

Efficiency of Filters Filled with Rockfos for Phosphorus Removal from Domestic Sewage

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ABSTRACT

The goal of the present study was to evaluate the efficiency of filters filled with Rockfos for removal of phosphorus (Total-P) from domestic wastewater. Rockfos is a material obtained by calcination of carbonate-silica rock (opoka) at a temperature of 900 °C. A field study was conducted in two filters with volumes of 2.0 and 0.8 m³ which were components of hybrid constructed wetlands with an average capacity of 2.0 m³/L, located in two national parks in south eastern Poland. Samples of the influent to and the effluent from the filters were analyzed for Total-P concentrations and pH. Eighty sewage samples were tested over a five year study period. It was shown that the test filters removed Total-P with an average efficiency of 31.5% and 30.2% and that they could be successfully used to remove phosphorus from domestic wastewater in small wastewater treatment plants.

Keywords: efficiency, domestic wastewater, chemical of phosphorus removal, filters, Rockfos

INTRODUCTION

Phosphorus is removed from wastewater in treatment plants to prevent the discharge of large loads of this element into inland waters. Intensive farming and densely populated areas are the main sources of nutrient pollution of Europe's inland and coastal waters [1]. In 2005–2012, the load of P discharged to European seas was 0.26–0.30 TgP/yr. The European Union (EU) has policies to protect and restore freshwater and marine ecosystems. As part of these policies, the EU supports the development of technological measures that can reduce the export of nutrients to the seas, improve the ecological status of rivers and lakes, and affect eutrophication [2].

The ecological condition of more than half of the EU's water bodies does not comply with the requirements of the EU Water Framework Directive (2000/60/EC), and nutrients are one of the main

causes of their degradation [3]. Eutrophication deteriorates water quality and changes the condition and functioning of aquatic ecosystems [4–7]. The concentrations of Total-P in domestic wastewater, as reported in the literature, range from about 4 to as many as 60 mg/L [8–11]; meanwhile, pursuant to Council Directive 91/271/EEC [12], the maximum P concentration in wastewater discharged from treatment plants serving <100000 PE should be 2 mg/L. In Poland, the P concentration limit for treated wastewater set in the Regulation of the Polish Minister of Maritime Economy and Inland Navigation [13] for wastewater treatment plants of different sizes ranges between 1 to 5 mg/L. In Sweden, the maximum concentration of this element in sewage discharged from wastewater treatment plants serving from <2000 PE to > 100000 PE is 0.5 mg/L, in Denmark it is 0.4 mg/L. In HELCOM countries [14], the maximum concentration of P in wastewater treatment

plants serving 300–2000 PE is 2 mg/L, in plants serving 2000–10000 PE – 1 mg/L, and in plants serving > 10000 PE – 0.5 mg/L. In China and the USA, the maximum concentration of P in treated sewage should be 0.5 mg/L and 1.0–0.1 mg/L, respectively, regardless of treatment plant size [15].

In this light, it is necessary to look for methods that would allow to effectively remove P from wastewater in order to meet the national and international requirements [16, 17]. In previous research, attempts have been made to remove P from wastewater using LWA [18–20], light aggregates [21], electric arc furnace slags [22], laterite [23], peat [24, 25], dolomite [26, 27], blast furnace slag [16], limestone [28], calcite [29], and opoka [30, 10]. These so-called reactive filter media, sometimes also referred to as P-sorbents or reactive substrates, have a high affinity for phosphorus [22, 31].

The technology of removal and subsequent recovery of phosphorus from wastewater is still in the experimental phase, but its development may contribute to the sustainable management of P resources in the future. The topic of the present paper fits very well within this line of research. The goal of the study reported below was to determine the effectiveness of a method for removing phosphorus from wastewater with the use of opoka, a type of carbonate-silica rock which has a high affinity for this element. To achieve this goal, we tested two full-scale filters filled with calcinated opoka (Rockfos® material), operating in south-eastern Poland.

MATERIALS AND METHODS

Characteristics of the test filters and Rockfos

A field study was conducted in two hybrid constructed wetlands to determine the efficiency of two full-scale filters filled with Rockfos in removing phosphorus from wastewater.

Filter 1 was located in the village of Kosobudy in the Roztocze National Park (50°37'48"N, 23°04'43"E). It was part of the technological system of a wastewater treatment plant which served 20 users. The designed flow capacity of the treatment plant was 2.0 m³/d. Apart from the filter in question, the wastewater treatment plant included a three-chamber primary settling tank, a vertical flow (VF) bed with reed mannagrass (*Glyceria maxima* (Hartm.) Holmb.), a horizontal

flow (HF) bed with common reed (*Phragmites australis* (Cav.) Trin. Ex Steud.), and an HF bed with common osier (*Salix viminalis* L.). Treated wastewater was discharged into an infiltration pond. The Rockfos filter was the last element of the system and was located downstream of the last bed of the constructed wetland system planted with common osier. Its task was to provide a final clean before the biologically treated wastewater was discharged into the receiver. The filter chamber was a rectangular tank made of concrete elements. The parameters of the chamber are given in Table 1. At the bottom of the filtration chamber, there was a coil of coconut fibre drainage pipe (approx. 4 m) covered with Rockfos. The volume of the filter medium was 2.0 m³. In the filter, wastewater flew vertically upwards and was discharged through a sewage pipe located above the surface of the Rockfos filter layer (Fig. 1).

Filter 2 was a component of a treatment plant located at the Educational–Museum Centre in Stare Załucze (51°23'45,1"N, 23°07'19,8"E) in the Polesie National Park. The wastewater treatment plant which the filter operated in served 20 users, and had a daily flow capacity of 2.0 m³/d. It consisted of a three-chamber primary settling tank, a VF bed with with reed mannagrass (*Glyceria maxima* (Hartm.) Holmb.), four parallel HF beds with common reed (*Phragmites australis* (Cav.) Trin. ex Steud.), a filter for P removal filled with Rockfos, and an infiltration pond which was the receiver of the effluent [32, 33]. The filter chamber was a polyethylene well with a diameter of 1.20 m and a height of 2.25 m (Table 1). The volume of the filter medium was 0.8 m³. The influent was supplied at the bottom of the chamber, and the effluent was discharged through a sewer pipe located above the surface of the Rockfos filter layer.

Rockfos, the medium used in the test filters, was formed by heat-treating opoka mined near the town of Piaski in the Province of Lublin, Poland. The rock was fired at 900 °C to obtain a material with CaO and SiO₂ contents of 43.336% and 36.047% by weight, respectively (Table 2). An important component of this material was also Al₂O₃. The remaining compounds were present in small amounts below 4% by weight (Table 2). The concept of the material was developed based on the experiments conducted by Józwiakowski [10, 34], Karczmarczyk and Mosiej [35], Brogowski and Renman [30], Renman [36], Cucarella [37], and the manufacturer of the opoka.

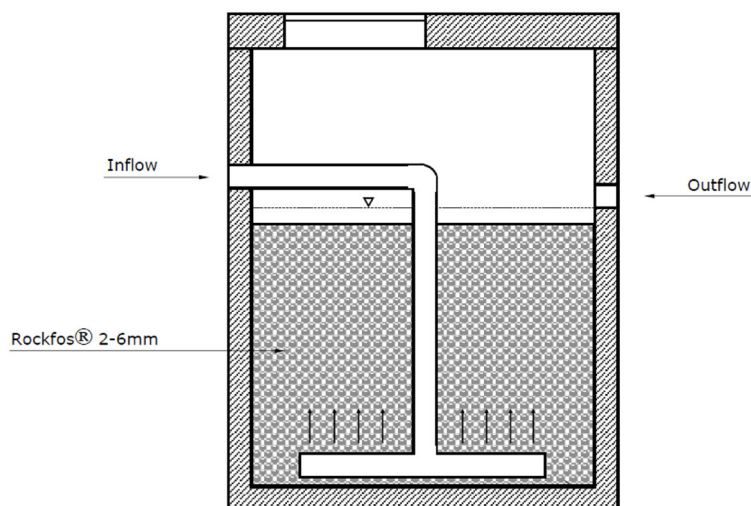


Figure 1. Schematic of the chamber of a P removal filter filled with Rockfos

Table 1. Characteristics of the filters filled with Rockfos used in the investigated hybrid constructed wetlands [32, 33].

Parameters	Filter 1 Kosobudy	Filter 2 Stare Załucze
Chamber depth [m]	2.50	2.25
Chamber width/diameter [m]	1.40	1.20
Volume of filter with Rockfos [m ³]	2.0	0.8
Wastewater retention time [h]	12.96	5.18
Design hydraulic load [m ³ /m ³ /d]	1.0	2.5
Design daily capacity [m ³ /d]	2.0	2.0
Start-of-operation date	Oct. 2014	Jul. 2015

According to the manufacturer’s data, Rockfos has a porosity of 54%. The granule sizes range between 2–5 mm. It is an alkaline material with a pH of 11–12. The material used in the present study was obtained from the Ceramika – Kufel company.

Table 2. Chemical composition of the Rockfos medium used in the present field study (<http://www.ceramika-kufel.pl/rockfos/>)

Chemical component	Content [% by weight]
CaO	43.336
SiO ₂	36.047
Al ₂ O ₃	5.932
Na ₂ O	2.856
Fe	1.340
MgO	0.938
TiO ₂	0.960
S	0.654
K ₂ O	0.489
P	0.480
Cl	0.237
MnO	0.117

Method

Analyses and physico-chemical measurements of wastewater treated in the filters filled with Rockfos were performed in the years 2015–2020. Wastewater samples were collected seasonally, four times in each year of the study, in accordance with Polish standards [45]. In each filter, samples of wastewater treated biologically in the constructed wetland systems and wastewater treated in the filters with Rockfos were analysed. A total of 80 wastewater samples were collected. The samples were analysed for Total-P concentration and pH. Physico-chemical analyses were carried out in accordance with the “Reference methodologies for the analysis of wastewater samples” [13] and the methodologies described in the Polish Standards. The reaction (pH) was determined by the electrometric method using a portable ORION Thermo Scientific meter STAR A329 SET [46]. Total-P was determined using the photometric method [47]. The Total-P concentration was determined with a MACHEREY-NAGEL Nanocolor VIS spectrophotometer after

Table 3. The sorption capacity of Rockfos and other filter materials according to literature data

Material	Fraction [mm]	Sorption [gP/kg]	Reference
Natural opoka	0.125 – 2.0	0.1	[16]
Natural opoka	–	19.6	[30]
Opoka heated at 1000 °C	–	119.6	[30]
Opoka heated at 900 °C	pylasta	79 – 182	[38]
Opoka heated at 900 °C	0.05 – 0.20	0.0123 – 0.0255	[39]
Opoka heated at 950 °C and 800 °C	1.0 – 5.0	0.01006 – 0.02085	[40]
Rockfos	0 – 2.0	0.0456 – 0.0457	[41]
Rockfos	0 – 2.0	0.25641	[42]
	2.0 – 8.0	0.000036	
White brick	2–5	0.00001	[43]
AAC	2–5	0.00002–0.00050	
Pollytag	8–11	0.00034–0.00267	
Shell sand	1–5	0.0002–0.001	
Coral sand	0.5–2	0.00002–0.00013	
Black sand	0.25–1	0.00007–0.00017	
Philippine limestone	2–5	0.00002–0.00004	
Philippine limestone heated	2–5	0.00011–0.00052	
Limestone	2–4	0.00018–0.00050	
Polonite®	2–5	0.00010–0.00121	
Red mud	< 0.194	0.1139	
Shellsand	3–7	0.0096	
Flay ash	< 0.149	0.0632	
Furnace slag	0–5	0.0089	
Filtratte P	0.5–4	0.000473	
Iron sludge	< 2	0.0161	
Electric arc furnace slag	2.5–10	0.00235	
	6.35–11	0.0013	
Ca-Fe oxide granules, fresh and pre-leached	2–5	0.0068	

oxidation of the test sample in a thermoreactor at 120 °C for 30 minutes.

The mean Total-P concentrations in influent (C_i) and effluent (C_e) wastewater were used to calculate the Total-P removal efficiency on the basis of the following formula:

$$\eta = 100 \cdot [1 - C_e/C_i] [\%] \quad (1)$$

The composition of the effluent from the filters was compared with the requirements set out in [12] and [13].

To assess the performance of the filters in the field facilities, technological reliability coefficients in relation to Total-P were determined using the following formula [48]:

$$RC = \mu_x/X_{lim} \quad (2)$$

where: WN – technological reliability coefficient
 μ_x – mean value of a pollution parameter in the effluent [mg/L],

X_{lim} – limit value of the given pollution parameter in the effluent [mg/L].

Statistical analysis was conducted to evaluate the influence of the operating time of the filters, pH and the Total-P concentration on P removal efficiency.

On the basis of the results, the basic statistical characteristics of the analysed pollution parameters were determined, including the mean, median, standard deviation, coefficient of variation, reliability coefficient, minimum, and maximum.

Multivariate analysis of variance (MANOVA) was performed to determine differences between filters 1 and 2 in P removal efficiency and changes in pH. Normality was assessed with the Shapiro-Wilk test, and the homogeneity of variances with Levene’s test.

In the case of the concentration of Total-P in the influent to and effluent from the filters, the null hypothesis of normality was rejected, and so the hypothesis of equality of mean P concentrations

in the wastewater samples collected from the investigated field facilities was tested with the non-parametric Kruskal-Wallis test. Wilcoxon’s test was used to check whether the concentration of phosphorus in the effluent from the filters differed from that in the influent.

A regression approach was used to describe the variability of parameters over time. The significance of the regression models was tested with the (Fisher-Snedecor) F-test. Pearson’s correlation coefficients were used to assess the strength and direction of changes in the examined parameters, and the coefficient of determination was used to determine to what extent the regression equation explained the dynamics of changes in the investigated phenomena over time. The test results were analysed using STATISTICA 13.3 at a significance level $\alpha = 0.05$.

RESULTS AND DISCUSSION

Total-P concentration and pH in the wastewater

Table 4 presents the basic descriptive statistics for Total-P concentrations and pH values for

the influent to and effluent from the filters filled with Rockfos.

In wastewater treated in filter 1, Total-P concentrations ranged from 0.04 mg/L to 5.56 mg/L. The mean concentration was 0.96 mg/L, and the standard deviation was 1.32 mg/L. The coefficient of variation was 138.08%, which points to a very high variability of Total-P concentrations in treated wastewater [49].

In the case of this filter, significant changes in Total-P concentration in the effluent were observed over time (Table 5, $p < 0.05$). The negative value of Pearson’s coefficient ($r < 0$) indicates that the Total-P concentration in the wastewater discharged from this filter decreased over time.

In the effluent from filter 2, Total-P concentrations ranged from 0.03 to 7.73 mg/L. The mean concentration was 1.08 mg/L, and the standard deviation was 1.95 mg/L. The Vs coefficient of 180.7%, shows that there was a very high variability in the Total-P concentration in effluent wastewater [49].

In the case of filter 2, the effluent concentration of Total-P was affected by the influent concentration of this element (Table 5, $p < 0.05$). The model of relationships developed for the effluent concentration of Total-P indicates that

Table 4. Descriptive statistics for influent and effluent Total-P concentrations and pH for filters filled with Rockfos

Descriptive statistic	Unit	Filter 1		Filter 2	
		Influent	Effluent	Influent	Effluent
Total-P					
Mean	mg/dm ³	1.31	0.96	1.22	1.08
Standard deviation		1.60	1.32	1.67	1.95
Maximum		5.46	5.56	6.52	7.73
Minimum		0.07	0.04	0.09	0.03
Coefficient of variation	%	122.87	138.08	136.24	180.70
Reliability coefficient acc. to Council Directive	-	0.26	0.19	0.61	0.54
Reliability coefficient acc. to Polish Regulation	-	0.65	0.48	0.24	0.12
pH					
Median	-	7.14	7.86	7.26	7.73
Maximum		8.17	11.28	7.72	9.25
Minimum		6.88	7.08	6.74	6.54
Coefficient of variation		%	4.14	13.37	3.53

Table 5. A linear relationship for Total-P concentration (P_{tot}) in the effluent and associated statistics

Filter	P_{tot} concentration	r	R ²	p-value
1	$0.33 - 0.02 \cdot t$	-0.53	0.28	0.0158
2	$0.12 + 0.46 \cdot P_{infl}$	0.82	0.67	0.0004

Note: t – time, P_{infl} – total phosphorus concentration in the influent, r – Pearson’s correlation coefficient, R² – coefficient of determination.

this concentration increased by an average of 0.46 mg/L as the influent concentration of Total-P grew by 1 mg/L.

The minimum and maximum pH values for the effluent from filter 1 were 7.08 and 11.28, respectively. Median pH was 7.86. The coefficient of variation was 13.37%, and it attested to the low variability in pH readings [49].

The analysis also showed a significant variability over time in the pH of the effluent (Table 6, $p < 0.05$). Negative Pearson correlation values ($r < 0$) indicate that the effluent pH values decreased over time.

The median pH of the effluent from filter 2 was 7.73. The minimum pH reading was 6.54, and the maximum pH was 9.25. The coefficient of variation was 9.65%, which meant the variability of the readings was low [49].

Similarly to filter 1, a significant variation over time was observed for effluent pH (Table 6, $p < 0.05$). The pH values for the wastewater discharged from filters 1 and 2 were similar to those obtained by [10]. Like in the present study, in his experiments, the pH of the effluent initially increased to then gradually decrease. Similar trends were observed by [50] and [51] in their research on Polonite.

The pH values of the effluent from both filters were similar to those set out in the Regulation of the Polish Minister of Maritime Economy and Inland Navigation [13, Annex 4] nearly throughout the entire study period. pH values of over 9 were recorded in both filters only during the first

months of the study; for the rest of the study period, they did not exceed the limit value (Fig. 2).

The non-parametric Kruskal-Wallis test showed that there were no significant differences between the two filters in influent Total-P concentrations (Fig. 3, KW test, $p > 0.05$), however, the facilities differed significantly when data for effluent wastewater were analysed (Fig. 3, KW test, $p < 0.05$). The Total-P concentration in the effluent was significantly lower than in the influent, as confirmed by the Wilcoxon test (Fig. 3, W, $p < 0.05$).

Outliers occurred because P was released from the medium to the treatment plant, and then penetrated into the influent to both filters.

The large spread of the results obtained over the 5-year study period was caused by the filters getting clogged on several occasions and the influent being diluted by rainwater and meltwater.

In the twenty test runs, one exceedance of the limit Total-P concentration of 5 mg/L, as set in [13], was observed in wastewater discharged from filter 1 and two in effluent from filter 2. The limit Total-P concentration specified in [12] for wastewater discharged from treatment plants that serve < 100000 PE (2 mg/L) was exceeded three times in each of the filters (Fig. 4).

Total-P removal efficiency of the Rockfos filters

Based on influent and effluent Total-P concentrations, the P removal reliability of the field

Table 6. Time trend model for the pH of the effluent from filters 1 and 2, and associated statistics

Filter	pH	r	R ²	p-value
1	$9.36 - 0.12^*t$	-0.67	0.45	0.0012
2	$8.26 - 0.06^*t$	-0.49	0.24	0.0343

Note: t – time, r – Pearson’s correlation coefficient, R² – coefficient of determination.

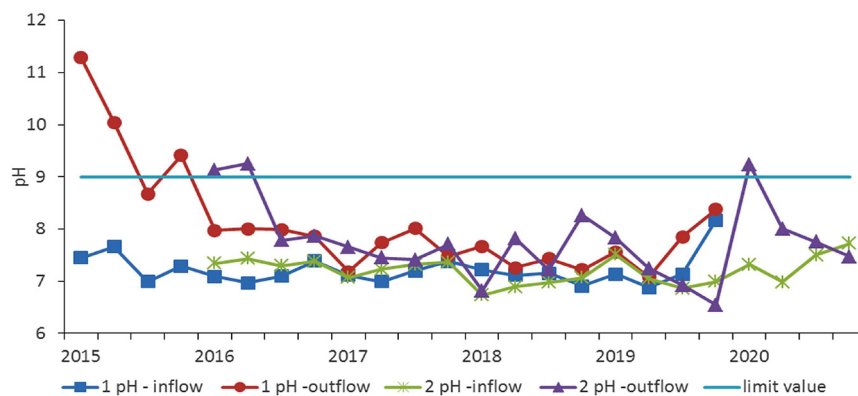


Figure 2. Influent and effluent pH values for filters 1 and 2

filters was determined by calculating technological reliability coefficients for each of them [48]. The values of the technological reliability coefficients confirmed that the filters used in the constructed wetlands improved the parameters of the wastewater treated in these treatment plants by reducing Total-P in the sewage to the levels specified in [12] and [13]. In filter 1, the reliability coefficients calculated in relation to the normative values specified in [12] and [13] were 0.19 and 0.48, respectively. In the case of filter 2, the respective coefficients were 0.54 and 0.12 (Table 4).

Figure 5 shows the efficiency of the investigated filters in removing Total-P, and Table 7 shows models of efficiency as a function of time.

The average annual Total-P removal efficiency of filter 1 was quite stable over the first three

years of the study and oscillated around 40%. In the following years, however, it gradually decreased to drop to 1.54% in 2019 (Fig. 5, no. 1). For filter 2, changes in the efficiency of Total-P removal over time were statistically significant (Table 7, $p < 0.05$). In the first year of the study, an over 80% efficiency of Total-P removal from wastewater was recorded. In the following years this figure regularly decreased. In 2020, the average concentration of Total-P in the effluent from the filter increased compared to that in the influent (-10.91%) (Fig. 5, filter 2).

The use of filters with Rockfos in the technological lines of the investigated constructed wetlands brought positive results, though the efficiency of the filters dropped over time. This was most likely due to Rockfos gradually losing its capacity to absorb P.

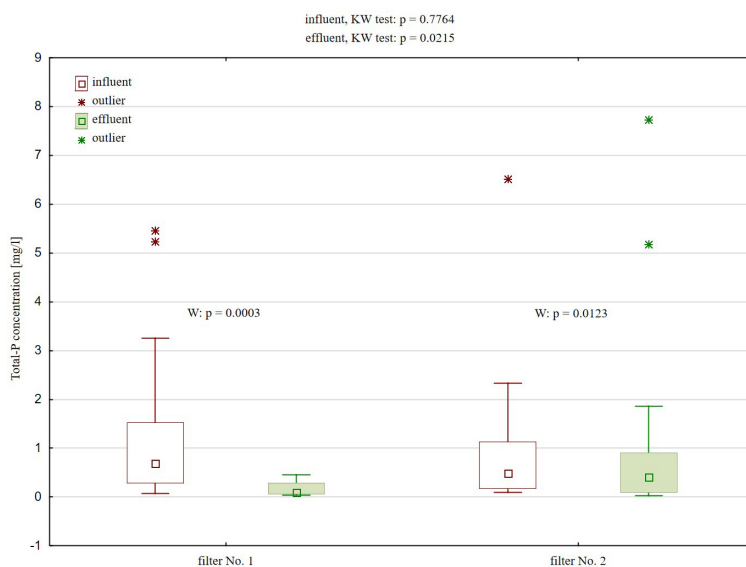


Figure 3. Influent and effluent Total-P concentrations (the square denotes the median; the box represents the lower and upper quartile range; the whiskers correspond to the minimum and maximum values; KW test is the result of the Kruskal-Wallis test; W stands for Wilcoxon’s test)

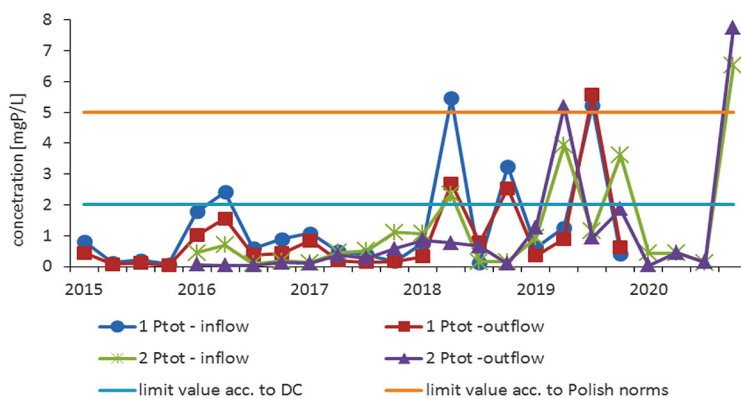


Figure 4. Total-P concentrations in effluent from filters 1 and 2

Table 7. Total-P removal efficiency of the test filters at time t and associated statistics

Filter	Efficiency	r	R ²	p-value
1	59.40 – 9.28.	-0.85	0.72	0.0672
2	96.73 – 22.18*t	-0.98	0.95	0.0047

Note: r – Pearson’s correlation coefficient, R² – coefficient of determination.

The efficiency levels we observed were usually much lower than those obtained in field studies conducted by other authors [36, 51, 53, 54, 55] with other filter media produced from opoka.

Renman [36], in a 94-week study of a domestic wastewater treatment plant with a bed filled with Polonite (a material similar to Rockfos), obtained an average Total-P removal efficiency of over 95%. Similarly [54], where conducted long-term field experiments (84 and 136 days) using wastewater with high and low BOD₇ levels, found that Polonite removed P significantly better ($p < 0.01$) than BFS (blast furnace slag). The efficiency of P removal by Polonite® for a high BOD₇ (120 mg/dm³) was 76%, and for a low BOD₇ (20 mg/dm³) – 93%. Overall, their results demonstrated that pre-treatment of wastewater played a large role in achieving good P removal rates in filters with reactive media and in extending their useful life [54].

According to [51], the average P removal rate for a filter bed with Polonite which had been used in a domestic wastewater treatment plant for 94 weeks was 89%. These values are higher than the Total-P removal efficiency observed in the plants investigated in this present study. In a 144-week study, Józwiakowski [10] found that filters with opoka used in facilities located in Jastków, Dąbrowica and Janów (Poland) removed P with an average efficiency of 18.2, 35.7 and 34.7%, respectively, and the average concentrations of Total-P in wastewater discharged from those treatment plants were 7.3, 4.1 and 1.0 mg/dm³, respectively. Our results from the initial period of operation of the filters with Rockfos were higher than those obtained by [10]. In experiments conducted by [56] on the efficiency of opoka rock fired at 1000 and 900 °C, the Total-P removal rate exceeded 95.

Figure 6 shows the P removal efficiencies of the two facilities tested in this paper as a function

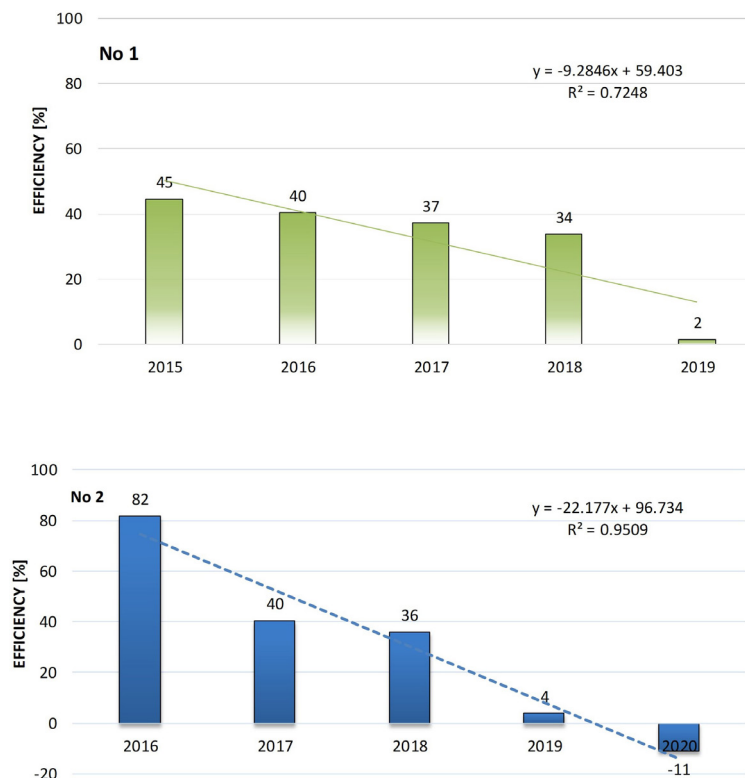


Figure 5. Average annual Total-P removal efficiency of filters 1 and 2

of the pH of the influent. A statistically significant model was obtained only for filter 1 ($p < 0.05$). It explained 32% of the variance in P removal efficiency, which means that the remaining 68% was due to factors other than pH, such as the chemical components of Rockfos and the operation times of the filters. The negative value of Pearson's coefficient ($r < 0$) indicated that the P removal efficiency for filter 1 decreased with increasing influent pH. The tendency for pH to increase in wastewater filtered through the Rockfos medium was observed in both test facilities. Figure 6 shows that the P removal efficiency of the filters was higher at higher pH values, above 9 (mainly in the first year of the study). With time, the pH of the treated wastewater decreased, as did the P removal efficiency of the filters. In [51] conducted 68-week experiments using Polonite to remove P in full-scale wastewater treatment systems, obtained a strong positive correlation between the efficiency of removal of P from sewage, and pH ($R^2 = 0.94$). The higher the pH of the effluent discharged from the filter with Polonite, the higher was the filter's P removal efficiency. A comparative study of various filter media carried out by [57] demonstrated that low effluent pH values were indicative of low P sorption, but higher pH values do not always reflect higher sorption, as demonstrated by [55].

Higher pH values promote the precipitation of calcium phosphate [58], which is the main phosphorus-retaining component [59]. Studies by [19], [53], [54], [56], and [60] on the efficiency of filter media in removing P from wastewater show that when the pH of the treated wastewater exceeds 9, P reduction is very high. Our present study leads

to similar conclusions. The lower the effluent pH, the lower was the P removal efficiency of the filters with Rockfos (Tables 6 and 7, $r < 0$).

The high pH values obtained in our own research, which point to a clear tendency for wastewater to become alkaline as it passes through filters filled with sorbents with a high content of calcium compounds, are problematic. They pose a vital problem when it comes to the safe discharge of treated wastewater to the aquatic environment. [61] showed that the pH of treated sewage could be reduced to an admissible level using peat. Another way to lower the pH of treated wastewater is to aerate and dilute it [22, 62].

The results of our field study indicated that filters filled with Rockfos ensured additional elimination of Total-P from wastewater before it was discharged to a receiver. The efficiency of filter 2, in which the hydraulic load was $2.5 \text{ m}^3/\text{m}^2/\text{d}$, decreased in the 4th year of operation from the initial level of above 80% obtained in the first year of operation. In the case of filter 1, with a hydraulic load of $1 \text{ m}^3/\text{m}^2/\text{d}$, a clear decrease in P removal efficiency occurred in the fifth year of the study, with the efficiency levels being more stable throughout this period.

According to [63], overly long retention times may reduce the capacity of media to remove P. In [22] reported that most of the filter media used had high P removal efficiencies in the first 4–5 years of use, but there were also media with a shorter useful life. The efficiency of these materials systematically and substantially deteriorated over the period of 5 years. Many authors found that media which had a very high P removal efficiency in the laboratory did not give similar results under field

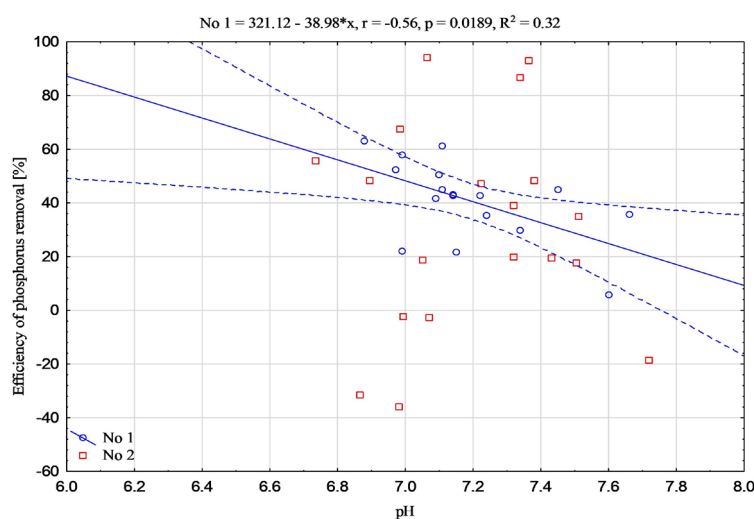


Figure 6. P removal efficiency as a function of influent pH (dashed lines mark the 95% confidence interval)

conditions [64, 65]. As reported by [66] and [67], it is advisable to use a separate filtering unit that contains replaceable material with a high P binding capacity, to extend the life of a filter medium.

CONCLUSIONS

The present study shows that Rockfos filters are suitable for Total-P removal from domestic wastewater in small wastewater treatment plants. Total-P was most effectively removed in the first year of filter operation; in that period, filter 1 removed more than 40% and filter 2 – more than 80%. In the next years, the efficiency of the filters systematically decreased to zero, or even to negative values in the fifth year of operation. The Total-P removal efficiency of the filter which was operated with a hydraulic load of 2.5 m³/m²/d decreased clearly in the fourth year of operation; for the filter with the lower load of 1 m³/m²/d, a prominent decrease in efficiency occurred in the fifth year of operation. The useful life of filters operated with these hydraulic loads is 3–4 years. After this time, the Rockfos filter medium should be replaced.

In one of the filters, a significant variation in effluent Total-P concentration over time was observed. The negative value of Pearson's coefficient indicated that the concentration of Total-P in the treated wastewater discharged from this filter decreased over time. In the case of the other filter, a significant effect was exerted by the concentration of Total-P in the influent.

In the initial stages of operation, wastewater treatment in filters with Rockfos led to an increase in the pH of the effluent. With time, the pH of treated wastewater decreased, and the differences between the individual years of the study were statistically significant. The pH values recorded in the initial period of operation exceeded the limits for treated sewage, which shows that the pH of the wastewater must be corrected before the effluent is discharged into a receiving body.

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