Increasing the Removal Efficiency of Pollutants from Municipal Wastewater Using Biological Filters

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Abstract

Biological filters are wastewater treatment systems that contain a granular filler, which forms a biologically active film that contributes to the bio-oxidation of impurities in wastewater. Recent research in this field has focused on improving conventional fixed aerobic film treatment plants by using cheap and readily available materials such as filterable fillers. Experiments have been carried out on volcanic tuff-filled biofilters with diameters ranging from 20-100 mm, supplied with municipal wastewater from primary sedimentation. The efficiency of biological filtration was determined during continuous operation of the experimental plant by physico-chemical analysis of the water. The indicators analyzed were those required by current legislation, namely: pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD5), total suspended solids (TS), total nitrogen (TN), total phosphorus (TP), etc. The wastewater samples analysed were average samples. Treatment efficiency was calculated under different assumptions, depending on: plant capacity, hydraulic load, organic load.

Keywords: biofilters, efficiency, pollutants, waste water.

1. Introduction

Maintaining the quality of surface water can be effectively achieved through the implementation of a well-designed wastewater treatment plant, thereby mitigating potential negative impacts on natural receptors [1-5]. The recent economic downturn has heightened interest in energy efficiency due to its potential to lower operational costs by reducing energy consumption [6, 7]. The treatment of wastewater using biofilters involves the cultivation of microorganisms on a biologically inert medium [8]. Biofilters, used in sewage treatment plants, typically contain a granular material (such as gravel, slag, coke, ceramic, or plastic) that supports the formation of a biological film. This film plays a crucial role in the biooxidation of pollutants present in wastewater [9]. The processes through which impurities are transformed into biomass and metabolites are akin to those found in activated sludge treatments [10, 11]. Current advancements in the microbiological and biochemical understanding of wastewater treatment processes have enhanced the design and efficacy of biological filters.

In operation, wastewater containing degradable pollutants is applied to the top of the biofilter's granular layer. The wastewater then flows counter-currently with air through the granular material, where an organic film develops. Since a single pass through the filter material may not suffice to achieve the desired treatment efficiency, the effluent is often recycled. This recycling gradually fosters the development of a community of biological organisms, forming a continuous biological film that aids in the oxidation of

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degradable substrates in the wastewater. As impurities are removed, the biological film thickens and periodically detaches (a process known as moulting) [12, 13]. The detached film is subsequently removed from the treated effluent through sedimentation, with secondary clarifiers typically following biological filters. Similar to activated sludge treatment, the primary role in biological filters is played by bacteria that constitute the fundamental components of the food chain [14]. The removal of dissolved organic substances is primarily achieved through adsorption onto the bacterial cell surfaces [15]. Heterotrophic bacteria and fungi are responsible for the initial oxidation of pollutants, while autotrophic bacteria (which only require carbon dioxide and an inorganic energy source for growth) continue the oxidation process. This group is mainly represented by *Nitrosomonas* (which oxidizes ammonium to nitrites) and *Nitrobacter* (which converts nitrites to nitrates) [16, 17]. Green algae and bacteria are typically found in the uppermost layers of the filter, or just below it. In biofilters with standard loads, ciliates are present in similar proportions to fungi; they feed on free bacteria suspended in the water, thus helping to purify the effluent. The conditions within a biological filter vary with height, supporting the growth of more evolved life forms-such as worms and insects-particularly in the upper, light-exposed sections. In general, the design parameters for biological filters are selected based on recommendations from existing literature, with variations depending on the type of filter employed.

2. Materials and methods

Laboratory experiments were conducted using biological tower filters and high-loading biological filters. The system was operated with a flow rate of 1.0 L/s, distributing 0.2 L/s to the high-load line and 0.8 L/s to the tower line. The experimental setup included three variations for each type of filter (tower or high-load) based on the size, purification degree of the granules, filter layer composition, and ventilation. These variations included filters filled with microcellular tuff, porous medium tuff, and crushed basalt.

The filter material was structured according to standard practices, consisting of a superficial layer (distribution) with a thickness of 20 cm and granule sizes between 20 mm and 40 mm; a working layer with granule sizes from 40 mm to 60 mm; and a lower supportive layer with a thickness of 50-60 cm and granule sizes ranging from 60 mm to 120 mm.

The superficial hydraulic loads applied to the experimental models adhered to the recommended values for such installations: approximately 10 $m^3/m^2 \cdot h$ for biological tower filters and around 1 $m^3/m^2 \cdot h$ for high-loading biological filters. The experiments were designed to subject the filter materials to the most extreme operating conditions, particularly in cold weather, where the risk of filter freezing, and subsequent material degradation is significantly higher. To evaluate the biological treatment process, the filters were charged with municipal wastewater from primary settling tanks, and their efficiency was continuously monitored through physico-chemical water analysis.

The parameters monitored during the experiments included air temperature, water temperature, pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), nitrites (NO_2^-), ammonia (NH_3), and sediments. The wastewater samples analyzed were composite samples collected at intervals corresponding to each stage of the purification process. The characterization of the wastewater used during the experiments is detailed in Table 1.

Overall, the treatment efficiencies achieved were satisfactory across all specific wastewater treatment indicators, given that the raw wastewater had a relatively low pollutant load.

During periods of higher temperatures, the treatment efficiencies significantly improved, achieving BOD_5 removal rates of 72-75% in biological tower filters at an optimal specific hydraulic loading (HL) of 10.18 $m^3/m^2 \cdot h$ and 62-72% in high-loading biological filters at an optimal HL of 0.92 $m^3/m^2 \cdot h$. The development of the biological film proceeded as expected, even though air temperatures were low during the initial phase of the experiments, fluctuating between 14.2°C and 38°C. This outcome was largely due to the raw water temperature, which remained above 9.5°C and reached up to 28°C during the summer.

Table 1. Characterization of wastewater during the experiment

Indicator	Unit	Range of values
Water temperature	^{O}C	10.5÷28
pH	pH units	6÷8
CID	mg O_2/dm^3	62-203
BOD_5	mg/dm^3	25÷63
TSS	mg/dm^3	60÷246
TN	mg N/dm^3	9.3÷104.8
TP	mg P/dm^3	0.1÷1.5
$NO^{-}_{2}{}^{-}$	mg N/dm^3	0.018÷3.6
NH_3	mg N/dm^3	5.4÷11.3
Sediments	cm^3/dm^3	0.9÷3.0

Seven to ten days after the experiments commenced, a well-developed biological film was observed on both the tuff and stone granules. Volcanic tuffs exhibited a more advanced film development compared to crushed stone, a finding corroborated by physico-chemical analyses, which indicated more efficient purification with volcanic tuffs during this period.

An analysis of the average values of technological parameters from the experimental installations revealed that the obtained values were quite consistent across all three types of tested filter materials. However, the highest values were observed in high-loading biological filters and particularly in biological tower filters, where the differences were more pronounced, with the highest values coming from the average porous tuff, followed by microporous tuff, and lastly, crushed stone.

At specific hydraulic loadings of HL=0.92 $m^3/m^2 \cdot h$ and HL=2.29 $m^3/m^2 \cdot h$ in high-loading biological filters, the oxidation processes achieved higher values.

3. Results and discussion

During the experiments, the hydraulic loadings (HL) for biological tower filters ranged between 5.08-15.26 $m^3/m^2 \cdot h$, with organic loads of 39.03-126.18 g $BOD_5/m^3 \cdot h$. For high-loading biological filters, HL values ranged from 0.46-2.29 $m^3/m^2 \cdot h$, with organic loads of 10.66-32.92 g $BOD_5/m^3 \cdot h$. The treatment efficiencies were satisfactory across all specific indicators, considering the relatively low load of the raw wastewater. The results are presented in Figures 1, 2, and 3.

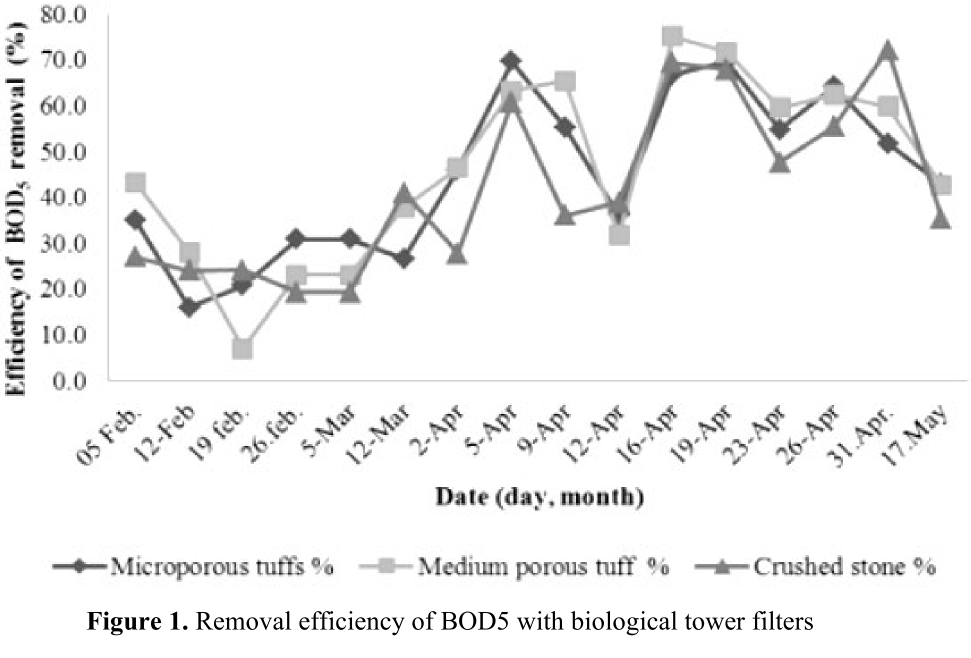

Figure 1. Removal efficiency of BOD5 with biological tower filters

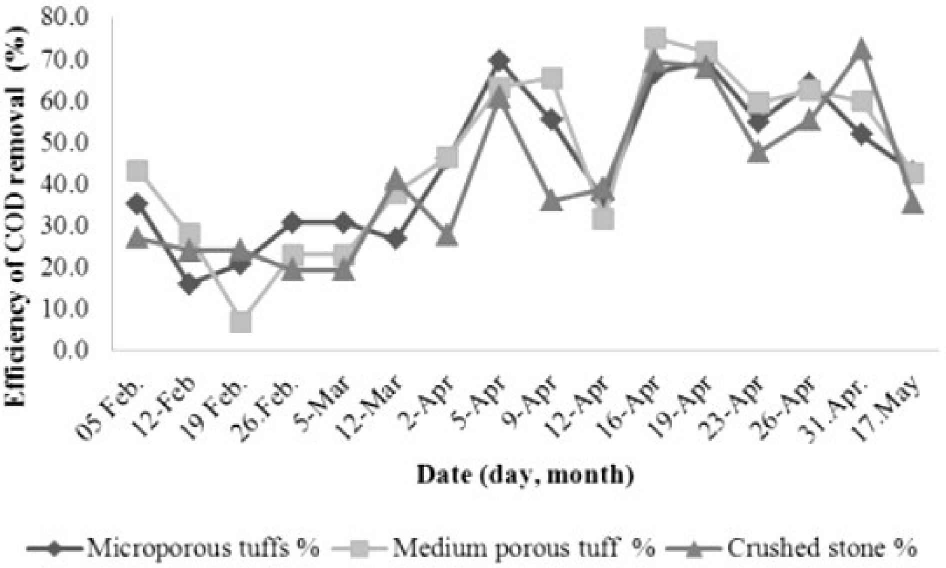

Figure 2. Removal efficiency of COD with high loading biological filters

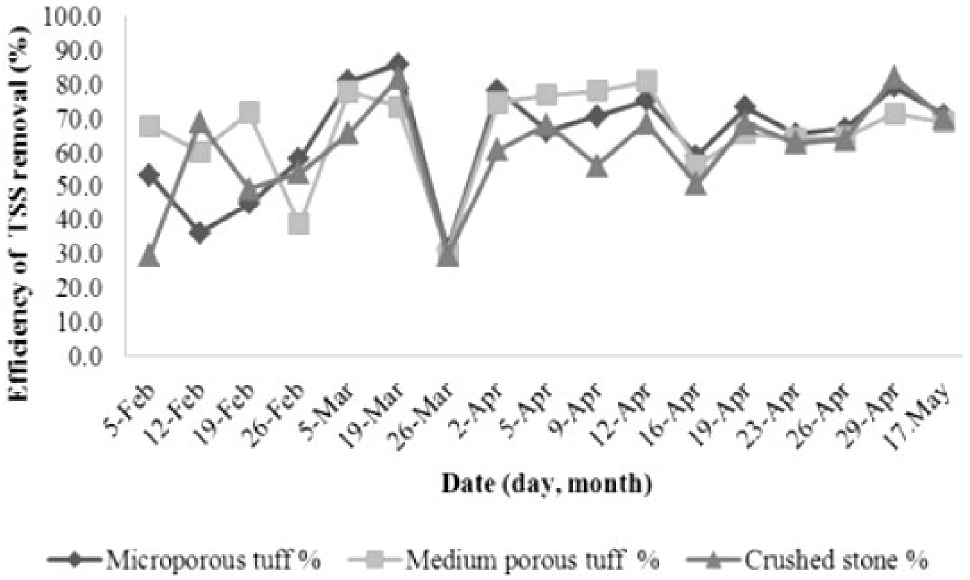

Figure 3. Removal efficiency of TSS with high loading biological filters

In warmer periods, treatment efficiency improved significantly, with biological tower filters achieving BOD_5 removal rates of 72-75% at an optimal HL of 10.18 $m^3/m^2 \cdot h$, and high-loading filters achieving 62-72% at an HL of 0.92 $m^3/m^2 \cdot h$. Despite low air temperatures during the initial phase, the biological film developed normally, with water temperatures ranging from 9.5°C to 28°C. After 7-10 days, a well-developed biological film was observed, particularly on volcanic tuffs, which showed more efficient purification compared to crushed stone, as reflected in the physico-chemical analyses.

Across all tested filter materials, similar values were obtained, with porous tuff showing the highest efficiency, followed by microporous tuff and crushed stone. For high-loading filters, BOD_5 removal efficiencies ranged from 15-72% depending on the material and HL, with the highest efficiency observed at HL=2.29 $m^3/m^2 \cdot h$ (Table 2). In biological tower filters, BOD_5 removal ranged from 13-75%, with medium porous tuff generally performing the best (Table 3).

Table 2. Removal efficiency of BOD_5, obtained for high loading biological filters

Specific hydraulic loadings (m^3/m^2xh)	Removal efficiency of BOD_5, obtained for high loading biological filters		
	Microporous tuff (%)	Medium porous (%)	Crushed stone (%)
0.46	50-66	46-64	36-40
0.92	15-67	15-68	15-72
2.29	51-52	41-69	31-61

Table 3. Removal efficiency of BOD_5, obtained for biological tower filters

Specific hydraulic loadings (m^3/m^2xh)	Removal efficiency of BOD_5, obtained for high biological tower filters		
	Microporous tuff (%)	Medium porous (%)	Crushed stone (%)
5.08	3-52	43-60	35-72
10.18	13-72	7-75	12-74
15.26	55-64	60-62	48-55

4. Conclusions

The experimental results obtained from treatment installations equipped with aerobic film systems, such as biological tower filters and high-loading biological filters, demonstrated consistent performance across all three types of tested filter loadings when operated with municipal wastewater. The technological parameters and biological observations of the fixed film showed that the efficiencies of these systems were closely aligned, regardless of the filter material used-whether it was microcellular tuff, porous tuff, or crushed basalt. The treatment efficiency of the wastewater was satisfactory across all specific indicators, which is particularly notable given the relatively low pollutant load of the raw water. This suggests that even under suboptimal conditions, such as low organic load, the tested systems were able to maintain effective treatment performance.
Considering the experimental findings, it is suggested that incorporating additional biological filters loaded with volcanic tuff into municipal wastewater treatment plants could significantly enhance the treatment efficiency of these systems. The volcanic tuff material, with its favourable characteristics, appears to contribute positively to the biological filtration process, making it a valuable addition to conventional wastewater treatment technologies.

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