf von der Schulenburg, D.; Kruithof, J.C.; Johns, M.L.; van Loosdrecht, M.C.M. Biofouling of spiral-wound nanofiltration and reverse osmosis membranes: A feed spacer problem. *Water Res.* **2009**, *43*, 583–594. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Zhao, R.; Wang, X.; Chen, X.; Liu, Y. Impacts of different aged landfill leachate on PVC corrosion. *Environ. Sci. Pollut. Res.* **2019**, *26*, 18256–18266. [\[CrossRef\]](#) [\[PubMed\]](#)

34. Silva, W. Avaliação da Toxicidade em Lixiviados de Aterro Sanitário Tratados Eletroquimicamente. Master Thesis, University of Beira Interior, Covilhã, Portugal, 2018.
35. Noerfitriyani, E.; Hartono, D.M.; Moersidik, S.S.; Gusniani, I. Leachate characterization and performance evaluation of leachate treatment plant in Cipayung landfill, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *106*, 012086. [[CrossRef](#)]
36. Albuquerque, A.; Oliveira, J.; Semitela, S.; Amaral, L. Influence of bed media characteristics on ammonia and nitrate removal in shallow horizontal subsurface flow constructed wetlands. *Bioresour. Technol.* **2009**, *100*, 6269–6277. [[CrossRef](#)] [[PubMed](#)]
37. Albuquerque, A.; Oliveira, J.; Semitela, S.; Amaral, L. Evaluation of the effectiveness of horizontal subsurface flow constructed wetlands for different media. *J. Environ. Sci.* **2010**, *22*, 820–825. [[CrossRef](#)] [[PubMed](#)]
38. Sátiro, J.; Neto, A.G.S.; Marinho, T.; Sales, M.; Marinho, I.; Kato, M.T.; Simões, R.; Albuquerque, A.; Florencio, L. The Role of the Microalgae–Bacteria Consortium in Biomass Formation and Its Application in Wastewater Treatment Systems: A Comprehensive Review. *Appl. Sci.* **2024**, *14*, 6083. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.