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The Efficiency of a Biological Reactor in a Domestic Wastewater Treatment Plant Operating Based on ABS (Acrylonitrile Butadiene Styrene) Material and Recycled PUR (Polyurethane) Foam

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Abstract: The primary objective of this research was to assess the efficacy of a novel solution under conditions closely resembling those of real-world scenarios. Biological beds, or filters, hold significant potential for widespread implementation in individual households, particularly in areas with dispersed housing. The system's aim was to improve the quality of wastewater treated in on-site domestic biological treatment plants. A pivotal aspect of the project involved developing a prototype research installation for conducting comprehensive testing. Our installation system consisted of several components designed to create a laboratory-scale model for domestic wastewater treatment. The model comprised four biological reactors filled with ABS material and secured by a PUR frame. Additionally, the tested model included a controller for wastewater dosing control, a septic tank as a reservoir, and four tanks for collecting purified wastewater. Through regression analysis using the Generalized Linear Model (GLM), a correlation between COD_{Cr} and TSS was revealed. This study presents the research findings concerning the development of a prototype installation that incorporates an advanced reactor or filter. The data derived from this research have the potential to contribute to the creation of products that enhance the performance and efficiency of household wastewater treatment systems.

Keywords: prototype filter; wastewater treatment efficiency; on-site domestic treatment; reuse e-waste

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1. Introduction

Wastewater management is a pressing global concern, with increasing emphasis on sustainable and efficient methods of removal and treatment [1–3]. A pragmatic shift marked a transformation in waste material management and wastewater treatment technology, responding to the substantial global waste production and the demand for economical adsorbents to reduce wastewater treatment costs [4]. Today, a new approach encompasses the integration of waste materials into wastewater treatment and the creation of value-added products from previously used waste adsorbents, including electric material and cementitious materials, ultimately enhancing both waste management efficiency and commercial viability [5–7]. Wastewater is generated from various sources, including industrial processes, agricultural activities, and domestic usage [8,9]. The effective removal and treatment of wastewater are essential for environmental protection and human health [10]. Numerous theoretical and practical approaches have been developed to address this challenge, with an emphasis on different shredded materials and their role in these methods [11–15].

The assessment of product materials in the context of wastewater removal is of paramount importance in addressing the ever-growing concerns of environmental sustainability and public health [16]. Critical to achieving cleaner water is the careful selection of materials [17]. A comprehensive examination of the advantages and limitations of various materials provides invaluable insights for shaping the development of wastewater removal solutions that are both more efficient and environmentally friendly [18,19]. Efficient wastewater treatment hinges on low biological oxygen demand (BOD) and chemical oxygen demand (COD) levels, reflecting successful removal of pollutants for environmental health. The reduction in COD in wastewater is primarily associated with the removal of organic pollutants [20].

Various materials can be used to treat wastewater in small municipal systems. Ceramic aggregate is very popular as a filtering medium. Shao et al. [21] developed a non-sintered fly ash filter material with sludge as an additive and studied the impact of pH on the adsorption efficiency of ammonium nitrogen in wastewater. In other research, Lu et al. [22] demonstrated the use of another novel material—prepared using municipal solid waste incineration (MSWI) fly ash and the fuel ash from coal power plants, together with small amounts of silicon carbide foaming agent and magnesia flux as additives. These media have high efficiency in removing contaminants from wastewater, but their production requires thermal treatment, which results in high costs. Therefore, it seems advisable to look for other alternative filter materials produced from waste but without energy inputs.

ABS (Acrylonitrile Butadiene Styrene) is a water-resistant plastic known for its durability and resistance to water degradation, making it a popular choice for various applications in industries such as electronics, the automotive industry, and construction. Its hydrophobic nature prevents water from infiltrating the material, contributing to its long lifespan and reduced environmental impact [23]. ABS proves to be a valuable material in a wide range of applications. Nevertheless, its suitability or potential challenges can be contingent upon its application or the particular context in which it is utilized [24].

This paper presents a critical assessment of the role of various product materials in theoretical and practical approaches to wastewater removal. We focused on shredded materials in wastewater removal, considering both theory and practical applications.

The research's primary objective was to evaluate the efficiency of a novel wastewater treatment process under conditions closely resembling those of real-world scenarios. This technical study focused on conducting scientific investigations into the effectiveness of innovative filters, specifically biological beds. At the laboratory research stage, a variant of the biological bed was developed and filled with finely crushed ABS. Our goal was to guide the development of sustainable solutions by emphasizing materials like ABS. The specific objectives were as follows:

(a) To assess various shredded materials, reducing reliance on resources and minimizing the environmental impact of production processes;

(b) To develop effective waste-material-based solutions for the removal of pollutants, as measured by COD_{Cr} and BOD_5;
(c) To support the principles of resource efficiency and the circular economy by exploring innovative methods for recycling and reusing electronic waste materials in a closed-loop system, thereby reducing waste generation and conserving natural resources;
(d) To establish reliable total suspended sediment efficiency indicators for the evaluation of waste-material-based sediment treatments, ensuring their effectiveness in water purification.

2. Materials and Methods

2.1. Construction of the Laboratory Model

The model was established in a laboratory-prototype setting. The test system was a filter bed with a vertical flow (Figure 1). This setup contained several compartments divided by specialized partitions where targeted research investigations were carried out. These compartments were supplied with wastewater from a sewage settling tank (Figure 2).

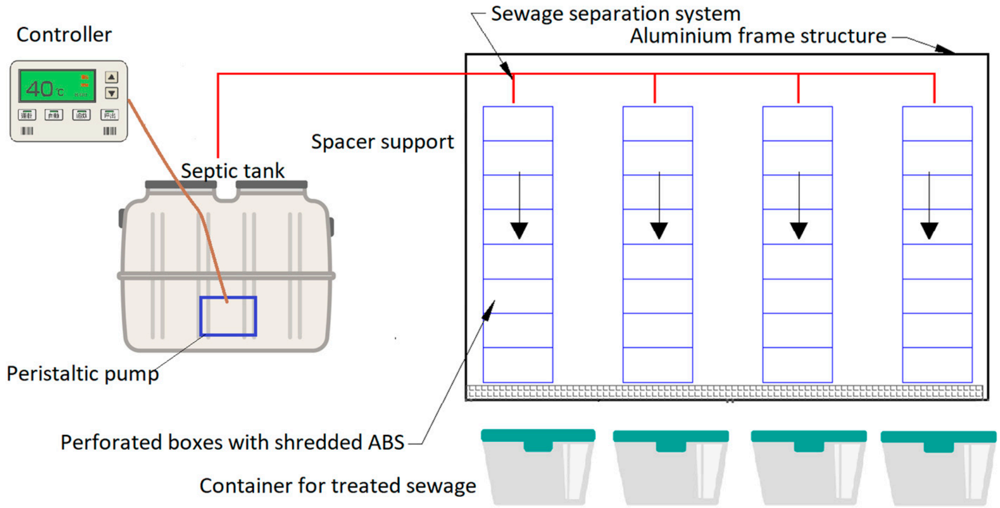

Figure 1. Schematic of experimental of biological reactor in a domestic wastewater treatment plant.

Figure 2. Septic tank of pre-treated wastewater utilized for research.

The research setup essentially comprised the following components:

(a) Supporting structure;
(b) Plastic reactors;
(c) System for dosing pre-treated wastewater into the reactors;
(d) System for discharging treated wastewater;
(e) Electrical power supply system.

Two types of plastic materials were examined: one black, with particle sizes ranging from 0.2 to 1.0 cm, and the other light yellow, with particle sizes from 0.2 to 0.8 cm. Additionally, colored plastic derived from crushed PET (Polyethylene Terephthalate bottles) was utilized. The container was lined with a layer of PUR (polyurethane) foam and then filled with finely shredded e-waste material. The biological bed of the setup was filled with crushed ABS material from used waste of electrical and electronic equipment (WEEE) and used to fill containers measuring 30 × 40 cm with a height of 11 cm. Furthermore, three of the compartments incorporated a special layer made of shredded polyurethane foam (recycled plastic material). An example photo of the packing of the bed is shown in Figure 3. ABS with a density of 1.1 g/cm^3 was used in the tests. The porosity of the ABS material was 45% (Figure 4). ABS (Acrylonitrile Butadiene Styrene) is a widely utilized plastic known for its robustness and longevity. Its environmental footprint is intricately tied to recycling practices, offering a sustainable approach by diminishing the demand for new materials and curbing waste. Appropriate recycling is pivotal for eco-friendly disposal since ABS has a slow biodegradation rate in landfills. Despite its petrochemical-based production, responsible disposal methods, especially recycling, can effectively temper its environmental impact. While ABS is inherently non-biodegradable, its overall influence on the environment hinges on disposal practices and the widespread adoption of recycling initiatives. Increased recycling of ABS contributes to resource conservation and eases the burden on waste management systems.

Figure 3. System of vertical flow filter.

Figure 4. The shredded ABS used in studies.

The studies were conducted with a hydraulic load on the filtration bed not exceeding 50 dm^3/m^2 daily, and a double recirculation of domestic wastewater was employed for the sprinkler system. The average wastewater quantity dosed into the reactors was approximately 20.8 mL per hour using peristaltic pumps. Additionally, the average total volume was at the level of 0.5 dm^3 per day. The evaluation of the reactor/filter's impact on wastewater (assessment of physicochemical properties of wastewater before and after reactor utilization) encompassed three primary wastewater pollution indicators: BOD_5, COD_{Cr}, and total suspended solids. Moreover, the research involved observing whether the proposed technical solution was prone to clogging.

2.2. Determination of the Basic Parameters for the Treatment Efficiency

In the treated wastewater, the following parameters were measured using a multifunctional device: pH, dissolved oxygen, oxygen saturation, and wastewater temperature with the pH-dissolved oxygen meter CPO-401 (Elmetron Sp. j., Zabrze, Poland). BOD_5 was determined using the respirometric BOD Measuring system WTW OxiTop-I IS 6 (Xylem Analytics Germany, Waldheim, Germany), and COD_{Cr} was measured using the WTW photoLAb 7200 VIS spectrophotometer (Xylem Analytics Germany). The TSS weight method was utilized to measure total suspended solids in wastewater. This method involved filtering a known volume of the sample through pre-weighed filter paper, drying it, and re-weighing it to calculate TSS concentration in mg/L. This approach ensured the precise quantification of suspended solid particles in water samples. Reductions in COD_{Cr}, BOD_5, and total suspended solids (TSS) were calculated according to the formula in reference [25]:

$$y = \frac{a \cdot 100}{b} - 100\%$$

where:

a—treated wastewater concentration;
b—wastewater concentration;
y—reduction efficiency.

We conducted a multivariate regression using COD_{Cr}, BOD_5, or TSS as independent variables and temperature (Temp) and dissolved oxygen (DO) as predictors. The optimal model was determined using a GLM (Generalized Linear Model) approach. Regression was performed using PAST version 4.11. Reduction in selected wastewater pollution indicators was determined. They were compared with the limit values specified in the Regulation of the Minister of Maritime Affairs and Inland Navigation on substances particularly harmful to the aquatic environment and on conditions to be met when discharging wastewater into waters or onto the ground and when discharging rainwater or snowmelt into waters or into a water installation (Journal of Laws from 2019, item 1311). According to this law, a value below 2000 PE for WWTPs is equal to a concentration of 40 mg O_2/dm^3, 150 mg O_2/dm^3, and 50 mg/dm^3 for BOD_5, COD_{Cr}, and TSS, respectively. Basic descriptive statistics of the quality of pre-treated and treated wastewater such as the mean, minimum, maximum, standard deviation, range, median, and coefficient of variation were estimated.

3. Results and Discussion

The raw wastewater used in this study came from a septic tank connected to the university building (Agricultural University of Krakow, Poland). The wastewater was directed to the septic tank for preliminary treatment. In Table 1, the qualitative values of pre-treated wastewater in the septic tank are given. In the next stage, the wastewater was pumped to the surface of a vertical biological filter.

Table 1. Parameters in wastewater after primary septic tank treatment.

Evaluated Indicators of Wastewater Quality							Days Since Model Startup
pH	Dissolved Oxygen mg O_2/dm^3	Temp. °C	TSS mg/dm^3	COD_{Cr}/BOD_5	COD_{Cr} mg O_2/dm^3	BOD_5 mg O_2/dm^3	
7.65	0.000	18.2	303.2	1.57	439	280	8
8.38	0.600	20.2	395.0	1.57	377	240	16
7.97	0.000	19.9	410.2	1.30	363	280	21
8.01	0.000	18.5	425.4	1.38	359	260	23
5.74	0.070	18	682.0	2.14	471	220	28
8.05	0.250	17	689.0	1.88	450	240	31
6.38	0.260	17.6	589.0	1.54	431	280	34
6.46	0.210	17.6	490.0	1.51	362	240	36
6.75	0.000	17.4	329.0	1.29	335	260	38
6.73	0.050	17.3	315.0	1.32	343	260	41
6.80	0.000	17.9	412.0	1.99	437	220	43
6.85	0.000	18.1	385.0	1.98	475	240	48
6.95	0.000	18.4	362.2	1.67	433	260	52
6.785	0.000	18.2	422.0	1.49	418	280	60
7.051	0.070	17.5	395.4	2.06	453	220	65
7.211	0.050	18.2	389.1	1.83	475	260	70
6.987	0.000	19.1	421.8	1.80	433	240	75
6.857	0.000	19.5	367.8	1.64	328	200	80
7.254	0.200	18.9	401.2	1.40	337	240	85
6.987	0.100	18.8	398.7	1.42	368	260	88
6.471	0.000	19.4	368.9	1.66	332	200	90

In technical documentation, the term ‘closed-loop system’ typically refers to a system where the output influences the input, creating a loop of information or control. This closed-loop nature often involves feedback mechanisms or continuous monitoring and adjustments within the filtration system. However, for our examination purposes, we have excluded these elements as they are unnecessary (Figure 1). While backwashing the filter is possible, it was not considered necessary in our examples. Filter clogging may occur under specific conditions, including significant changes in the source or composition of wastewater (e.g., industrial wastewater) and the direct introduction of wastewater into the filtering system without utilizing a preliminary settling tank. It is recommended to use coarser particles at the top of the filtration bed and progressively finer material at the bottom; this enhances anti-clogging properties.

In this context, our material operates within a closed-loop system, meaning it is not disposed of in landfills but is instead reused within the system. Although this concept may not be explicitly depicted on the graph, the emphasis is on highlighting the sustainable reuse of materials within the system.

Optimal conditions, such as a 45 min treatment with an aluminum cathode and a current density of 75 A/m^2, achieved over 90% removal of BOD_5, COD_{Cr}, turbidity, chromium, iron, and nitrate. However, the electrocoagulated sludge contained problematic substances, including chromium (50%), Total Carbon (15%), and Sulfide (0.3%), posing disposal challenges. One piece of research highlighted electrocoagulation's potential for tannery wastewater treatment while emphasizing the importance of addressing sludge disposal issues [26]. The wastewater, following the septic tank, exhibited the highest BOD_5 concentration, peaking at 280 mg O_2/dm^3 (Table 1). Research findings indicated that BOD_5 reduction to the required regulatory level occurred after 34 days (Figure 5). Similarly, the maximum COD_{Cr} concentration after the septic tank reached 475 mg O_2/dm^3,with a satisfactory reduction observed after 38 days.

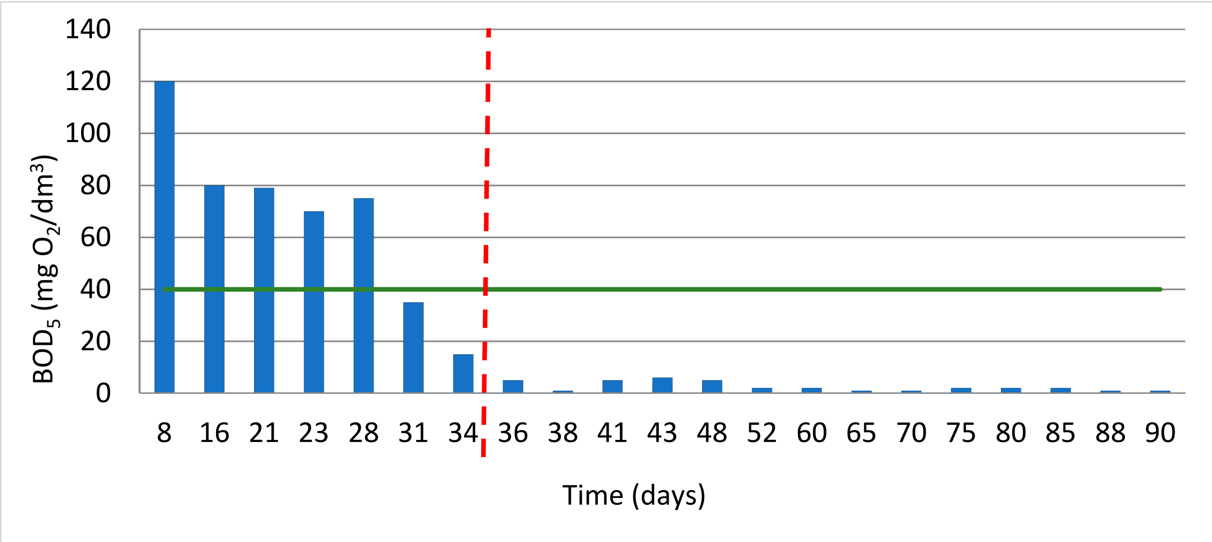

Figure 5. BOD_5 values for the finer filter media, with the red dashed line indicating the moment of compliance. The green line represents the permissible value.

In the pre-treated wastewater, periodic anaerobic conditions were observed. The dissolved oxygen concentration reached a maximum of 0.26 mg O_2/dm^3, while the pH fluctuated within the range of 5.75 to 8.38 (Table 1).

The results indicated that there was an enhancement in wastewater quality in each system within 30 days. For the first month, BOD_5 values were high, reaching up to 120 mg O_2/dm^3 in the first week of reactor operation. Only after 30 days did a noticeable decrease occur, which was below the allowable level (Figure 5). During the initial phase of the filter bed's operation, the reduction fell within the range of 51.7% to 85.4%. It was only after more than one month of continuous operation that the reduction achieved a substantial, consistent level exceeding 90% (Figure 6). In the studies [27] conducted by other researchers, it was observed that the BOD_5 level in wastewater following a settling tank reached 774.7 mg O_2/dm^3. In contrast, our investigations indicated a BOD_5 level not exceeding 120 mg O_2/dm^3. Furthermore, the maximum COD_{cr} concentration in raw wastewater was reported at 1524 mg O_2/dm^3, whereas, in our study, it remained below 350 mg O_2/dm^3 (Figure 7).

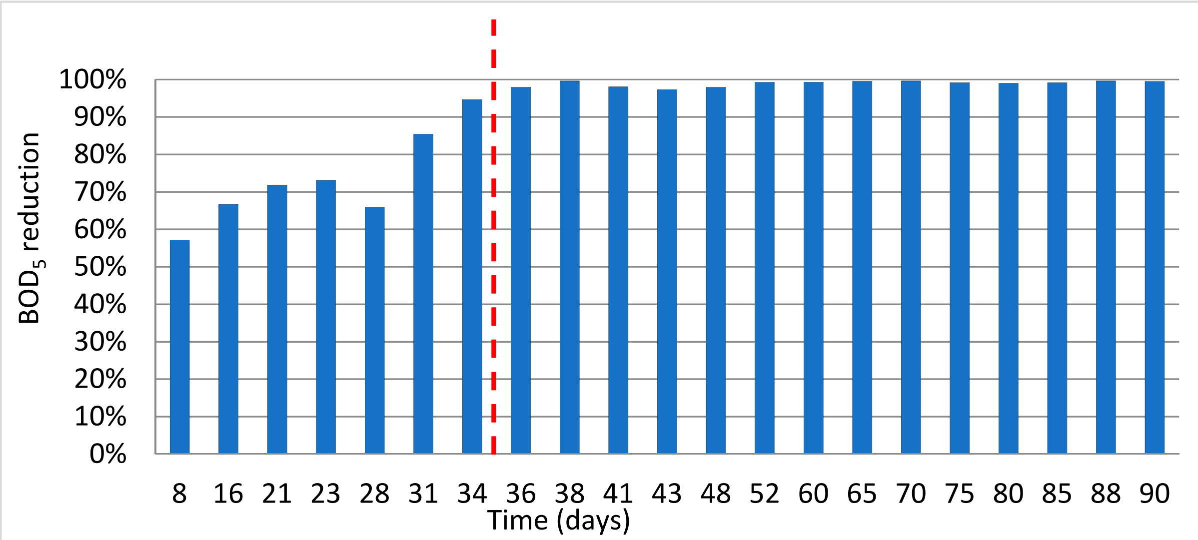

Figure 6. BOD_5 reduction for the finer filter media, with the red dashed line indicating the moment of achieving the appropriate reduction.

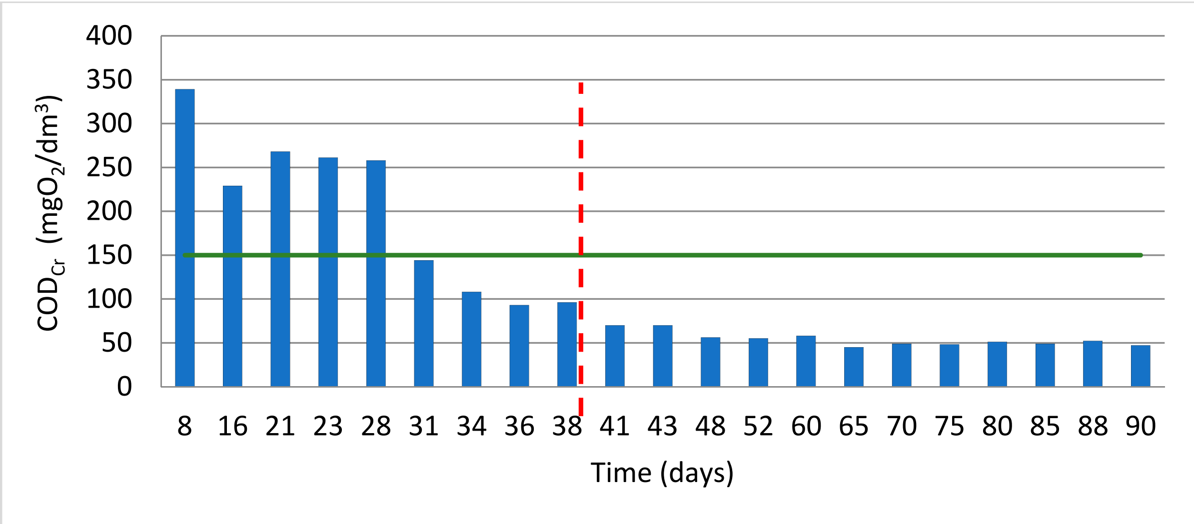

Figure 7. COD_{Cr} values for the finer filter media, with the red dashed line indicating the moment of achieving the appropriate value. The green line represents the permissible value.

In our experiments, we observed variability in the BOD_5 values. Beyond 28 days, higher values may arise due to the persistence of complex organic compounds and microbial adaptation during the adjustment process. Factors such as external sources of pollution introduced after day 23 and favorable environmental conditions supporting increased microbial activity could further contribute to this increase. These fluctuations in experimental conditions may influence the nature of organic matter and alterations in environmental parameters. As a result, additional data and analyses are essential for a precise identification of contributing factors (Figure 5).

It took 38 days of operation in the biological reactor for the COD_{Cr} values to achieve a significant reduction to one fourth of their initial levels (Figure 7). During the initial weeks of the filter bed's operation, COD_{Cr} reduction varied in the range of approximately 20–70%. It was only after 38 days of operation that a more stable reduction exceeding 80% was achieved (Figure 8). In another study involving shredded ABS, the most significant reduction in COD was noted with the sprayed loaded system. For BOD_5 reduction, the highest efficacy was attained through the aeration system [25].

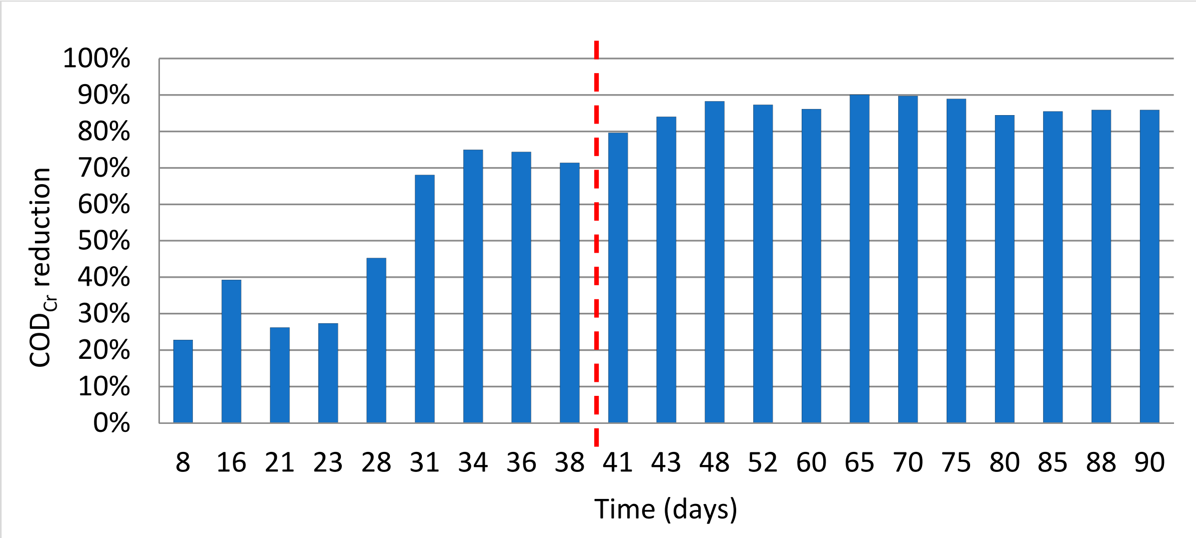

Figure 8. COD_{Cr} reduction for the finer filter media, with the red dashed line marking the moment of achieving the desired reduction.

In the textile industry, water and chemicals are essential for raw material processing. Untreated wastewater poses environmental risks. Another study used chitosan extracted from prawn shells to treat textile wastewater, significantly reducing BOD_5 and COD_{Cr} levels. Compared to microorganism treatment, prawn shell treatment proved more effective and cost efficient, offering a promising eco-friendly wastewater treatment method. Similarly, the maximum COD_{Cr} concentration after the septic tank reached 475 mg O_2/dm^3 (Table 1), with a satisfactory reduction observed after 38 days.

In the initial week, TSS levels were notably elevated, and it took over a month to achieve a satisfactory value which fell below 50 mg/dm^3, complying with the established regulatory standard (Figure 9). Substantial TSS reduction was attained beginning in the second week of filter operation, with the required reduction, in line with regulatory standards, documented after 31 days (Figure 10). Based on the GLM and multivariate regression, the relationship between TSS and COD_{Cr} has been established (Figure 11). Substantial TSS reduction was attained beginning in the second week of filter operation, with the required reduction, in line with regulatory standards, documented after 31 days.

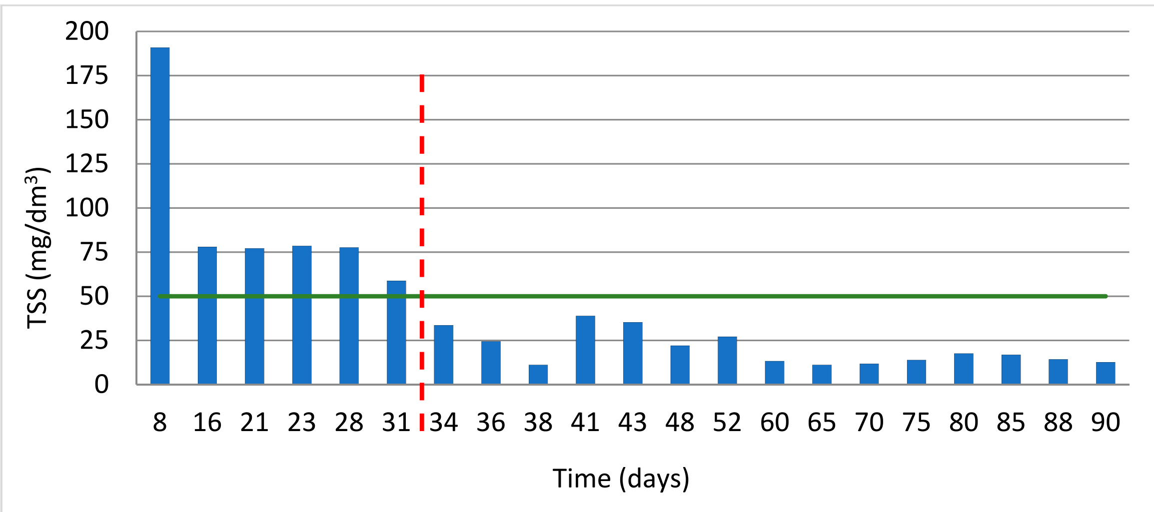

Figure 9. TSS values for the finer filter media, with the red dashed line indicating the point of achieving the desired value. The green line represents the permissible limit.

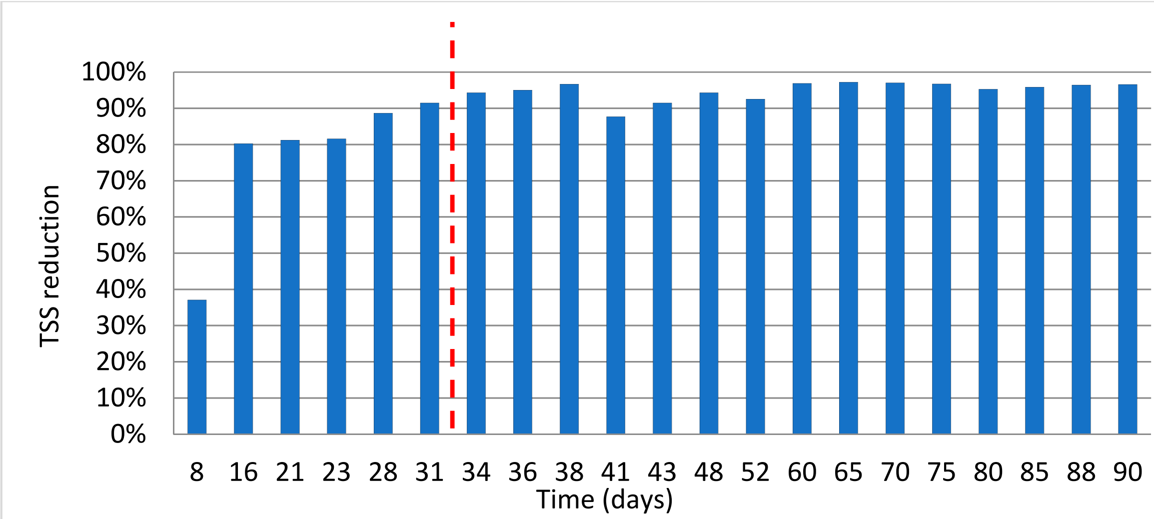

Figure 10. TSS reduction for the finer filter media, with the red dashed line.

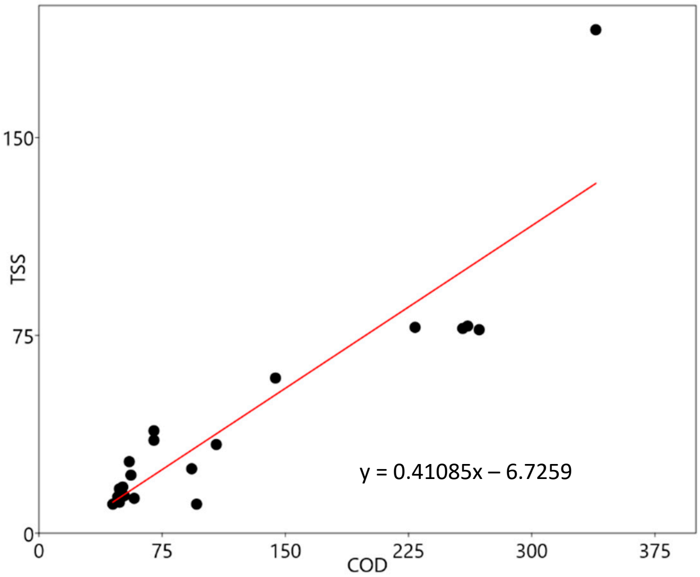

Figure 11. A Generalized Linear Model (GLM) for TSS (mg/dm^3) and COD (mg O_2/dm^3).

The COD_{Cr}:BOD_5 ratio suggested effective removal of nitrogen compounds through advanced biological treatment of the wastewater [28]. During the four-month study, a filter filled with 0.5 V of polyurethane foam sponge waste proved highly stable and effective, achieving reductions averaging 87.8% for COD_{Cr}, 91.0% for BOD_5, 80.0% for suspended solids. Additionally, poly(ethylene terephthalate) flakes exhibited comparable performance, with average COD_{Cr} and suspended solids reductions of 87.1% and 84.0%, respectively [29]. The COD_{Cr}/BOD_5 ratio of 1.31 indicated that the incoming wastewater was highly biodegradable and relatively easy to treat. In simple terms, this means that the influent wastewater's composition can be readily broken down through biological processes, making it a desirable characteristic for wastewater treatment [30]. The COD_{Cr}-to-BOD_5 ratio helps gauge the balance between pollutants that can be chemically or biologically treated. A high ratio means more chemical treatment potential, while a low ratio indicates effective biological pollutant degradation. Wastewater facilities use this ratio to tailor treatment methods to the pollutants present in the water [31]. The TSS level in untreated municipal (raw) wastewater did not surpass 340 mg/dm^3. TSS levels in the effluent after the septic tank reached a maximum of 689 mg/dm^3 (Table 1), and reduction to the required norm took place between the 31st and 34th day of operation (Figure 10).

This study has shown that the average reduction level for BOD_5 was 98.9%, while, for COD_{Cr}, it was 84.4%, and, for TSS, it was 95% (Table 2). Throughout the four-month research period, the 60 cm foam filter consistently achieved substantial reductions of 60–80% in pollutants, including organic compounds and bacteria, demonstrating its superior performance. The evaluation of materials used in wastewater removal is crucial for addressing concerns related to process efficiency [27], environmental sustainability [32–34], and public health [35]. Preventing the formation of stagnant zones within the filtration bed is essential for effective wastewater management systems [36], especially in the context of a circular economy [36], particularly within urban wastewater management systems [37]. This section emphasizes key points in wastewater management, stressing the importance of exclusive domestic wastewater that avoids reacting with recycled ABS material. COD statistically correlated with TSS, suggesting that the chemical degradation of organic compounds was influenced by the level of suspended solid (Table 3). Furthermore, in the studies conducted on PUR sponge, a substantial reduction in COD of 87.1% and in TSS of 84.0% was observed [29]

Table 2. Basic descriptive statistics and the mean percentage reduction for BOD_5, COD_{Cr}, and TSS in the investigated filter bed after treatment.

Descriptive Statistics	COD_{Cr}	BOD_5	TSS
Mean	84.4%	98.9%	95.0%
Median	85.9%	99.2%	96.1%
Minimal	71.3%	97.3%	87.7%
Maximal	90.1%	99.6%	97.2%
Interval	18.7%	2.3%	9.5%
Standard dev.	5.4%	0.8%	2.6%
Variation coefficient	0.06%	0.01%	0.03%

Table 3. Multivariate regression analysis for the examined indicators following the filtration bed purification process. BOD was used as dependent value.

p	r	Error	Intercept	Error	Slope	Variable
<0.001	0.984	4.772	56.146	0.108	2.507	COD
<0.001	0.934	4.319	15.057	0.098	1.081	TSS
0.437	0.184	0.263	16.785	0.006	0.005	Temp
0.001	−0.691	0.131	4.699	0.003	−0.012	DO
<0.001	0.889	0.057	7.807	0.001	0.011	pH

The elevated *p*-value associated with temperature in Table 3 indicates, upon analyzing the data, that temperature may not exert a statistically significant influence on the measured outcome. Possible explanations for this observation include temperature having no significant effect on the outcome, restricted variability in temperature within the sample, a small sample size, or the statistical model not effectively capturing the relationship. A thorough consideration of these factors, along with the study context, is crucial for a precise interpretation of the results. After the filtration process, there is often sludge to manage. We can handle it in various ways. We might let it settle in tanks, remove the water, or use processes like composting or anaerobic digestion to reduce its volume. Some sludge can be applied to land as a soil conditioner, while other sludge might be incinerated or sent to landfills. The choice depends on the type of sludge and environmental regulations. Combining different methods helps manage sludge effectively in the filtration system.

Based on research evaluating the efficiency of a biological reactor in a domestic wastewater treatment plant, selecting key process parameters is imperative for optimizing the intermittently dosed biological filter bed solution. ABS, among the studied polymers, exhibits the highest microplastic release, posing a potential threat [38]. When contemplating the incorporation of plastic materials, particularly ABS, in biological treatment processes, environmental considerations take precedence. ABS, akin to numerous plastics, holds the potential to release microplastics into treated wastewater during its degradation process. This raises ecological concerns. In the realm of biological treatment, where organic filtration materials are frequently efficacious, the utilization of plastics prompts inquiries about sustainability and environmental impact. Whenever possible, giving preference to organic filtration materials over plastics is recommended due to their lower environmental risk.

4. Conclusions

The laboratory-tested biological filter bed technology presents several notable advantages. Its design is straightforward, requiring no specialized solutions. The absence of movement within the biological bed minimizes friction between bed elements, preventing the loss of plastic particles (ABS). Moreover, the optimal oxygen conditions within the bed create an ideal environment for the biological processes essential for wastewater pollutant removal. However, certain challenges accompany this laboratory-tested filter bed technology. During the preparatory stage, it is crucial to thoroughly rinse the bed to eliminate impurities such as plastic dust and residues from printer toner, especially black ABS, potentially originating from laser printers. Ensuring the even distribution of wastewater across the filtration bed's surface to prevent hydraulic breakthroughs or the formation of preferential filtration pathways is another challenge. Periodic dosing of the bed is necessary, with a recommended minimum frequency of once per hour based on the assumed hydraulic load. The bed's height is a minimum of 150 cm and divided into independent segments, numbering between 10 and 14. Each segment's height is recommended to be no less than 11 cm and ought not exceed 20 cm. The hydraulic load should not exceed 50 dm^3/m^2 daily. The PUR foam must not react with the wastewater and must stay within typical wastewater values. Ensuring a uniform distribution of the wastewater load across the bed is crucial for optimal performance. We suggest implementing wastewater recirculation to improve treatment efficiency and protect the bed from exposure to low temperatures. The bed's design, aimed at facilitating oxygen access from the air, is another essential consideration. The findings suggested considering placing the filter bed within a reinforced concrete tank buried in the ground for enhanced functionality. The research has demonstrated the importance of implementing robust safeguards to prevent the entry of hazardous gases into the bed tank, such as incorporating a siphon at the sedimentation tank inlet. In summary, the research has led to the selection of a recirculating dosed-bed technology that can also function as a biological filter, primarily due to the relatively small grain sizes of the filter media. It is worth emphasizing the significant reduction achieved in wastewater pollutant indicators such as BOD_5, COD_{Cr}, and total suspended solids. Assessing the recyclability of plastics, including ABS, and exploring eco-friendly alternatives in biological treatment processes are crucial. A thorough evaluation of the environmental impact and risks tied to microplastic release informs responsible material choices for sustainable wastewater treatment practice.

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