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Use of Meltblown Nonwoven Fabric Filter for Stormwater Runoff Treatment

Jaime A. Cárdenas Sánchez [1], Hunter Szewczyk [2], Judy Assaad [1], Carlos Zimeri [3], Eunkyoung Shim [3], Xiaomeng Fang [3] and Kyana R. L. Young [1,2,4,*]

1 Department of Biology, Wake Forest University, 1834 Wake Forest Road, Winston-Salem, NC 27109, USA
2 Department of Engineering, Wake Forest University, 455 Vine Street, Winston-Salem, NC 27101, USA
3 Department of Textile Engineering, Chemistry and Science, North Carolina State University, 1020 Main Campus Drive, Raleigh, NC 27606, USA
4 Center for Functional Materials, Wake Forest University, Winston-Salem, NC 27109, USA
* Correspondence: youngk@wfu.edu; Tel.: +1-336-702-1965

Abstract: Anthropogenic activities (e.g., rural urbanization) play major roles in preventing the achievement of sustainable water quality, where eutrophication—the exacerbation of increase in nutrient concentrations combined with warmer temperatures and lower light availability, leading to the dense growth of plant life depleting the amount of available oxygen and killing aquatic life—remains a major challenge for surface water bodies. Filtration mechanisms, with a wide range of applicability, capture common waterborne pathogens as small as 0.1–20.0 µm (bacteria, cysts, spores) and 0.001–0.100 µm (protein, viruses, endotoxins) through the process of microfiltration and ultrafiltration. This study follows the premise of using a designed water flow-through system, with meltblown nonwoven fabrics to measure its performance to capture water contaminant constituents of surface water contamination and eutrophication: total coliforms, nitrate, and orthophosphate. The achieved fabric filtration mechanism showed capture of total coliforms (59%), nitrate (51%), and orthophosphate (46%). The current study provides an alternative solution to more common and traditional water treatment technologies, such as chlorine and ozone disinfection, which (1) introduces disinfection or treatment byproducts and (2) cannot adapt to the permanent changing conditions and newer environmental challenges.

Keywords: meltblown nonwoven; microfiltration; water treatment; eutrophication; and climate change

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1. Introduction

There are ~844 million people worldwide lacking access to safe drinking water, where 159 million of them rely on surface water as their main supply [1]. The United Nations (UN) established the Sustainable Development Goals to address poverty, inequality, health, justice, and protect the planet. Goals 6 and 13 specifically address the need to ensure sustainable and accessible water management of water sanitation and taking action to current climate change consequences, respectively; calls for countries to ensure these goals are met by 2030 prove the urgency for equitable access to safe and affordable drinking water [2]. Controlling the effects of anthropogenic activities, (e.g., rural urbanization) is one mechanism that plays a major role in attempting the achievement of sustainable water quality, where eutrophication—high nutrient concentrations combined with warmer temperatures and lower light availability leading to dense growth of plant life—remains as one of its major challenges. In understanding the impact of climate change on water quality, there is a need for adaptable and ease of use water treatment solutions.

Point sources of water pollution are composed of wastewater effluent, runoff leachate from waste disposal sites, runoff from animal feedlots, runoff from mines, storm sewer outfalls, and combined sewer outfalls. Non-point sources, on the other hand, are runoff from agriculture lands, runoff from pasture and range, and atmospheric deposition over a water source [3]. Stormwater runoff, a naturally occurring source of pollution due to its nutrient-rich and microbially dense runoff, can be classified as point or non-point source of pollution depending on its origin from a location. Stormwater runoff control can be ambiguous and its subsequent impacts are underestimated; it exists as a pathway to introduce eutrophication-causing nutrients and microbial communities into receiving bodies of water [4].

The need to treat stormwater runoff is imperative and acquires a determinant role for water security. Understanding the variety of treatment technologies will provide the baseline guidance on how to address stormwater runoff chemical and microbial composition. Among the different treatment techniques explored are photodegradation, distillation, active sludge, bioretention ponds, bioswales, coagulation, and biodegrading. Filtration is also widely recognized as a promising alternative due to its cost-effectiveness and modular characteristics. Its main mechanism for contaminant removal relies on size exclusion (sieving), although adsorption contributes to the overall efficiency as well. Clogging is challenge to use filtration as a treatment mechanism for stormwater runoff. Due to the small target particle size, sustained flow rate is desired to ensure flow through the filtering membranes using high water pressures, thus, increasing cost of operation and employment of multiple stages of pre-treatment [5]. Looking to overcome such limitations, we have studied the use of meltblown nonwoven fabrics as a simple non-point treatment technology.

Meltblown nonwoven fabrics are a low-cost (1.76 and 2.31 USD/m^2) alternative to microfiltration membranes; its unique formation process in which a polymer is transformed into fibers within the range of 1–10 μm provides the fabric with a high surface area. Moreover, the fabric can act as carriers for the addition of adsorptive material to improve filtration performance and selectivity of the mechanism, making it ideal for non-point source runoff, and potentially leading to increased financial returns due to higher efficiency [6]. A wide range of adsorbent materials, such as granular-activated carbon (GAC), molecular sieves, activated alumina, pillared clays, silica gels, synthetic polymers, zeolites, aluminosilicate zeolites, zirconia, and metal-organic frameworks, can be introduced into meltblown nonwoven structure and offer engineered chemical/physical functionalities [7]. The lack of fundamental knowledge required to develop and improve water purification devices, based on textile structures, is an ongoing challenge in this field [8]. The repercussions of climate change, where eutrophicated surface water sources—increased demand and competition for available oxygen under high concentrations of nutrients- promote the occurrence of harmful algal blooms (HABs), compromising the access to safe, drinking water in communities; traditional drinking water plants are not commonly designed to remove HABs. The economic consequences of HABs have been well documented, and highlight, increased costs associated with drinking water treatment, maintaining positive public health, and surface water restoration, with the subsequent impact of significant losses in property values, commercial fishing, tourism, and recreation [9]. Hence, the importance in developing and improving new treatment technologies while testing the technologies under real-world conditions.

High Rock Lake, located in North Carolina (United States), is a highly studied lake due to its historic eutrophic conditions and failure to meet national water quality standards established by the United States Environmental Protection Agency [10]. As a result, a water quality monitoring campaign is being carried out by the North Carolina Department of Environmental Quality (NCDEQ) to measure water quality parameters: turbidity (cloudiness of water), chlorophyll-a (algal growth), and dissolved oxygen (amount of oxygen available for plants and aquatic life). Regulating bodies have focused on reducing point source discharges in the environment, providing the opportunity of novel treatment alternatives to improve water quality from stormwater runoff discharge to the lake's tributaries.

This following study was conducted in High Rock Lake and was designed to carry out a strategic water sampling and testing of the meltblown nonwoven fabric for the capture of nutrients and microbes such as nitrates, reactive phosphorus, and total coliforms. The changes of concentrations of all parameters before and after the treatment will determine the efficiency of the flow through system and balance critical competing needs of high flow rate, long filter life, low filter production, and operational cost.

2. Materials and Methods

The meltblown nonwoven fabrics were produced using a lab-scale dual beam meltblown equipment at The Nonwovens Institute (Raleigh, NC, USA). The equipment consists of two meltblown spinning beams, and the processing parameters of each beam can be controlled separately and capable of producing wide ranges of unique meltblown fabric structures [11]. In this experiment, we used biax annular meltblown die blocks [12]. The main beam was placed at the same level as the collector drum so extruded polymer melt strands and hot process air from the main die block travel horizontally and were collected on the drum at 32 cm die to collector distance (DCD). The second beam was placed 40° above, and fibers extruded from the second beam will be entangled with fiber streams from the main beam forming meltblown fabrics. For both die blocks, die temperature, and hot processing air were kept constant at 220 and 210 °C, respectively. Metocene® 650 W Polypropylene (PP; LyondellBasell, The Netherlands; melt flow rate: 500 g/10 min; density: 0.91 g/cm^3) was used as the raw material. The fiber diameter of samples were modified by varying polymer throughput to 0.1, 0.135, 0.17 g/hole/min (ghm) for PPDual-S, PPDual-M, and PPDual-L at a constant process air pressure of 55.2 kPa (Table 1). The speeds of drum collector were adjusted to achieve a similar basis weight of three samples.

Table 1. Physical properties of meltblown nonwoven fabrics Polypropylene Dual fiber Small (PPDual-S), Polypropylene Dual fiber Medium (PPDual-M), Polypropylene Dual fiber Large (PPDual-L).

Process Conditions			Structural Analysis Results				
Sample ID	Polymer Throughput (ghm)	Collector Drum Speed (m/min)	Total Basis Weight (gsm)	Thickness (μm)	Solidity (%)	Mean Flow Pore Diameter (μm)	Bubble Point * (μm)
PPDual-S	0.10	1.20	117.20 ± 1.64	820.20 ± 10.68	15.70	12.48 ± 1.75	22.92 ± 0.54
PPDual-M	0.14	1.90	108.20 ± 0.84	578.60 ± 14.68	20.60	11.51 ± 0.44	23.33 ± 0.42
PPDual-L	0.17	2.20	121.40 ± 0.55	576.00 ± 12.89	23.20	13.38 ± 0.53	27.00 ± 0.79

* Largest pore.

The Phenom XL SEM microscope with thermionic source (CeB6) and 160–200,000× magnification (Thermo Fisher Scientific Inc., Waltham, MA, USA) was used to observe meltblown web structures. The basis weight of the samples and thickness were measured according to the ASTM D3776 and ASTM D1777, respectively. Five replicas per sample for basis weight and ten replicas per samples for thickness were tested, and average and standard deviations were reported. Fabric solidity (i.e., fiber volume fraction (SVF); S_f) was used to evaluate the structural compactness of the meltblown fabrics using the following Equation:

$$S_f = \frac{m}{T \times \rho} \times \mathbf{100}\ (\%),$$

where m is the sample weight, T is the sample thickness, and ρ is the density of PP (=0.91 g/m^3).

A capillary flow porometer (CFP-1100-Ax; Porous Materials, Inc., Ithaca, NY, USA), was used to measure the mean flow pore diameter and bubble point pore diameter (diameter for largest pore). Three replicas per sample were tested.

For implementation of the technology at impaired water bodies, it was imperative to conduct initial lab-scale testing. A baseline sampling event was carried out to determine the location of tributary entry ports that serve as "hot spots"–significantly higher contaminated area in comparison to its surrounding region—for the introduction of nutrient loadings and microbial loadings to High Rock Lake. The existence of poultry farms near High Rock

Lake can act as relevant sources of contamination by means of the use of fertilizers that are carried and loaded in stormwater runoff [13].

Following North Carolina's Department of Environmental Quality current water sampling campaign, seven exact locations from their campaign were selected plus five more where higher chlorophyll-a and bacterial concentrations are expected. The latter five sampling locations are Cove 1, Cove 2, Cove 3, Skipjack Marina, and Boat Ramp and Boat Ramp Access, see Figure 1.

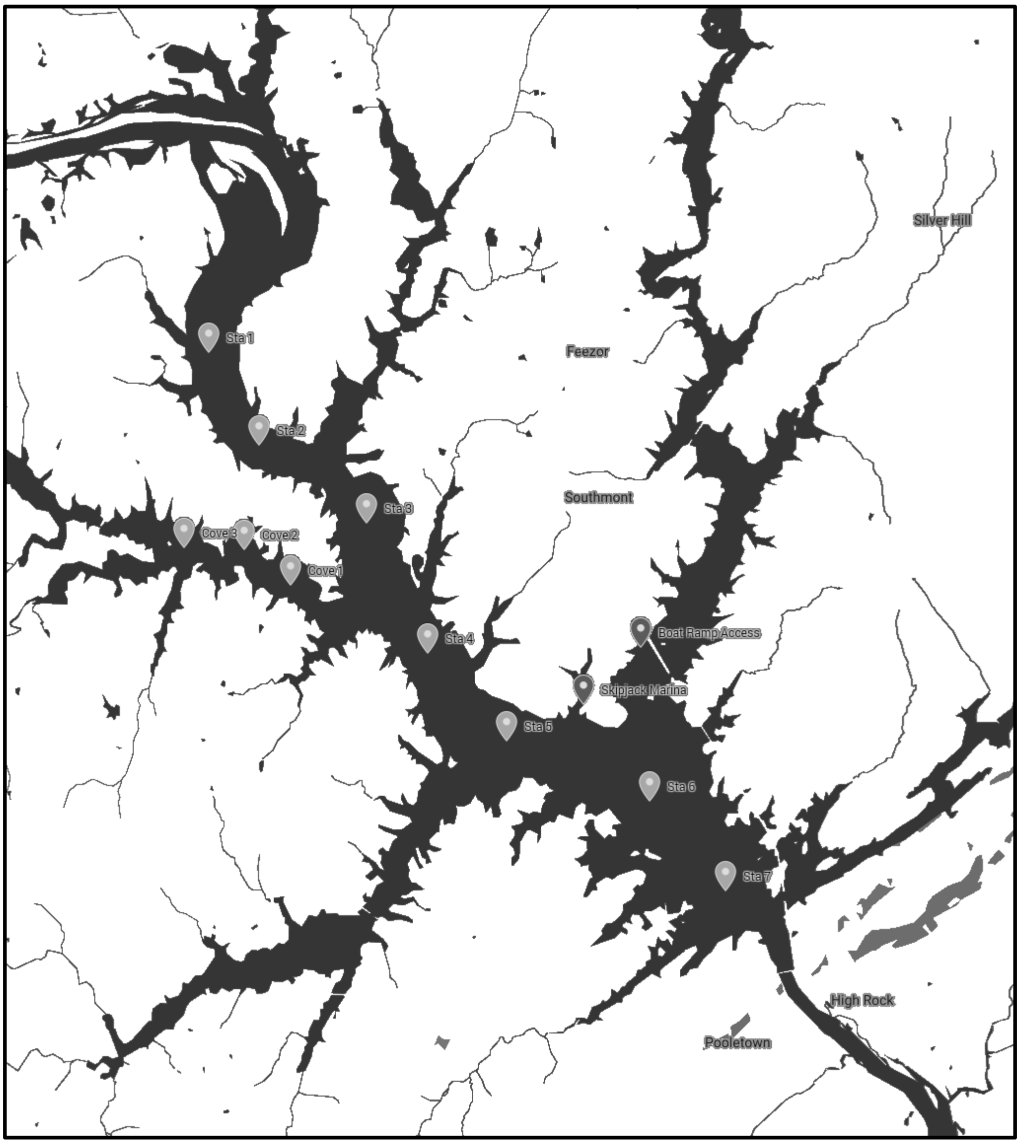


Figure 1. High Rock Lake, North Carolina. Sampling points of interest.

The collection of samples was conducted during the summer season of 2022 measuring water quality parameters such as total coliforms and *E. coli*, nitrate, orthophosphate, turbidity, chlorophyll-a, total suspended solids, and total dissolved solids with standard analytical methods 9223B, 4500-N, 4500-P, 180.1, 445.0, 2540 D, and 2540 C, respectively. The soluble conditions of the experiment meant the dissolved forms for either nitrogen or phosphorus are the concern of the research; therefore, nitrate and orthophosphate are the ions to be measured [14].

To analyze the effect of fiber diameter size for contaminant removal and test the efficiency of meltblown nonwoven fabrics as a physical barrier, a vertical flow-through experiment was conducted on three different fiber diameter sizes of polypropylene meltblown nonwovens controlled by polymer throughput (Table 1).

Accordingly, Milli-Q (18.2 Ω, 25 °C) water served as negative control and spiked samples from High Rock Lakes served as the positive control. Water samples (500 mL) were of 100 mL of sample water from High Rock Lake's Skipjack Marina Station (n = 3) and stored at 4 °C before experimentation. Samples were used for experimentation when room temperature (25 °C) was achieved. A Pall magnetic filtration funnel system (Pall Corporation, Port Washington, NY, USA) was used to hold the nonwoven fabrics in place as flow through system. Filtered samples were analyzed for total coliforms and *E. coli* using Standard Method 9223B, while nitrate and orthophosphate concentrations were measured using Standard Methods 4500-N and 4500-P, respectively [15].

Filtration performance was assessed by comparing the influent and effluent concentration by each one of the meltblown nonwoven fabrics according to [16] and using the following equation:

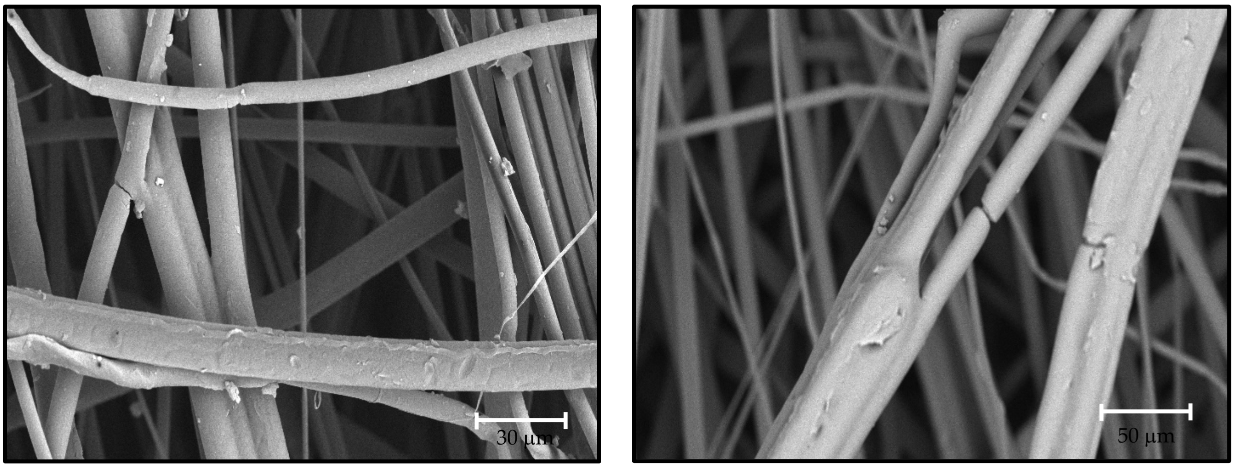
$$\textbf{Removal percentage} = \left(\frac{\boldsymbol{N_0 - N_F}}{\boldsymbol{N_0}}\right) \times \mathbf{100\%},$$

where $\boldsymbol{N_0}$ is the filtration system influent concentration and $\boldsymbol{N_F}$ is the filtration system effluent. The data were processed in Microsoft Excel 365 (Microsoft Corporation, Albuquerque, NM, USA) and tested by one-way ANOVA with 95% of confidence, followed by a Tukey–Kramer test to determine if there is a significant difference between meltblown nonwoven fabric treatments.

3. Results

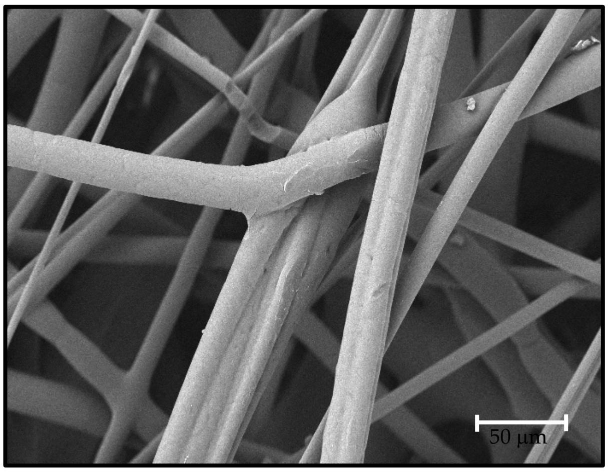
3.1. Nonwoven Fabrics Characterization

Fiber diameter size was controlled by polymer throughput following PPL series > PPM series > PPS series distribution. The representative SEM images of meltblown PP nonwovens are shown in Figure 2a–c. All PP series showed interconnected open structures with randomly oriented and smooth fibers.



(**a**) (**b**)

Figure 2. *Cont.*



(**c**)

Figure 2. Structural surface morphology SEM images of (**a**) PPDual-S; (**b**) PPDual-M; (**c**) PPDual-L.

Increasing polymer throughput tends to decrease the thickness and increase solidity. Solidities of meltblown fabrics are determined by combinations of two contradicting factors—fiber size and interfiber bonding. Low throughput reduces the fiber diameter, and a fabric with finer fibers tends to collapse more easily and form thinner and denser structures as fiber bending rigidity and compression resistance decrease with fiber diameter. However, at lower throughput level, the polymer cools and solidify faster, so it creates open structures with less interfiber bonding at given DCD [17]. In the dual beam setup used in this experiment, where multiple hot polymer melt streams and air are converged, the reduction in polymer solidification rate due to higher throughput is more significant. This effect overcomes the higher fiber bending resistance of larger fibers and creates thinner and denser structures with a high degree of interfiber bonding.

PPDual-L fabric has the largest pore sizes, as expected due to its large fiber size. However, pore sizes of PP-Dual-S and PP-Dual-M do not follow fiber diameter trends. This is because of the huge increase in solidity. In general, pore size is determined by fiber size and solidity. The increasing solidity reduces the space between fibers, so it also reduces the pore diameters [17]. PP-Dual-S has smaller fibers but more open structures, while PP-Dual-M has larger fibers but more dense structures. The combined effect of those two factors results in similar pore sizes between these two samples.

3.2. High Rock Lake's Baseline

Concentration fluctuation among each sampling location for water quality parameters: total coliforms, *E. coli*, nitrate, orthophosphate, turbidity, chlorophyll-a, total suspended solids, and total dissolved solids (Figure 3). Total coliforms, *E. coli*, total suspended solids, and total dissolved solids demonstrated to be greater at the last two sampling locations (South Boat Ramp and Skipjack Marina) corresponding to the sites where higher human activities are present with concentrations of >2419.6 MPN/100 mL, 13.4 MPN/100 mL, 1148 mg/L, and 499,672 mg/L, respectively at South Boat Ramp and > 2419.6 MPN/100 mL, 160.7 MPN/100 mL, 1159 mg/L, and 506,090 mg/L, respectively at Skipjack Marina. However, nitrate, orthophosphate, and turbidity showed higher levels as you move upstream, corroborating the saturation with fertilizers upon the Yadkin River and obtaining 1.13 mg/L, 0.389 mg/L, and 35.5 NTU, respectively at Station 2. Chlorophyll-a on the other hand displayed higher concentrations in enclosed locations such as the three coves and moving downstream indicating an inversely relation with nutrients and turbidity with concentrations of 61.6 mg/L and 48.46 mg/L at Cove 1 and Station 5, respectively. Due to the overall high concentration of Skipjack Marina, water samples from this location were further collected to test the efficiency of the three different types of meltblown nonwoven fabrics.

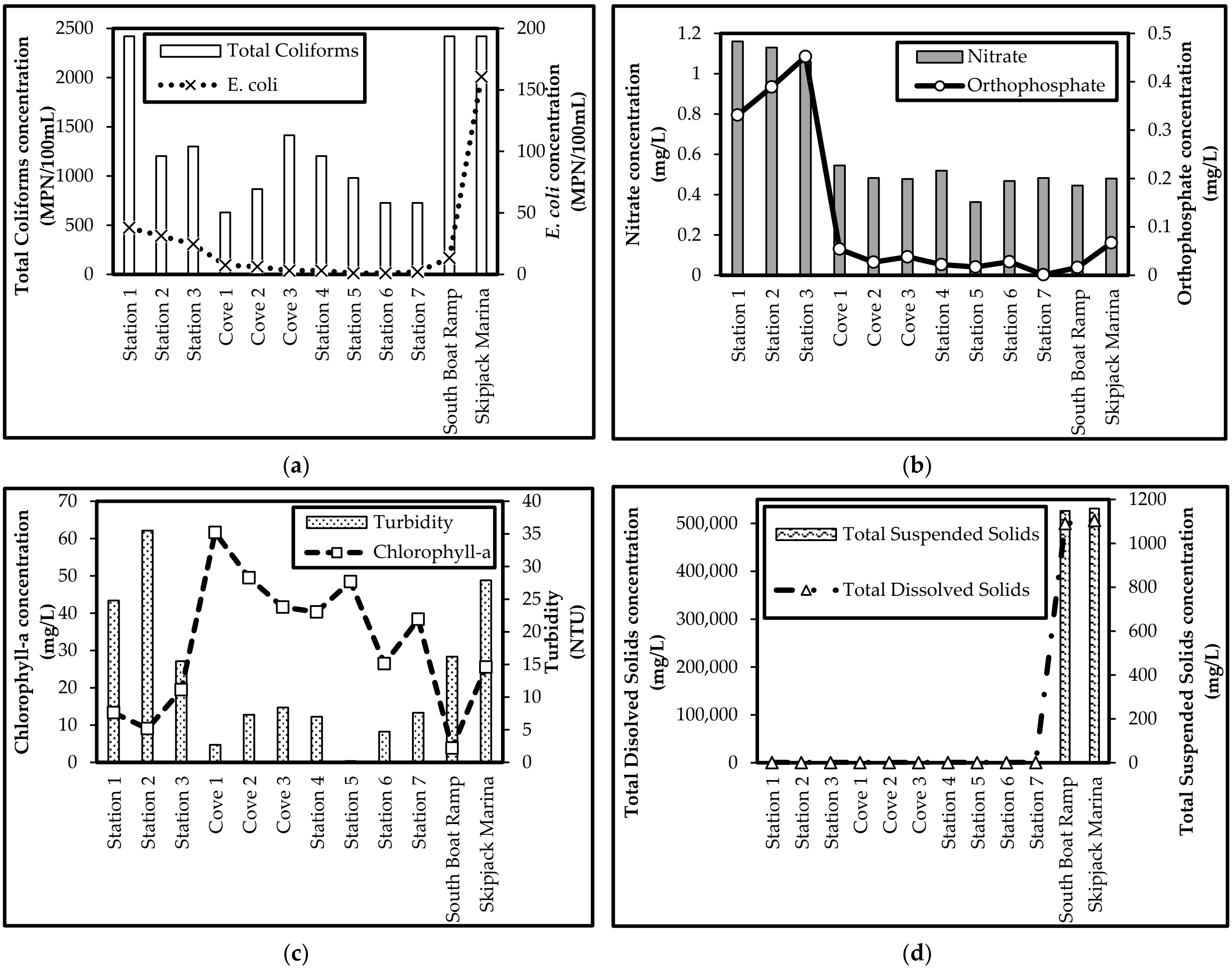


Figure 3. Concentration for each sample point at High Rock Lake during the sampling campaign for (**a**) Total coliforms and *E. coli*; (**b**) Nitrate and orthophosphate; (**c**) Turbidity and Chlorophyll-a; (**d**) Total dissolved solids and total suspended solids.

3.3. Bacterial Removal

Unlike previous baseline samples, *E. coli* concentrations were below detection—one organism per 100 mL—to demonstrate significant reduction when filtered. Nonetheless, total coliforms showed a significant difference between High Rock and PPDual-S with a 60% ± 3% average removal. PPDual-M and PPDual-L had no significant differences with 23% ± 19% and 10% ± 2% average removals, respectively. Removals were significant different between High Rock Lake and PPDual-S, except PPDual-M. Current results indicate, smaller fiber diameter sizes performed better against bacteria than large and even medium for polypropylene meltblown sizes, proving size exclusion still has a greater impact than adsorption (Figure 4).

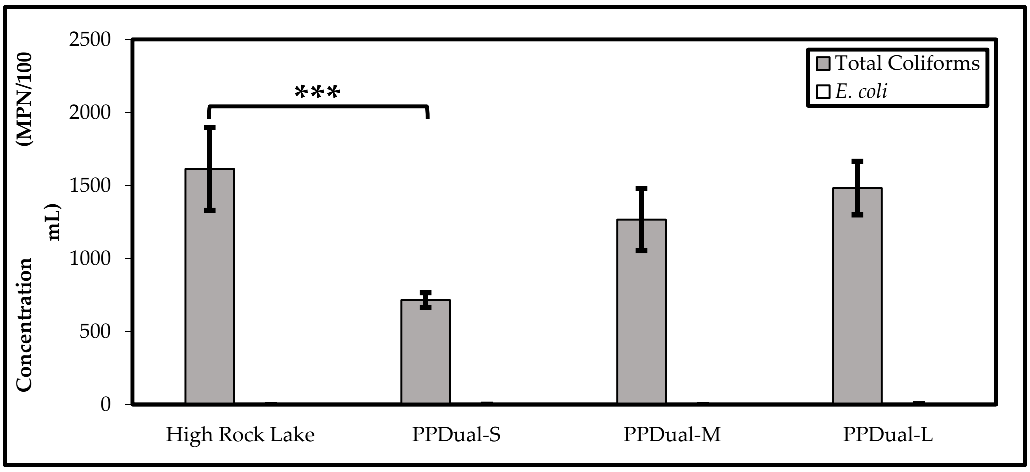


Figure 4. Total coliforms and *E. coli* concentration after PPDual-S, PPDual-M, and PPDual-L filtration. *** Significant difference.

3.4. Nutrient Removal

Significant difference between fabric diameter sizes and baseline showed another behavior (Figure 5). Unlike bacterial removal, both nitrate and orthophosphate demonstrate higher reductions with larger fiber diameter sizes with 51% ± 14% and 46% ± 18% average removals in PPDual-L, respectively. Both removals were significantly different against High Rock Lake and PPDual-S, except PPDual-M. Values were lower in comparison to total coliforms removal, nevertheless, achieved average nitrate reductions of 42% ± 15%, 42% ± 16%, and 51% ± 14% for PPDual-S, PPDual-M, and PPDual-L, respectively. Average orthophosphate percentage removals obtained values of 37% ± 20%, 37% ± 21%, and 46% ± 18% for PPDual-S, PPDual-M, and PPDual-L, respectively. Of note, there is evidence of residual concentration of nitrate during the filtration process. Filtration efficiency for PPDual-S, PPDual-M, and PPDual-L series are shown in Figure 5.

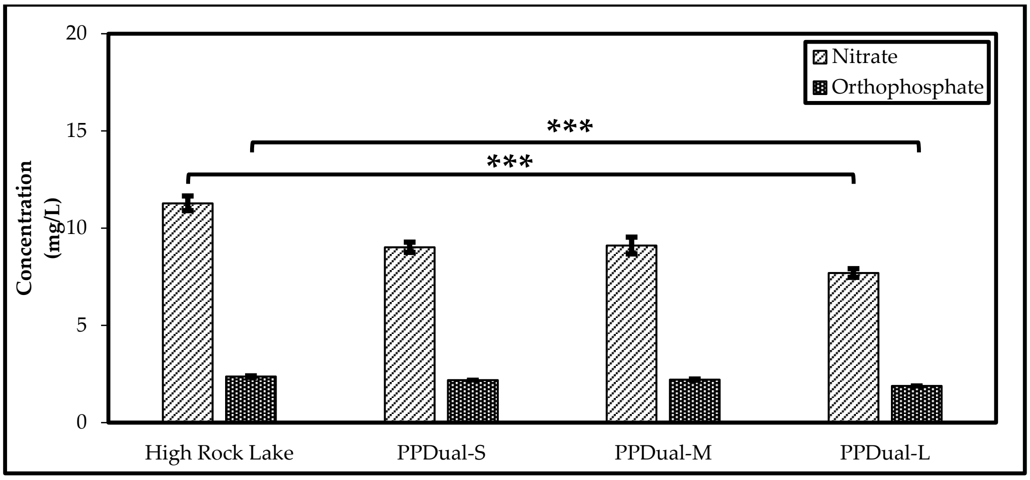


Figure 5. Nitrate and orthophosphate concentration after PPDual-S, PPDual-M, and PPDual-L filtration. *** Significant difference.

4. Discussion

The effects of fiber diameter size proved to be contaminant specific for performance. Eutrophication-contributing nutrients such as nitrate and orthophosphate are keener to be removed by PPDual-L while total coliforms are more likely to be removed by PPDual-S. Even more, PPDual-M filtration never demonstrated significant removals for any contaminant. This emphasizes the importance of sieving and fouling as determinant factors of filtration performance [16]. Microfiltration is commonly used for the removal of bacteria, cysts, and spores as examples, separating species between 0.1 and 20 μm, and with typical operation pressure and flux of 0.2–1 bar and >2 $m^2/(m^2$ day bar), respectively [18]. The soluble nature availability of nitrogen and phosphorus excludes the occurrence of sieving but opens the possibility of other filtration mechanisms, e.g., diffusion, coagulation, electrostatic interaction, and adsorption. Although size exclusion demonstrated higher removals for bacteria considering *E. coli's* size range between 1.0 and 2.0 μm, it obtained significant removals of nutrients due to the combination of coagulation mechanism and electrostatic interaction as shown by [19].

The challenge of a sustained flow rate that allows significant contaminant removal without clogging the filter media still needs to be addressed for future testing. The eutrophic status of High Rock Lake conveys that turbidity is due to high solids concentrations and microbial loads, thus increasing the risk of biofouling. The presence of biofilms can compromise the removal performance but, if handled adequately, may work as another mechanism of nutrient capture [20]. Furthermore, the capacity of meltblown nonwoven fabrics to act as carriers of absorptive/adsorptive material can serve to promote the growth of biofilms; under controlled and beneficial conditions, these biofilms can resemble secondary treatment mechanics and expand the fabric applicability.

These results provide an insight of the promising potential of adding absorptive media (e.g., granular-activated carbon (GAC)) within the fibers of meltblown nonwoven fabrics to enhance chemical/physical functionalities and consequently its performance. For example, meltblown nonwoven fabrics can provide strong beds for absorbent materials, while withstanding high working pressures (≈7 bar) and carry heavy loads of contaminant per unit area (≈150 g m^{-2}) [21]. Storm events water samples with precipitation rates greater than 8.0 mm per hour are expected to add an extra constraint to the fabrics potentially compromising its performance due to their higher nutrient and microbial load, but as well as debris, higher flow rates, humic acids, and other particles that affect the specificity and long-term performance to which initial fabric test designing aimed for [22]. A future prototype design where a vertical flow-through filter composed of multiple different layers will be able to test the adaptability of the treatment technology. Removal is expected to become more specific and superior as water flows through each one of the layers while encountering smaller pore sizes and increased surface area. Initial layers will prevent fouling and fabric damage to protect and complement the inner layers filtration performance. Depending on the results of the prototype, a pilot study at High Rock Lake will be considered for future steps.

The proposed research demonstrated the potential to create a highly adaptable platform that can be optimized based on the context (target contaminants) and needs (water quality standards) of each situation. Meltblown nonwoven fabrics have the potential to reduce the nutrient and microbial loading in stormwater runoff. The understanding of such a novel solution will build the knowledge about the different interactions that occur between filter materials and stormwater runoff contaminants. Furthermore, insights into the potential of nonwoven-based hybrid filters, and the key role of filtration performance, can be acquired to ensure water safety [23]. Access to newer and adaptable treatment technologies capable of managing the rapidly evolving water environment is imperative, as water security continues to gain more traction. Achieving sustainability becomes a unified pursued consensus providing innovative water filtration technologies the opportunity to be the vehicle to achieve Sustainable Development Goals 6 and 13.

5. Conclusions

In conclusion, the fiber diameter size proved to be a determinant variable in the fabric filtering performance showing higher removals for bacteria the smaller they are, while nutrient removal performed better using larger fiber sizes. These results are the product of the different mechanisms involved in filtration, where non-soluble contaminants are prone to be removed by means of absorption while soluble pollutants require other types of mechanisms such as coagulation and electrostatic interaction. Filtering performance average removals of 60% ± 3%, 51% ± 14%, and 46% ± 18% for total coliforms, nitrate, and orthophosphate, respectively. These results not only proved to achieve significant removals for eutrophicated related contaminants but show the capabilities and promising efficiency, modularity, and specificity when acting as carriers of complementing treatment technologies. Therefore, the future steps of his study become present in the form of two directions: (1) the addition of already proven adsorbents, such as granular-activated carbon (GAC) and (2) photocatalysts such as titanium dioxide (TiO_2) and graphitic carbon nitride (g-C_3N_4) for advanced oxidation processes to inactivate waterborne pathogens. Furthermore, in the event of analyzing its durability and layering of multiple fabrics to prevent fouling, the presence of biofilms will be another variable to take into consideration where if treated adequately, it may have the capability to act as a source of secondary treatment improving its efficiency and specificity since it would be expected of those biofilms to be unique to their water source.

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