

Article

Circular Economy Approach to Wastewater Treatment: Reuse of Synthetic Wool Waste as a Filtration Material for Domestic Wastewater Treatment

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Abstract

The treatment of domestic wastewater remains a significant environmental challenge, particularly in rural areas where the construction of sewer systems is often not economically viable. Vertical-flow filters offer an alternative, but traditional filter media are prone to clogging, which justifies the search for new waste-based fillers. The aim of this study was to evaluate the potential of synthetic waste wool as a filter medium and biofilm carrier in vertical filters for domestic wastewater treatment, with particular emphasis on the effects of active bed height and hydraulic loading rate. Experimental models were used to assess the influence of these parameters on treatment performance. High removal efficiencies of organic pollutants and suspended solids were achieved. The filter with an active bed height of 0.9 m that operated at a hydraulic loading rate of 80 dm³·m⁻²·d⁻¹ achieved removal efficiencies of 93.06–97.65% for BOD₅, 86.53–94.20% for COD, 62.69–87.53% for TSS, and 65.73–94.31% for NH₄⁺-N. The most favorable treatment results were obtained for a greater bed depth and lower hydraulic load values. An increase in hydraulic load resulted in a deterioration of the quality of the treated wastewater. The results obtained indicate that waste synthetic wool can serve as a promising filtration material in decentralized wastewater treatment systems, aligning with the principles of the circular economy and the sustainable development of environmental technologies.

Keywords: circular economy; synthetic wool waste; vertical-flow filters

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1. Introduction

1.1. Domestic Wastewater Treatment in Sparsely Populated Areas

Domestic wastewater treatment in rural and sparsely populated areas remains one of the major challenges facing modern water and wastewater management. The construction of centralized sewer systems in such areas is often limited by low population density, significant distances between households, terrain conditions, and high investment and operating costs. Consequently, in areas lacking centralized sewer systems, it is necessary to employ local solutions that enable wastewater treatment directly at the point of generation or in its immediate vicinity [1–3].

Decentralized wastewater treatment systems are currently viewed not as competition for centralized systems, but as a complementary solution—particularly in rural, peripheral areas and regions with limited technical infrastructure [1]. Their importance is also growing in the context of the circular economy. They enable local treatment and potential reuse of water, reduce resource losses and minimize the environmental impact of wastewater. Sahu et al. point out that decentralized wastewater treatment systems can support the transition toward energy-efficient, low-carbon and resource-efficient solutions, particularly when they are designed with local conditions and resource recovery opportunities in mind [1].

This problem is particularly significant in the case of domestic wastewater generated in rural areas, where treatment is often inadequate or carried out using systems with low efficiency. Hong et al. emphasize that improperly treated domestic wastewater from rural areas can lead to water quality degradation, eutrophication, sanitary hazards and adverse effects on human health [2]. For this reason, technologies that are simple, inexpensive, operationally stable, and capable of being used with limited technical support are of particular importance [2,3].

1.2. Vertical-Flow Filters in Decentralized Treatment Systems

Vertical-flow filters play a significant role among the technologies used in on-site and decentralized wastewater treatment systems. They are most commonly used as a secondary treatment stage following a septic tank, where preliminary treatment of wastewater takes place. In a vertical filter, wastewater flows through a layer of filter material, where processes of mechanical filtration and biological treatment occur, including the organic matter biodegradation and nitrogen compound transformations [4–6].

Classic vertical filters are most often filled with sand or a system of sand–gravel layers. The effectiveness of the filters depends on the properties of the filter material, oxygen conditions, the contact time of the wastewater with the bed, the hydraulic load and the degree of biofilm development. The literature indicates that sand filters can achieve high pollutant removal efficiency, provided that appropriate design and operating parameters are maintained [4–7].

This is also confirmed by more recent studies on biofilters and vertical-flow systems. Rasool et al. demonstrated that a pilot-scale sprinkler biofilter with a stone bed, operating under natural conditions, can effectively treat domestic wastewater, achieving an average reduction in COD and BOD₅ of 85.6% and a very high reduction in total suspended solids of 99.9% [8]. In turn, Hamdani et al. demonstrated the high efficiency of a vertical-flow fixed-bed reactor made of plastic in removing organic compounds and nitrogen, achieving a reduction in COD of 93.5%, Kjeldahl nitrogen of 87.5%, and ammonium nitrogen of 55.8% [9]. These results confirm that fixed-bed systems can be an effective solution for biological wastewater treatment if they provide suitable conditions for biomass growth.

1.3. Limitations of Conventional Sand Filters

Despite their high treatment efficiency, conventional sand filters have significant operational limitations. One of the most significant problems is bed clogging, resulting from the retention of suspended solids, the accumulation of organic matter, and the intensive growth of a biological film. This process leads to a reduction in hydraulic permeability, deterioration of wastewater distribution within the bed, and the risk of backwater or surface runoff of wastewater [4–6,10].

The properties of the filter media are critical to the operational stability of the filters. A grain size that is too fine may increase the efficiency of suspended solids retention but simultaneously promote bed clogging. Conversely, a grain size that is too coarse may improve hydraulic permeability but shorten the contact time between wastewater and the

filter material and limit treatment efficiency [4–6]. Therefore, the selection of filter material should simultaneously take into account hydraulic, biological and operational requirements.

The importance of hydraulic properties is confirmed by the research of Khomenko et al., who analyzed the effect of the sediment layer on the performance of vertical gravel filters in constructed wetland systems [10]. The authors demonstrated that the properties of the sediment layer, including dry matter and organic matter content, affect permeability and the ability to withstand hydraulic loading. This means that when designing vertical filters, it is necessary to seek materials that ensure both biofilm development and the maintenance of adequate hydraulic conductivity [10].

1.4. Biofilm and the Immobilization of Microorganisms as the Basis for the Operation of Biological Filters

The effectiveness of biological filters depends largely on the development of biofilm on the surface of the filter material. A biofilm is a structure formed by microorganisms attached to the surface of the support and surrounded by extracellular substances. Within this, processes such as the biodegradation of organic matter, nitrification, partial denitrification, bioaccumulation, and the transformation of selected pollutants take place [11–13].

Microorganism immobilization can occur on the surface of the carrier, within its porous structure, or in the form of cell self-aggregation. In the case of biological filters, immobilization on the surface and within the carrier is of particular importance, as it enables the retention of biomass within the system and limits its washout with the effluent. This mechanism is particularly advantageous in small wastewater treatment systems, where biomass stability directly affects the quality of the treated wastewater [12,14–17].

Saini et al. note that biofilm-based technologies are considered cost-effective and environmentally friendly solutions because they enable the effective removal of pollutants while requiring less energy compared to many conventional technologies [12]. Biofilm can grow on inert, porous, textile and synthetic surfaces, with the properties of the carrier surface influencing the rate of colonization, biofilm stability and microbial activity [12,17,18].

The importance of the carrier structure is confirmed by studies on geotextiles and textile carriers. Yaman demonstrated that geotextiles can function as biofilm filters, combining suspended solids retention, biomass retention and biological wastewater treatment [17]. Lenfeldová et al., on the other hand, indicated that textile biofilm carriers made of polypropylene and polyester fibers can serve as an alternative to conventional plastic carriers used in MBBR reactors. The authors emphasized the importance of the three-dimensional structure, the extensive fiber surface area, and rapid colonization by microorganisms [19].

1.5. Natural, Synthetic and Organic Materials as Filter Media

The literature on biofiltration indicates that the effectiveness of wastewater treatment depends not only on the type of treatment system but also on the type of filter medium used. In conventional systems, the primary materials used are sand, gravel, expanded clay, zeolite, anthracite or activated carbon. These materials are characterized by their availability, stability, and well-established filtration properties; however, their cost, weight, susceptibility to clogging and hydraulic limitations have led to growing interest in alternative materials [4–6,20].

The literature indicates that alternative filter media can include both natural and organic materials as well as synthetic waste materials. This group includes, among others, wood chips, nut shells, straw, plant waste, waste polyurethane foam, PET waste, shred-

ded plastics, geotextiles and textile biofilm carriers [20–27]. These materials can perform mechanical and biological functions, and their use aligns with the principles of the circular economy.

Previous studies have demonstrated the applicability of geotextiles and non-woven textile materials as filter media and biofilm carriers in wastewater treatment systems. However, these materials were typically designed and manufactured specifically for engineering applications [28]. More recent studies have highlighted the need to investigate alternative filter media, including waste-derived and recycled materials, which may contribute to reducing environmental impacts and support the implementation of circular economy principles [29]. Despite the growing interest in waste-based materials, the use of waste synthetic wool originating from the textile industry as a filter bed material in vertical-flow wastewater treatment systems has not been sufficiently investigated. Furthermore, information on the influence of operational parameters, such as bed depth and hydraulic loading rate, on treatment efficiency when using this specific waste material remains limited.

Aslam et al. used waste cotton stalks as a biofilter medium in a spray filter for wastewater treatment. They achieved a reduction in BOD₅ of 69–77%, COD by 65–79%, and TSS by 38–56%, confirming the potential of using inexpensive agricultural waste as a substrate to support biofilm growth [20]. These results demonstrate that waste materials with the appropriate structure can serve as an alternative to conventional mineral media.

1.6. Plastic Waste as Alternative Filter Media

Plastic waste represents a particularly important group of alternative materials. It can serve both as a filter medium and as a biomass carrier while simultaneously enabling the reuse of polymer waste, the management of which remains a significant environmental challenge [18,21–23,30].

In recent years, many authors have investigated the effectiveness of domestic wastewater treatment in a vertical-flow filter filled with plastic waste, including PET flakes [26,27,31,32], recycled PET sponge pieces [33], plastic bottle caps [34,35], plastic straws [36] and waste polyurethane foam [21,37]. The filter with waste polyurethane foam demonstrated the most stable performance, with average reductions in COD, BOD₅, TSS, and NH₄⁺-N of 87.8%, 91.0%, 80.0%, and 74.1%, respectively [21]. These findings demonstrate that waste plastics can serve not only as functional filter media but also as effective biomass carriers in domestic wastewater treatment systems, supporting further investigations into alternative polymer-based filtration materials.

Dacewicz and Grzybowska-Pietras analyzed the properties of polyurethane foams as biomass carriers, taking into account, among other factors, cell structure, porosity, specific surface area, hydrophobicity, biomass adsorption capacity and regenerability [22]. The authors demonstrated that waste polyurethane foams can create favorable conditions for the immobilization of microorganisms and serve as an innovative biomass carrier in domestic wastewater treatment [22].

Another study closely related to the present work was conducted by Chmielowski et al., in which ground-up recycled ABS plastic was used as a filter medium in vertical-flow filters, in on-site wastewater treatment systems [23]. The authors demonstrated that this material is characterized by a large surface area, mechanical strength and chemical inertness. The resulting reduction in BOD₅, COD, and TSS was 94.4%, 77.8%, and 92.8%, respectively [23]. These findings further support the application of recycled plastic waste as filter media in decentralized vertical-flow wastewater treatment systems.

1.7. Textile Waste, Geotextiles and Fibrous Materials

From the perspective of this article, fibrous materials are of particular importance. Waste synthetic wool has a three-dimensional structure that is functionally similar to that of textiles and geotextiles. Materials of this type can provide a large contact surface, numerous sites for microorganism adhesion, retention of suspended solids, and favorable conditions for biofilm formation [17,19,23,24].

Morais et al. analyzed the use of geotextiles as filters in the treatment of synthetic wastewater. The authors demonstrated that geotextiles support biofilm development and can remove organic and biogenic pollutants. The study achieved COD removal of 80%, nitrogen removal of 52%, and phosphorus removal of 36%, with greater effectiveness associated with greater thickness and mass of the geotextile material [24]. These results confirm the importance of the fibrous structure for biomass development and treatment efficiency.

Charchalac Ochoa et al. studied polypropylene geotextiles as pre-filters for greywater prior to sand filtration [25]. The authors demonstrated that the geotextiles removed suspended solids at a rate of 25–85% and COD at a rate of 3–30%, and their use limited the accumulation of organic matter in the upper layer of sand filters. This means that fibrous materials can serve a protective function for conventional sand beds and reduce the risk of their premature clogging [25].

The results of studies on geotextiles and textile media are particularly important for justifying the use of waste synthetic wool. Its fibrous structure may promote biomass retention, biofilm development, and prolonged contact between wastewater and the biologically active surface of the filter medium. At the same time, as a synthetic material, it may exhibit greater durability than some natural and organic materials, which can degrade when in contact with wastewater.

1.8. Waste Plastics and On-Site Sanitation Systems in the Context of the Circular Economy

A new area of research involves the use of waste plastics as biofilter media in on-site sanitation systems. Dorji et al. used shredded waste PET bottles as a biofilter medium for wastewater treatment [26]. The authors noted that shredded PET provides a large surface area for biomass growth while simultaneously helping to reduce the problem of plastic waste. The combination of an UASB reactor for preliminary wastewater treatment and a biofilter resulted in effluent with a COD below 50 mg/L and turbidity below 3 NTU [26].

In subsequent studies, Dorji et al. used strips of waste plastic bottles as a biofilter medium in a sustainable onsite sanitation system [28]. It was demonstrated that this material supported biofilm formation, and the average COD reduction was 70–72%, depending on the width of the strips [27]. These studies confirm that waste plastics can serve a dual role: a technological one—as biofilm carriers—and an environmental one—as secondary raw materials, utilized in accordance with the principles of the circular economy.

1.9. Waste-Derived Materials for Wastewater Treatment

Literature reports indicate that materials derived from biomass, cellulose and coal are also being extensively studied as sorbents for water and wastewater treatment. This approach is significant from the perspective of the circular economy, as it involves transforming waste into functional materials with practical value [30,38]. Although many waste-derived materials are investigated as sorbents, they may also serve as filtration media or biofilm carriers in wastewater treatment systems.

Priya et al. indicate that bioaerogels derived from biomass waste, as materials with high porosity, a developed structure and potential for use in adsorption, filtration, oil–water separation, catalytic processes and biodegradation, can play a significant role in wastewater treatment [30]. The authors emphasized that the valorization of waste biomass

into materials for wastewater treatment can create closed material cycles and support sustainable development [30].

Mishra et al., on the other hand, highlighted the potential of cellulose-based materials in wastewater treatment. They point out their renewability, low cost, biodegradability, hydrophilicity and potential for use as membranes, adsorbents, sorbents and composite materials [38]. Although cellulose-based materials differ from waste synthetic wool, the literature indicates a general trend in wastewater treatment technology away from traditional mineral-based materials toward functional, waste-derived and custom-designed materials, tailored for specific treatment mechanisms [30,38].

1.10. Research Gap

A review of the literature indicates that there is growing interest in the use of alternative and waste materials in domestic wastewater treatment. Previous studies have included, among others, polyurethane foams, PET flakes, shredded ABS plastics, waste plastic bottles, geotextiles, textile carriers, agricultural waste, bioaerogels and cellulose-based materials [20–30]. It has been demonstrated that these materials can serve as filter media, biomass carriers and their use can support the principles of a circular economy.

At the same time, the literature still lacks detailed studies on the use of synthetic waste wool as a filter material and biofilm carrier in vertical-flow filters for domestic wastewater treatment.

This represents a significant gap in research, as this material has a fibrous structure, high porosity, and potential resistance to rapid degradation in a wastewater environment. These characteristics may facilitate the retention of suspended solids, prolong the contact time between wastewater and the filter medium and promote the growth of microorganisms responsible for biological wastewater treatment. This justifies research into waste synthetic wool as a filtration medium and biofilm carrier in decentralized domestic wastewater treatment and forms the basis of this article.

This study aimed to evaluate the potential of using waste synthetic wool as a filtration material and biofilm carrier in the treatment of domestic wastewater in vertical-flow filters. Particular attention was paid to the effectiveness of removing organic pollutants, total suspended solids, and ammonium nitrogen, as well as to the possibility of treating waste synthetic wool as a functional biofilm carrier. This study aligns with the principles of the circular economy, as it involves the reuse of waste synthetic material in wastewater treatment technology.

2. Materials and Methods

2.1. Research Concept

The study was conducted to investigate the potential use of waste synthetic wool as a filter material and biofilm carrier in vertical-flow filters for domestic wastewater treatment. The concept of this study aligns with the principles of the circular economy, as it involves the reuse of waste synthetic material as a functional medium for vertical-flow filters.

The study analyzed the possibility of using waste synthetic wool as an alternative to conventional filtration materials used in wastewater treatment. Particular attention was paid to the fibrous properties of the material, which could facilitate the retention of suspended solids, biofilm growth, and prolong the contact time between wastewater and the filter bed.

The scope of the research included:

- Selection of the most suitable fibrous material;
- Evaluation of the effectiveness of domestic wastewater treatment;

- Analysis of the effect of the active bed depth;
- Analysis of the effect of hydraulic load;
- Evaluation of the functional role of waste synthetic wool in the wastewater treatment process.

The research was conducted in a laboratory setting and constituted a preliminary assessment of the technological potential of waste synthetic wool as a material suitable for use in vertical-flow filters.

2.2. Characteristics of Synthetic Wool Waste

The test material used in the filters was synthetic wool waste in the form of non-siliconized polyester fiber. This material was selected due to its fibrous structure, three-dimensional architecture, porosity, and potential resistance to rapid biological degradation in a wastewater environment. These characteristics may promote:

- The retention of suspended solids and prolonged contact between wastewater and the filter medium;
- The growth of biofilm-forming microorganisms;
- An increase in the contact surface area between wastewater and the material;
- The maintenance of the bed's hydraulic permeability.

The choice of non-siliconized fiber resulted from a prior evaluation of various fibrous materials, including both synthetic and natural materials. The study assumed that waste synthetic wool could simultaneously serve as a filtration material and a biofilm carrier responsible for biological wastewater treatment. Figure 1 presents representative photographs of the waste synthetic wool before operation, during filtration operation, and after the completion of the experiment. The visible accumulation of retained contaminants and biofilm on the filter material is consistent with its function as a filtration medium and a carrier for biological wastewater treatment processes. However, the material presented in Figure 2 represents a local sample collected from the upper part of the filter bed, where the greatest accumulation of biofilm and retained contaminants was visually observed, for SEM analysis. This sample is not intended to characterize the spatial distribution of deposits throughout the entire filter bed.

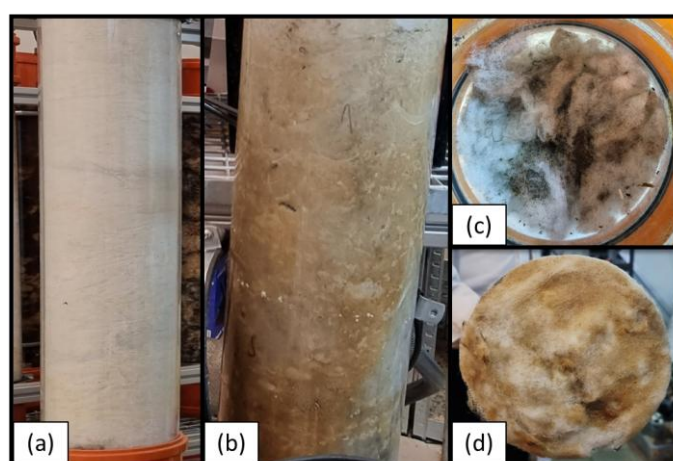


Figure 1. Representative photographs of the waste synthetic wool used as a filtration material: (a) filter bed before operation; (b) filter bed during operation; (c) upper layer of the filter material after operation showing localized accumulation of biofilm and retained solids; (d) lower layer of the filter bed after operation.

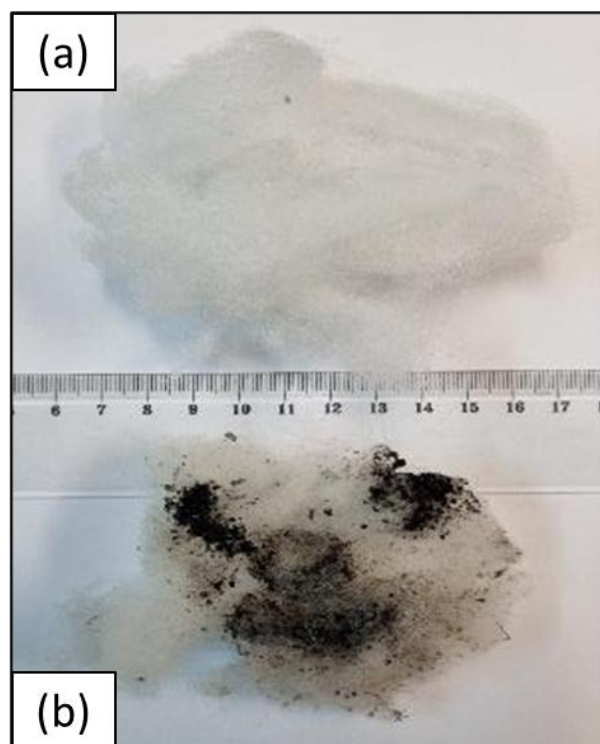


Figure 2. Synthetic wool waste used as filtration material: (a) before operation; (b) after wastewater treatment in the vertical-flow filter.

In addition, to conduct a preliminary assessment of the structural stability of the polyester fibers, scanning electron microscopy (SEM) observations were performed before and after the experiment. Figure 3 shows representative SEM images. In the post-operation image, deposits and biofilm-like structures were observed on the fiber surface. Despite the presence of trapped material, no significant fiber fragmentation or structural degradation was observed during the study.

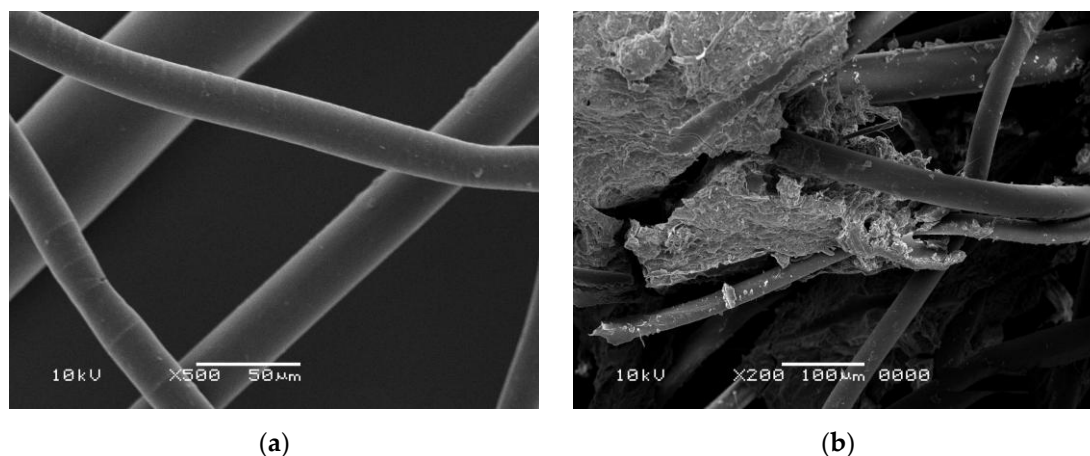


Figure 3. SEM images of synthetic wool fibers before (a) $\times 500$ and after (b) $\times 200$ operation in the vertical-flow filter.

2.3. Wastewater Characteristics

The study utilized domestic wastewater that had been preliminarily treated in a septic tank. This wastewater had a composition typical of domestic wastewater fed into small and decentralized treatment systems. The average characteristics of the septic tank effluent used in the experiments are presented in Table 1. The composition of the wastewater

was comparable in both experimental series, although somewhat higher COD and TSS concentrations were observed during the hydraulic loading rate experiment.

Table 1. Average characteristics of pretreated domestic wastewater supplied to the filters during the bed height (15-month) and hydraulic loading rate (10-month) experiments (mean $\pm$ standard deviation).

Parameter (mg O ₂ ·dm ⁻³)	Bed Height Experiment (n = 15)	Hydraulic Loading Rate Experiment (n = 10)
BOD ₅	564 $\pm$ 218	568 $\pm$ 223
COD	873 $\pm$ 282	1043 $\pm$ 319
TSS	203 $\pm$ 169	347 $\pm$ 216
NH ₄ ⁺ -N	124.7 $\pm$ 9.4	113.4 $\pm$ 7.8

The analysis focused on standard wastewater quality indicators used to assess the effectiveness of biological and mechanical treatment. The following were evaluated:

- Five-day biochemical oxygen demand (BOD₅);
- Chemical oxygen demand (COD);
- Total suspended solids (TSS);
- Ammonium nitrogen (NH₄⁺-N).

The significance of each indicator in the evaluation of the treatment process is presented in Table 2.

Table 2. Main wastewater quality indicators analyzed in the study.

Parameter	Unit	Significance in Treatment Assessment
BOD ₅	mg O ₂ ·dm ⁻³	Assessment of biodegradable organic matter removal
COD	mg O ₂ ·dm ⁻³	Assessment of total organic pollutant removal
TSS	mg·dm ⁻³	Assessment of filtration and solids retention
NH ₄ ⁺ -N	mg·dm ⁻³	Assessment of ammonium nitrogen removal and nitrification potential

2.4. Experimental Setup

The experiments were conducted under laboratory conditions using vertical-flow filter models. The experimental setup consisted of transparent tubular columns made of acrylic glass with an internal diameter of 150 mm and a total height of 1000 mm. The columns operated as independent filters, fed in batches with pre-treated wastewater. The experimental setup reflected the operating principle of filters used as a secondary stage of wastewater treatment following a septic tank. The filters were filled with waste synthetic wool in the form of non-siliconized polyester fiber.

Wastewater was fed onto the upper surface of the bed, from where it flowed with gravity through the filter material. During flow, suspended solids were retained, the wastewater came into contact with the fiber surface, and biological treatment occurred with the participation of microorganisms growing on the filter material. The treated wastewater effluent flowed from the bottom of the column into a collection tank. The filters operated under laboratory conditions that ensured control of basic operating parameters. At the bottom of the column, a wire mesh support was installed to retain the synthetic wool bed while allowing free drainage of the treated wastewater. A simplified conceptual scheme of the experimental vertical-flow filtration system filled with synthetic wool waste is presented in Figure 4.

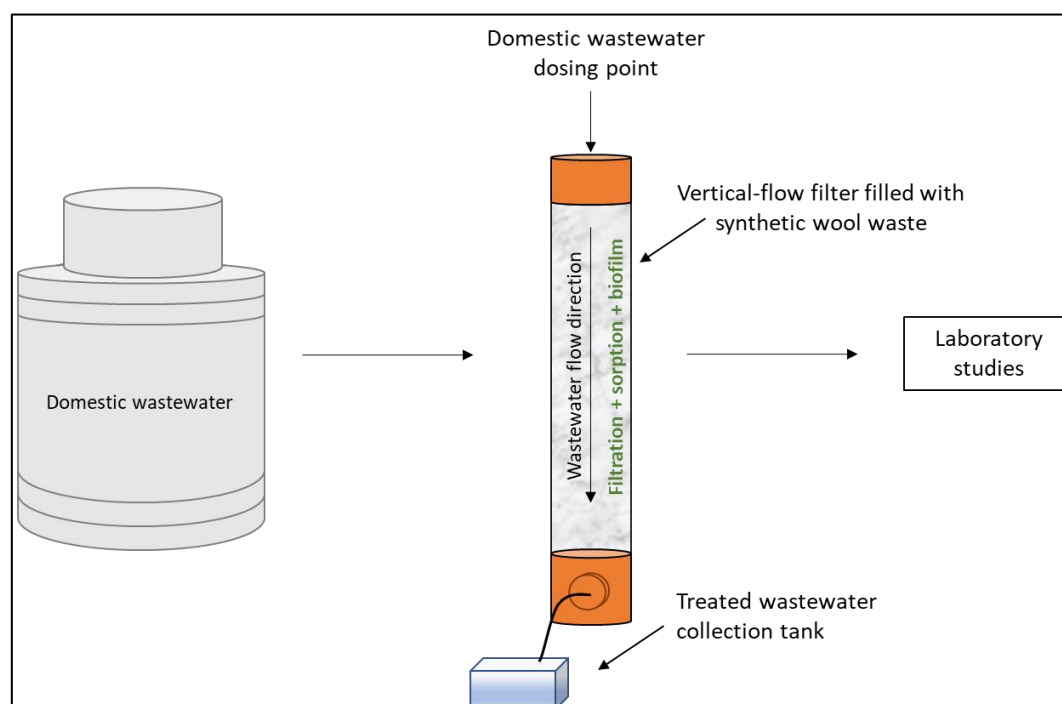


Figure 4. Simplified conceptual scheme of the experimental vertical-flow filtration system filled with synthetic wool waste.

Three bed heights were evaluated in the experiment investigating the effect of bed depth: 0.30, 0.60, and 0.90 m. In the experiment assessing the effect of hydraulic loading rate, the bed height was maintained at 0.90 m. Wastewater was applied at hourly intervals (24 dosing events per day). The volume of each dose was adjusted to achieve the assumed hydraulic loading rates of 40, 80, 120, and 160 $\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, corresponding to approximately 29.5, 58.9, 88.4, and 117.8 mL per dose, respectively. Each experimental variant was represented by a single filter column. Before the start of data collection, a two-week start-up period was applied to allow biofilm development and stabilization of filter operation. Results obtained during this period were excluded from further analysis. The experiment evaluating the effect of active bed height was conducted for 15 months, whereas the experiment evaluating the effect of hydraulic loading rate was conducted for 10 months. Only data collected after the completion of the start-up phase were used to evaluate treatment performance and represent stable operating conditions of the filters. No backwashing, media replacement, or maintenance procedures were performed during the experimental period.

2.5. Operating Conditions

During the study, various operating conditions were analyzed for vertical-flow filters filled with waste synthetic wool. The scope of the study included different active bed heights and various hydraulic load values. The active bed height was considered a parameter influencing:

- The length of the wastewater flow path;
- The contact time between wastewater and the filter medium;
- The surface area available for biofilm growth.

Hydraulic load was analyzed as a parameter determining the intensity of wastewater inflow to the filter and the hydraulic operating conditions of the system.

The study found that the most favorable treatment conditions were achieved with a greater active bed depth and at lower or moderate hydraulic load values. Detailed tech-

nological relationships between filter operating parameters and treatment efficiency are presented in the Results section of this paper.

2.6. Analytical Methods

The quality of wastewater entering and leaving the filters was assessed based on selected physicochemical parameters. Analyses of raw and treated wastewater were performed in accordance with commonly used analytical procedures applied in wastewater testing and treatment technology, in accordance with the relevant standards listed in Table 3.

Table 3. Analytical methods used in the study.

Parameter	Unit	Standard/Method
BOD ₅	mg O ₂ ·dm ⁻³	PN-EN 1899-2:2002 [39] (electrochemical method)
COD	mg O ₂ ·dm ⁻³	PN-ISO 15705:2005 [40] (method using sealed test tubes)
TSS	mg·dm ⁻³	PN-EN 872:2007 [41] (filtration through glass-fibre filters)
NH ₄ ⁺ -N	mg·dm ⁻³	PN-C-04576-4:1994 [42] (Nessler method)

The analytical methods used in this study were based on standardized procedures commonly applied in accredited environmental laboratories in Poland. The PN-EN and PN-ISO standards represent European and international standard methods adopted within the Polish standardization system.

2.7. Calculation of Pollutant Removal Efficiency

Pollutant removal efficiency was calculated based on the concentrations of specific parameters in the influent and effluent wastewater from the filters. Treatment efficiency was expressed as the percentage reduction in a given parameter, according to the following equation:

$$\eta = \frac{C_d - C_o}{C_d} \cdot 100 \quad (1)$$

where

- η —removal efficiency of a given contaminant [%];
- C_d —concentration of the indicator in the influent wastewater [mg·dm⁻³];
- C_o —concentration of the indicator in the effluent wastewater [mg·dm⁻³].

The removal efficiency index was calculated separately for BOD₅, COD, TSS, and NH₄⁺-N. The obtained values allowed for an assessment of the suitability of waste synthetic wool as a filtration material and biologically active biomass carrier in domestic wastewater treatment.

2.8. Statistical Analysis

The research results were analyzed using Statistica 13 (TIBCO Software Inc., Palo Alto, CA, USA) and MS Excel 2019 (Microsoft Corporation, Redmond, WA, USA). Basic descriptive statistics were calculated for the analyzed indicators, including the mean, standard deviation, and ranges of variation.

The statistical significance of differences between the analyzed variants was assessed at a significance level of $\alpha = 0.05$ using appropriate parametric and nonparametric tests. The normality of the distribution was tested for the variables using the Shapiro–Wilk test. In the absence of normality, the nonparametric Kruskal–Wallis test was used. When the

assumptions of normality and homogeneity of variance were met, one-way ANOVA was applied, followed by Tukey's HSD post hoc test.

This article presents analyses focusing on the effectiveness of wastewater treatment using waste synthetic wool. Detailed analyses are presented to the extent necessary for interpreting the results and evaluating the potential of waste synthetic wool as a filter material in domestic wastewater treatment in the Results section.

3. Results

3.1. Selection of Synthetic Wool Waste as a Filter Medium

The first stage of the research aimed to select the fibrous material most suitable as filter medium and a biofilm carrier in vertical-flow filters for domestic wastewater treatment. Four materials were compared in the model: non-siliconized polyester fiber, siliconized polyester fiber, sheep's wool, and woven wool dust. Each material served as a homogeneous filling for a separate filter column with an active height of 0.9 m.

The selection of materials for further research (Table 4) was based on three criteria: treatment efficiency, bed stability, and the material's resistance to degradation when in contact with wastewater.

Table 4. Selection of fibrous materials for application in vertical-flow wastewater filters.

Tested Material	Material Group	Main Observation	Selection Result
Non-siliconized polyester fibre	Synthetic	Favorable treatment performance, stable bed structure, no visible degradation	Selected
Siliconized polyester fibre	Synthetic	Lower treatment efficiency compared with non-siliconized polyester fibre	Rejected
Sheep wool	Natural	Biofilm development possible, but fibre degradation observed during wastewater contact	Rejected
Woven wool dust	Natural	Biomass immobilization possible, but bed stability limited by degradation and reduction in active height	Rejected

A comparison of materials showed that synthetic materials were more suitable for use as filter media in vertical-flow filters than natural materials. Natural wool and woven wool dust could serve as biomass carriers; however, during filter operation, fiber degradation and a reduction in the active bed height were observed, which limited their operational suitability.

Among the synthetic materials, non-siliconized polyester fiber was selected for further research. This material exhibited more favorable operational properties than siliconized polyester fiber and did not undergo the degradation observed in natural materials. Siliconized fiber was rejected due to less favorable values of treated wastewater quality indicators. Consequently, non-siliconized polyester fiber was adopted as the target form of synthetic waste wool for further stages of research.

The choice of this material was also justified by its physical structure. The fibrous and porous structure of the waste synthetic wool could facilitate wastewater flow, the retention of suspended solids, and the colonization of the surface by microorganisms. The irregular arrangement of the fibers increased the contact surface area between the wastewater and the material and created voids within the bed, which could support the simultaneous occurrence of filtration and biological treatment processes.

In this article, the material selection stage is presented to justify the choice of waste synthetic wool for further research. A comprehensive comparison of different natural and synthetic filter materials, together with a detailed assessment of long-term fiber degradation, remains the subject for future research.

3.2. Pollutant Removal Efficiency in Synthetic Wool-Based Vertical-Flow Filters

The use of synthetic waste wool as a filter medium in vertical-flow filters resulted in high efficiency in treating domestic wastewater in terms of key pollution indicators. The reduction in five-day biochemical oxygen demand, chemical oxygen demand, total suspended solids, and ammonium nitrogen was analyzed. These indicators were adopted as the primary parameters for evaluating process efficiency, as they describe both the removal of organic compounds and the retention of suspended solids, as well as conditions conducive to nitrogen transformations. Average pollutant removal efficiencies obtained in the synthetic wool-based filters are presented in Figure 5.

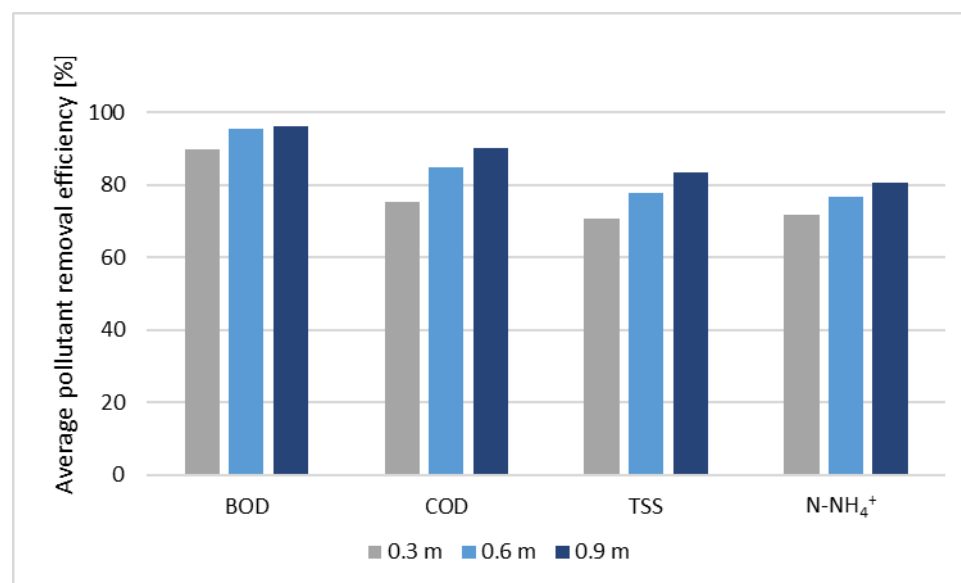


Figure 5. Average pollutant removal efficiencies.

The highest and most stable treatment efficiency was achieved for organic compounds measured as BOD₅ and COD. The BOD₅ removal efficiency ranged from 93.06% to 97.78%, while the COD removal efficiency ranged from 51.22% to 94.20%. Such high values indicate that the synthetic waste wool provided favorable conditions for wastewater contact with the bed surface and promoted the growth of microorganisms responsible for the biological degradation of organic substances.

Lower and more variable removal efficiencies were obtained for total suspended solids. The reduction in this parameter ranged from 29.49% to 95.83%. This variability may result from the nature of the mechanical filtration process, which is highly dependent on hydraulic conditions, the manner of wastewater distribution over the bed surface, the fibrous structure of the material, and the degree of particle retention in the spaces between the fibers. Despite this variability, the results confirm that waste synthetic wool can effectively serve as a filtration material that retains a significant portion of the suspended solids present in pre-treated wastewater.

Significant efficiency was also achieved in the removal of ammonium nitrogen. The reduction in NH₄⁺-N ranged from 62.10% to 94.72%. The wide range of values obtained indicates that nitrogen transformations depended on the filter's operating conditions, particularly the bed depth and hydraulic load. The effective removal of ammonium nitrogen suggests that conditions favorable for the growth of nitrifying microorganisms may have developed in the bed of synthetic waste wool, especially with longer contact time between the wastewater and the bed and moderate hydraulic loading.

The results obtained indicate that waste synthetic wool can play a multifunctional role in the domestic wastewater treatment process. This material acted as a filtration bed

retaining suspended solids and as a biofilm carrier supporting biological treatment processes. Its fibrous structure also provided favorable conditions for wastewater contact with the biologically active surface of the bed. The high efficiency of BOD₅ and COD removal confirms the material's suitability for reducing organic pollutants, while the reduction in ammonium nitrogen indicates its potential for supporting biological processes related to nitrogen transformation.

3.3. Influence of Active Bed Height on Treatment Performance

The active bed height was one of the key parameters affecting the treatment efficiency of domestic wastewater in filters filled with waste synthetic wool. This parameter primarily determined the length of the wastewater flow path through the filter material, the contact time between the wastewater and the fiber surface, and the potential for biofilm development within the bed structure. The tests were conducted at a hydraulic load of 80 dm³·m⁻²·d⁻¹. The effectiveness of reducing individual parameters is presented in Table 5.

Table 5. Descriptive statistics of pollutant removal efficiencies in vertical-flow filters filled with synthetic wool waste depending on active bed height.

Indicator	Statistic	Symbol	Unit	0.9 m	0.6 m	0.3 m
BOD ₅	Mean	$\bar{X}$	[%]	95.77	94.74	89.74
	Median	Me		96.43	95.24	88.24
	Minimum	Min		93.06	90.28	84.44
	Maximum	Max		99.17	97.78	96.67
COD	Mean	$\bar{X}$	[%]	89.26	83.53	75.99
	Median	Me		89.26	83.89	78.78
	Minimum	Min		79.94	74.85	51.22
	Maximum	Max		94.20	90.77	85.61
TSS	Mean	$\bar{X}$	[%]	81.16	74.88	67.42
	Median	Me		80.14	75.93	68.98
	Minimum	Min		62.69	74.85	29.49
	Maximum	Max		95.83	92.36	93.75
NH ₄ ⁺ -N	Mean	$\bar{X}$	[%]	80.90	76.95	71.63
	Median	Me		78.51	73.26	70.83
	Minimum	Min		65.73	62.10	63.71
	Maximum	Max		94.31	94.72	84.40

The results of the study indicated that increasing the active bed depth had a positive effect on the quality of the treated wastewater. A greater bed depth meant longer contact time between the wastewater and the fibrous material, a larger active surface area for retaining suspended solids and more favorable conditions for microorganisms growing on the surface of the fibers. For this reason, the filter with a greater active bed height exhibited higher operational stability and better treatment efficiency compared to variants with a lower bed height. The overall effect of active bed height on treatment efficiency is presented in Table 6.

Table 6. General influence of active bed height on treatment performance.

Active Bed Height	General Effect on the Treatment Process	Assessment
0.3 m	Shorter contact time, smaller active surface, potentially lower treatment stability	Less favorable
0.6 m	Improved contact between wastewater and filter medium	Favorable

0.9 m	Longest contact path, better biofilm development conditions, and higher treatment stability	Most favorable
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The most favorable operating conditions were achieved for a bed with an active height of 0.9 m. This configuration provided the best conditions for the removal of BOD₅, COD, TSS, and NH₄⁺-N. The average removal efficiency for these pollutants was 95.77%, 89.26%, 81.16%, and 80.90%, respectively. It can be assumed that at this bed height, a favorable balance existed between the contact time of the wastewater with the filter material, the contaminant retention capacity, and the availability of oxygen necessary for biological processes, including nitrification.

Changes in bed height observed during the 15-month experimental period are presented in Table 7.

Table 7. Changes in bed height during the 15-month experiment evaluating the effect of bed depth.

Initial Bed Height (m)	Final Bed Height (m)	Reduction (m)	Reduction (%)
0.300	0.285	0.015	5.0
0.600	0.580	0.020	3.3
0.900	0.870	0.030	3.3

During the 15-month experimental period, a slight reduction in bed height was observed. The bed height decreased by approximately 0.015 m, 0.020 m, and 0.030 m for initial bed heights of 0.3, 0.6, and 0.9 m, respectively. No clogging, surface ponding, overflow, deterioration of infiltration, or reduction in hydraulic performance was observed during filter operation.

Shorter bed heights limited the flow path length of the wastewater and reduced the contact time with the filter material. This could lead to a reduction in treatment efficiency, particularly for parameters dependent on biological processes. This applies primarily to ammonium nitrogen, the effective removal of which requires appropriate oxygen conditions, a stable biofilm, and sufficient contact time between the wastewater and the bed.

Statistical analysis showed that the height of the active layer significantly influenced the efficiency of wastewater treatment in vertical-flow filtration systems (Table 8). The Kruskal–Wallis test confirmed the presence of statistically significant differences between the analyzed bed depth variants for all tested wastewater quality indicators, i.e., BOD₅, COD, TSS, and NH₄⁺-N ($p < 0.05$).

Table 8. Summary of the Kruskal–Wallis test results and post hoc multiple comparisons for treated wastewater quality indicators under a hydraulic loading rate of 80 dm³·m^{−2}·d^{−1}.

Parameter	Kruskal–Wallis χ^2	p -Value	Significant Post Hoc Comparisons *
BOD ₅	20.4049	<0.001	0.9 m vs. 0.3 m; 0.6 m vs. 0.3 m
COD	26.3241	<0.001	0.9 m vs. 0.6 m; 0.9 m vs. 0.3 m
TSS	7.6482	0.0218	0.9 m vs. 0.3 m
NH ₄ ⁺ -N	16.1858	<0.001	0.9 m vs. 0.3 m

* Significant pairwise differences identified using Dunn’s post hoc test at $\alpha = 0.05$.

For BOD₅, significant differences were observed between the 0.9 m and 0.3 m variants and the 0.6 m and 0.3 m variants, indicating that biodegradation conditions improve as the height of the active layer increases. A similar relationship was observed for COD, where the highest efficiency in removing organic pollutants was achieved in the 0.9 m variant. These results confirm the beneficial effect of extending the contact time of wastewater with the biofilm and the filter medium.

For total suspended solids (TSS), statistically significant differences occurred only between the 0.9 m and 0.3 m variants, suggesting greater filtration and retention efficiency of suspended solids in the taller bed. Significant differences were also observed between the 0.9 m and 0.3 m variants for ammonium nitrogen ($\text{NH}_4^+\text{-N}$), indicating improved nitrification conditions in the deeper filtration layer.

These results confirm that the active bed depth should be considered one of the key design parameters when designing vertical-flow filters filled with waste synthetic wool. Increasing the height of the active layer had a positive effect on the stability of the treatment process and the efficiency of contaminant removal, with a bed height of 0.9 m proving to be the most effective option.

3.4. Influence of Hydraulic Loading on Treatment Performance

Hydraulic loading was the second key process parameter affecting the treatment efficiency of domestic wastewater in filters filled with waste synthetic wool. This parameter determined the amount of wastewater supplied per unit area of the filter per unit of time, and thus influenced the contact time of the wastewater with the bed, oxygen conditions, retention of suspended solids, and the stability of biological processes. To analyze the effect of hydraulic load, the most effective bed height of 0.9 m was adopted. The results of the experiment are presented in Table 9 and Figure 6.

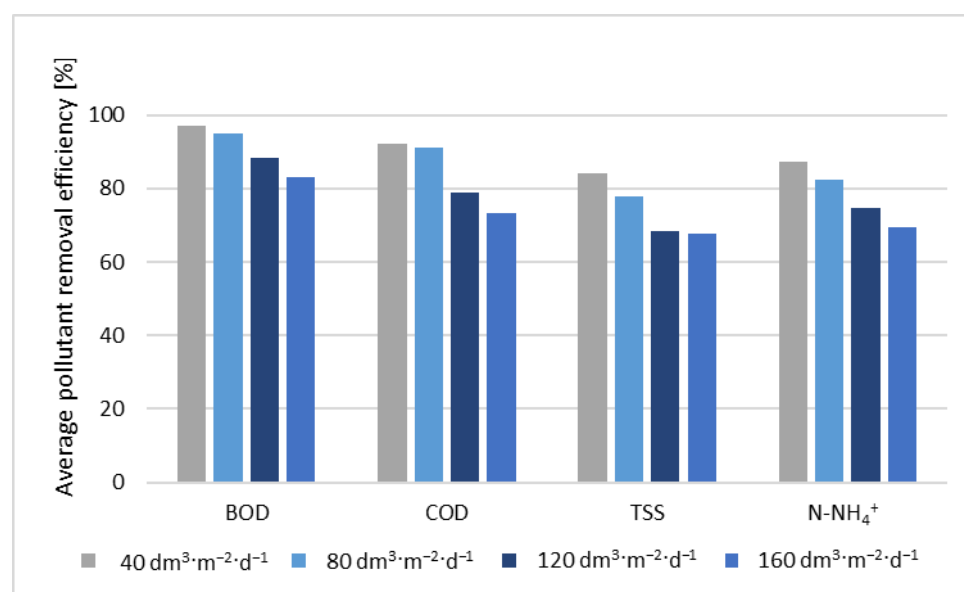


Figure 6. Influence of hydraulic loading on the average pollutant removal efficiency in vertical-flow filters filled with synthetic wool waste.

Table 9. Descriptive statistics of pollutant removal efficiencies under different hydraulic loading conditions in vertical-flow filters filled with synthetic wool waste.

Indicator	Statistic	Symbol	Unit	40 $\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$	80 $\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$	120 $\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$	160 $\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$
BOD ₅	Mean	$\bar{X}$	[%]	97.20	95.11	88.26	83.21
	Median	Me		97.10	94.08	89.97	84.96
	Minimum	Min		96.00	93.06	77.78	70.83
	Maximum	Max		98.86	97.65	93.33	91.11
COD	Mean	$\bar{X}$	[%]	92.06	90.99	79.03	73.36
	Median	Me		92.67	91.95	79.03	76.65
	Minimum	Min		86.23	86.53	66.94	57.99
	Maximum	Max		96.28	94.20	89.39	83.67

TSS	Mean	$\bar{X}$	[%]	84.02	78.02	68.55	67.54
	Median	Me		84.54	79.15	72.17	74.70
	Minimum	Min		76.85	62.69	27.05	13.04
	Maximum	Max		93.00	87.53	89.15	86.05
NH ₄ ⁺ -N	Mean	$\bar{X}$	[%]	87.40	82.43	74.62	69.38
	Median	Me		87.10	78.88	75.23	70.28
	Minimum	Min		77.58	65.73	58.47	55.24
	Maximum	Max		95.53	94.31	85.77	81.30

The results of the study showed that the efficiency of wastewater treatment in filters filled with waste synthetic wool was clearly dependent on the hydraulic loading rate. The best filter operating conditions were observed at a loading rate of 40 dm³·m⁻²·d⁻¹. In this configuration, the highest average removal efficiencies for the analyzed pollution indicators were achieved, amounting to 97.20% for BOD₅, 92.06% for COD, 84.02% for TSS, and 87.40% for NH₄⁺-N. These results indicate that a long wastewater retention time in the bed facilitated both the retention of suspended solids and the intensive course of biological processes related to the decomposition of organic compounds and nitrogen transformations.

A loading rate of 80 dm³·m⁻²·d⁻¹ can be considered an operationally favorable and technologically feasible option. Despite a slight decrease in treatment efficiency compared to the 40 dm³·m⁻²·d⁻¹ option, the filter maintained high operational efficiency. The average removal efficiency for BOD₅ was 95.11%, COD 90.99%, TSS 78.02%, and NH₄⁺-N 82.43%. This variant may be of particular practical significance, as it allows for an increase in the hydraulic capacity of the system while maintaining high-quality treated wastewater.

Increasing the hydraulic load to 120 and 160 dm³·m⁻²·d⁻¹ worsened the filter's operating conditions. For a load of 120 dm³·m⁻²·d⁻¹, the average removal efficiency for BOD₅ dropped to 88.26%, for COD to 79.03%, for TSS to 68.55%, and for NH₄⁺-N to 74.62%. Even lower results were obtained at a loading rate of 160 dm³·m⁻²·d⁻¹, where the average removal efficiency was 83.21% for BOD₅, 73.36% for COD, 67.54% for TSS, and 69.38% for NH₄⁺-N, respectively.

The deterioration in treatment efficiency at higher hydraulic loading rates can be attributed primarily to the reduction in the contact time between the wastewater and the fibrous material. This limited the effectiveness of mechanical filtration and impaired the conditions for the development of the biofilm responsible for biological wastewater treatment.

Ammonium nitrogen removal was particularly sensitive to hydraulic overload. The nitrification process requires sufficiently long wastewater retention time, a stable biofilm, and good oxygen conditions. Under conditions of increased hydraulic loading, oxygenation of the bed and wastewater-biofilm contact could become less favorable, resulting in lower nitrogen transformation efficiency.

A high hydraulic load can also increase the risk of washing out retained contaminants and limit the uniform utilization of the entire filter bed volume. In fibrous filters, it is essential to maintain a balance between hydraulic permeability and the contact time between the wastewater and the fiber surface. Excessively high wastewater flow rates can cause short-circuiting and reduce the effective filtration path. The overall impact of hydraulic load on filter operating conditions and treatment efficiency is presented in Table 10. The summary confirms that as the hydraulic load increased, filtration and biological conditions deteriorated, leading to a reduction in contaminant removal efficiency.

Table 10. General influence of hydraulic loading on treatment performance.

Hydraulic Loading Rate	General Effect on the Treatment Process	Assessment
40 dm ³ ·m ⁻² ·d ⁻¹	Long contact time, favorable filtration and biological conditions	Most favorable
80 dm ³ ·m ⁻² ·d ⁻¹	Good treatment efficiency with higher hydraulic capacity	Favorable/acceptable
120 dm ³ ·m ⁻² ·d ⁻¹	Shorter contact time, possible decrease in treatment stability	Less favorable
160 dm ³ ·m ⁻² ·d ⁻¹	Highest hydraulic stress, increased risk of reduced pollutant removal	Not recommended

To confirm the significance of the observed differences between the analyzed hydraulic loading scenarios, a statistical analysis was performed, the results of which are presented in Table 11.

Table 11. Statistical significance of the influence of hydraulic loading on pollutant removal efficiency.

Indicator	Statistical Test	<i>p</i> -Value	Significant Effect of Hydraulic Loading	Significant Differences Between Hydraulic Loadings
BOD ₅	Kruskal–Wallis	<0.001	Yes	40 vs. 120; 40 vs. 160; 80 vs. 120; 80 vs. 160
COD	Kruskal–Wallis	<0.001	Yes	40 vs. 120; 40 vs. 160; 80 vs. 120; 80 vs. 160
TSS	Kruskal–Wallis	0.0321	Yes	No statistically significant pairwise differences
NH ₄ ⁺ -N	ANOVA	0.000736	Yes	40 vs. 120; 40 vs. 160; 80 vs. 160

The statistical analysis presented in Table 11 confirmed a significant effect of hydraulic load on the removal efficiency of all analyzed pollution indicators. For BOD₅ and COD, very high statistical significance was obtained ($p < 0.001$), indicating that changes in hydraulic load significantly affected the efficiency of organic pollutant removal. A multiple comparison analysis revealed significant differences mainly between the lower hydraulic load values (40 and 80 dm³·m⁻²·d⁻¹) and the higher filter operating variants (120 and 160 dm³·m⁻²·d⁻¹).

For TSS, a significant effect of hydraulic load was also observed ($p = 0.0321$); however, post hoc analysis did not reveal statistically significant differences between individual pairs of hydraulic loads. This may indicate greater variability in the process of retaining suspended solids within the fibrous structure of the bed and greater resistance of the filtration mechanism to changes in hydraulic conditions.

For NH₄⁺-N, a significant effect of hydraulic load was obtained at the $p = 0.000736$ level. Significant differences occurred primarily between the lowest and highest values of hydraulic load, which confirms the high sensitivity of nitrification processes to a reduction in the contact time of wastewater with the bed and a deterioration of oxygen conditions in the filter.

The results obtained confirm that hydraulic loading should be considered a key operating parameter in the design and operation of vertical-flow filters filled with waste synthetic wool. The influence of this parameter was particularly evident in relation to the biological removal of organic compounds and the transformation of ammonium nitrogen. For the analyzed system, a loading of 40 dm³·m⁻²·d⁻¹ resulted in the highest pollutant removal efficiency, while a value of 80 dm³·m⁻²·d⁻¹ may represent a practical compromise between treatment performance and system capacity. Loads of 120 and 160 dm³·m⁻²·d⁻¹ are not recommended as standard operating conditions for the filter, as they may lead to a reduction in treatment efficiency.

In addition to treatment efficiency, changes in bed height were monitored during the hydraulic loading experiment. The observed bed settlement after 10 months of operation is presented in Table 12.

Table 12. Changes in bed height during the 10-month experiment evaluating the effect of hydraulic loading rate.

Hydraulic Loading Rate ($\text{dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Initial Bed Height (m)	Final Bed Height (m)	Reduction (m)	Reduction (%)
40	0.900	0.885	0.015	1.7
80	0.900	0.870	0.030	3.3
120	0.900	0.860	0.040	4.4
160	0.900	0.845	0.055	6.1

As shown in Table 12, bed settlement increased with increasing hydraulic loading rate. Despite the greater reduction in bed height observed at higher loading rates, no clogging, surface ponding, or overflow was observed during filter operation.

3.5. The Functional Role of Synthetic Wool Waste in Wastewater Treatment

These results indicate that waste synthetic wool can perform several technological functions simultaneously in vertical-flow filters. This material should not be treated solely as a passive bed filling but as a structure supporting the processes of mechanical filtration and biological wastewater treatment. A hydraulic load of $80 \text{ dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ can be considered an operationally favorable and technologically acceptable option. This value corresponds to the range of hydraulic loads encountered in practice in small and decentralized wastewater treatment systems, such as on-site wastewater treatment plants and vertical-flow filters. This variant may be of particularly practical importance, as it allows for an increase in the system's hydraulic capacity while maintaining high wastewater treatment efficiency.

The primary function of the waste synthetic wool was filtration. The fibrous and three-dimensional structure of the material enabled the retention of suspended solids present in the pre-treated wastewater. A reduction in TSS ranging from 62.69% to 87.53% confirms that the fiber structure formed an effective filtration barrier. At the same time, the variability of the results indicates that the efficiency of suspended solids retention depended on hydraulic conditions, including the active bed depth and hydraulic load.

The second function of the material was to provide a large surface area for microbial colonization and biofilm development responsible for biological wastewater treatment. The surface of the synthetic fibers may have contributed to the retention of some dissolved and colloidal pollutants, particularly in the initial contact zones between the wastewater and the bed. The high COD reduction, ranging from 86.53% to 94.20%, indicates that the bed could support both biological processes and physicochemical processes related to the retention of pollutants on the material's surface.

The third and most important function of the waste synthetic wool was its biological function. The material served as a potential biofilm carrier, i.e., a surface on which microorganisms responsible for the decomposition of organic substances and the transformation of nitrogen compounds could develop. The very high BOD₅ reduction, ranging from 93.06% to 97.65%, indicates the intensive removal of readily biodegradable organic compounds. Similarly, the efficiency of NH₄⁺-N removal, ranging from 65.73% to 94.31%, indicates that biological processes related to nitrification may have occurred in the bed.

The results of the study confirm that the effectiveness of waste synthetic wool depends on the proper selection of filter operating parameters. The most favorable conditions were achieved with a sufficiently high active bed depth of 0.9 m and a moderate

hydraulic load of $80 \text{ dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. This means that the mere presence of fibrous material is not sufficient to ensure high treatment efficiency. It is also necessary to maintain an adequate contact time between the wastewater and the material, limit hydraulic overload, and ensure conditions conducive to the development of an active biofilm.

From a technological standpoint, waste synthetic wool can be considered a multi-functional material. It combines the characteristics of a lightweight filter medium, a contact surface facilitating wastewater interaction with the bed, and a substrate for microorganisms. Compared to natural materials, its significant advantage is greater resistance to degradation in the wastewater environment, which is important for bed depth stability and long-term filter operation.

From the perspective of the circular economy, it is particularly significant that the material under study originated from a waste stream. Its use as a filter medium enables the beneficial reuse of waste synthetic wool in environmental protection technologies. In this context, the waste material is not treated as a problem requiring disposal, but as a potential secondary raw material that can be used in decentralized wastewater treatment systems. The technological significance of waste synthetic wool is summarized in Table 13.

Table 13. Functional role of synthetic wool waste in vertical-flow filters.

Function of Synthetic Wool Waste	Mechanism	Technological Significance
Filtration material	Retention of suspended solids in the fibrous structure	Reduction in TSS and protection of lower filter zones
Contact medium	Contact of wastewater with a fibre surface	Improved conditions for biological wastewater treatment processes
Biofilm carrier	Microbial colonization of fibre surface	Biological removal of organic matter and ammonium nitrogen
Hydraulic structure	Creation of void spaces between fibres	Maintenance of wastewater flow through the bed
Circular economy material	Reuse of synthetic waste	Reduction in waste and replacement of conventional filter media

In summary, waste synthetic wool has demonstrated potential as a functional filter medium for vertical-flow filters used in domestic wastewater treatment. It simultaneously performed filtration functions and provided conditions favorable for biofilm development and biological treatment processes. The results obtained justify further research into optimizing the operating parameters of such a bed, particularly the active height, hydraulic load, material durability, and long-term biofilm stability.

4. Discussion

The results of this study confirmed that waste synthetic wool can be effectively used as a filter material in vertical-flow filters designed for the treatment of domestic wastewater. This material simultaneously exhibited filtration properties and the ability to support biofilm development responsible for biological wastewater treatment. The high efficiency of BOD₅ and COD removal indicates that the fibrous structure of the material provided favorable conditions for wastewater contact with the bed surface and stable conditions for microbial growth.

The results obtained are consistent with observations reported in the literature regarding the use of alternative waste and fibrous materials in wastewater treatment technologies. Dacewicz and Chmielowski demonstrated that waste plastics can effectively serve as a filter medium in vertical-flow filters for domestic wastewater treatment, achiev-

ing high removal efficiency for organic compounds and total suspended solids [21]. The results obtained for waste synthetic wool can also be compared to the research by Aslam et al., in which cotton stalks were used as a biofiltration medium in a trickling filter. The authors achieved a reduction in BOD₅ of 69–78%, COD of 65–80%, and TSS of 38–56% [20]. Compared to these results, waste synthetic wool demonstrated higher efficiency in removing organic compounds and suspended solids, which may result from the greater durability of the synthetic material and a more favorable spatial structure for contaminant retention and biofilm development.

The importance of fibrous structures in wastewater treatment is confirmed by research on geotextiles. Yaman demonstrated that geotextiles can function as biofilm filters, combining mechanical filtration with biological wastewater treatment [17]. Morais et al. demonstrated that geotextiles can support biofilm growth and remove COD, nitrogen, and phosphorus, with effectiveness being related to the thickness and mass of the geotextile material [24]. Charchalac Ochoa et al., on the other hand, confirmed that geotextiles used as pre-filters can limit the inflow of suspended solids to sand filters and reduce the risk of their clogging [25].

Other synthetic materials have also been successfully applied as biomass carriers in wastewater treatment systems. Szychala et al. demonstrated that carriers made of wood–plastic composites (WPC), polyethylene (PE), plastic straws, and Raschel mesh provided favorable conditions for wastewater treatment. Among the tested materials, Raschel mesh achieved average removal efficiencies of 83.6% for TSS, 84.6% for COD, and over 92% for NH₄⁺-N [29]. These findings confirm that synthetic polymer-based materials can effectively support biofilm development and pollutant removal in biological treatment processes. Similarly, the waste synthetic wool investigated in the present study achieved high removal efficiencies for organic pollutants, suspended solids, and ammonium nitrogen, indicating that fibrous synthetic waste materials may serve as effective filter media and biofilm carriers in decentralized wastewater treatment systems.

Waste synthetic wool exhibits some functional similarity to geotextiles, as it also has a fibrous structure and can serve as a surface for microbial growth. However, unlike flat geotextile materials, synthetic wool forms a three-dimensional, voluminous bed structure. This can increase the number of contact points between wastewater and the material and improve conditions for the immobilization of microorganisms throughout the entire volume of the filter.

The significant reduction in BOD₅ and COD suggests that an active biofilm responsible for the biodegradation of organic pollutants developed within the bed. Biofilm-based wastewater treatment technologies are considered stable, economical, and environmentally friendly solutions, as they allow biomass to be retained on the surface of the carrier and limit its leaching from the system [12]. In the case of waste synthetic wool, the fibers could have served as a biofilm carrier, similar to other textile and synthetic materials used in biological wastewater treatment systems [12,17,19].

The results of the study showed a clear influence of the active bed depth on wastewater treatment efficiency. The most favorable results were obtained at a depth of 0.9 m, while reducing the bed depth led to a gradual decline in pollutant removal efficiency. This result is consistent with the general principles of biological filter operation. A greater bed depth prolongs the contact time between wastewater and the media and increases the biologically active volume. This can improve the removal of organic pollutants, suspended solids, and ammonium nitrogen. At the same time, excessive bed depth or excessive bed density could potentially lead to reduced flow and an increased risk of clogging. Therefore, bed height should be treated as a parameter requiring optimization, not merely maximization.

The observed bed settlement remained relatively low under all tested conditions and did not adversely affect filter hydraulics. During the 15-month experiment evaluating the effect of bed height, the reduction in bed height ranged from 3.3% to 5.0% of the initial bed height. In the 10-month experiment evaluating the effect of hydraulic loading, bed settlement ranged from 1.7% to 6.1%, with greater settlement observed at higher hydraulic loading rates. Despite these changes, no clogging, surface ponding, overflow, deterioration of infiltration, or reduction in hydraulic performance was observed during long-term operation. These findings indicate satisfactory operational stability of the synthetic wool and suggest that the material did not undergo excessive compaction under the applied operating conditions.

Hydraulic loading was the second key operating parameter of the system. The best results were obtained at a loading of $40 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, while a loading of $80 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ can be considered acceptable from a practical standpoint. Higher loads, amounting to 120 and $160 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, were less favorable and should not be treated as the basic operating conditions for the filter.

The lower TSS removal efficiencies observed under higher hydraulic loading rates may be associated with the reduced retention of suspended solids within the filter bed. Increased wastewater flow can promote the transport of previously retained particles and deposits to the effluent. Detached biofilm may also contribute to this phenomenon; however, no direct analyses were performed to determine the origin of these solids. SEM observations performed after the completion of the experiments (Figure 2) did not indicate substantial degradation or fragmentation of the synthetic fibers. Therefore, the reduced TSS removal efficiency cannot be attributed to the washing away of the filter material itself.

The effect of hydraulic loading can be explained by the reduction in the contact time between the wastewater and the bed at higher inflow rates. Excessively high loading may limit filtration efficiency, reduce wastewater contact with the biofilm, and promote short-circuiting. Similar relationships were observed in studies on biofilters, where retention time, aeration, and start-up conditions influenced the efficiency of nitrogen and organic contaminant removal [5]. Research by Khomenko et al. also indicates that the hydraulic behavior of vertical-flow filters is critical to their effectiveness and operational stability [10].

The use of synthetic waste wool as a filter medium for domestic wastewater treatment is significant not only from a technological standpoint but also from an environmental one. This waste material, which in a traditional economic model might have been sent to landfills or disposed of, has been repurposed as a functional filter bed. This approach aligns with the principles of a circular economy, in which waste is treated as a potential secondary raw material. Priya et al. emphasized that the valorization of waste biomass into wastewater treatment materials can create closed material cycles and yield environmental, economic, and social benefits [30]. Mishra et al., on the other hand, indicated that renewable and functional materials can serve as an alternative to conventional materials used in water and wastewater treatment [38].

Our research findings indicate that waste synthetic wool could potentially be used in small, decentralized domestic wastewater treatment systems, particularly as a medium for vertical-flow filters. This material is lightweight, fibrous, and can create favorable conditions for the retention of suspended solids and the development of biofilm. The use of such a material could be particularly interesting in on-site wastewater treatment systems or local treatment systems in areas with scattered development.

An important issue requiring further research is the potential release of microplastics from waste synthetic wool during long-term use. Although SEM observations made before and after the experiment did not reveal any visible signs of extensive fiber fragmen-

tation, direct analysis of microplastics in treated wastewater was not within the scope of this study. Therefore, further research should include a long-term assessment of the material's durability and an analysis of the potential for microplastic release under operational conditions. Detailed characterization of physical properties of the filter material, such as specific surface area, bed porosity and hydraulic conductivity, was not included in the present study. Future investigations should address these parameters to better understand the relationship between material structure and treatment performance. The monitoring program did not include nitrate ($\text{NO}_3\text{-N}$) or total nitrogen (TN) measurements. Therefore, the nitrogen transformation pathways occurring within the filters could not be fully assessed and should be investigated in future studies. In addition, the present study focused on physicochemical treatment performance, while microbiological indicators such as *E. coli* and total coliforms were not included in the monitoring program. Future studies should therefore also evaluate the sanitary efficiency of synthetic wool filters. A limitation of the present study is the absence of a parallel control filter filled with a conventional filtration medium. Future studies should include direct comparative analyses under identical operating conditions. Furthermore, future research should investigate hybrid filtration systems combining waste synthetic wool with conventional mineral filtration media, such as sand. Previous studies have demonstrated that layered filtration systems consisting of an upper polymer-based layer and a lower sand layer can effectively improve the removal of indicator microorganisms, including *Escherichia coli* and coliform bacteria [43]. A similar configuration should therefore be evaluated for waste synthetic wool filters, not only to assess their sanitary performance but also to investigate whether the sand layer could act as an additional barrier limiting the migration of potential microplastic particles into the treated wastewater. Such an approach would provide a more comprehensive assessment of the long-term environmental safety of the proposed filtration technology.

5. Conclusions

The conducted research confirmed the potential of using waste synthetic wool as an alternative filtration material and biofilm carrier in vertical-flow filters for domestic wastewater treatment. The results indicate that this material can serve as a functional filter medium in small, decentralized wastewater treatment systems.

Based on the analyses conducted, the following conclusions were drawn:

1. Waste synthetic wool proved to be highly suitable as a filter medium for vertical-flow filters used in domestic wastewater treatment. Among the fibrous materials analyzed, non-siliconized polyester fiber was selected for further research, as it exhibited greater operational stability than natural materials and more favorable treatment results compared to the siliconized variant.
2. The tested material served a multifunctional role in the wastewater treatment process. The waste synthetic wool acted simultaneously as a filtration material retaining suspended solids and as a biofilm carrier enabling the growth of microorganisms responsible for biological wastewater treatment. The fibrous structure of the material also promoted prolonged contact between wastewater and the biologically active surface of the filter bed.
3. The highest treatment efficiency was achieved for organic pollutants. The reduction in BOD_5 ranged from 93.06% to 97.65%, while the reduction in COD ranged from 86.53% to 94.20%. These results confirm that the bed made of waste synthetic wool provided favorable conditions for the removal of organic matter and the development of an active biofilm.
4. Synthetic waste wool effectively retained suspended solids. The reduction in total suspended solids ranged from 62.69% to 87.53%, confirming the filtration function of

the material's fibrous structure. However, the variability in the results indicates that the efficiency of suspended solids retention depends on the hydraulic operating conditions of the filter.

5. A significant reduction in ammonium nitrogen was achieved. The removal efficiency of $\text{NH}_4^+\text{-N}$ ranged from 65.73% to 94.31%, indicating the potential for biological processes, including nitrification, to develop within the synthetic waste wool bed.
6. The active bed height and hydraulic load were of significant importance for the filter's operation. The most favorable treatment conditions were associated with a bed height of 0.9 m and a low or moderate hydraulic load. A loading rate of $40 \text{ dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ was the most favorable, while $80 \text{ dm}^3\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ can be considered technologically advantageous and practically acceptable in small and decentralized wastewater treatment systems.
7. The use of synthetic waste aligns with the principles of the circular economy. The waste material has been given a new technological function in the wastewater treatment process, which helps reduce the consumption of traditional filter media and supports the reuse of synthetic waste in environmental technologies.

In summary, waste synthetic wool can be considered a promising material for use in vertical-flow filters. Its use combines effective treatment of domestic wastewater with the reuse of synthetic waste.

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Abbreviations

The following abbreviations are used in this manuscript:

BOD ₅	five-day biochemical oxygen demand
COD	chemical oxygen demand
$\text{NH}_4^+\text{-N}$	ammonium nitrogen
TSS	total suspended solids

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