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Pollutant removal efficiency in a meander flow filter applied in the outflow of a constructed wetland wastewater treatment plant – A case study

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ABSTRACT

The aim of the study was to determine the phosphorus removal efficiency of Rockfos® material used to fill a full-scale meander-flow P-filter. The filter constitutes the final stage of a hybrid constructed wetland wastewater treatment plant located in Białka, Dębowa Kłoda commune in southeastern Poland. During the May 2022–July 2025 study, phosphorus removal efficiency and pH changes were analyzed based on wastewater analysis before and after the P-filter. Additionally, an extended wastewater analysis was conducted between August 2024 and July 2025, including analysis of total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), electrolytic conductivity, and total nitrogen (TN). The phosphorus removal efficiency of the meander-flow filter during the full study period was 44.43%. Statistical analysis showed a significant effect of P-filter on pH, turbidity, conductivity, and changes in phosphorus concentrations, total alkalinity, as well as BOD_5. No significant effect was found on total nitrogen and COD.

Keywords: wastewater treatment, phosphorus removal, meander flow filter, Rockfos® material, constructed wetlands.

INTRODUCTION

Sustainable development and growing environmental demands require environmental engineering to implement innovative, yet environmentally friendly solutions for domestic wastewater treatment, particularly in rural areas. Hybrid constructed wetlands have attracted particular attention in recent years. These facilities integrate natural biological processes with technological structures, enabling the effective removal of pollutants from domestic wastewater, including total suspended solids, nitrogen compounds, and phosphorus (Jóźwiakowski et al., 2019; Kataki et al., 2021; Obarska-Pempkowiak et al., 2015; Stefanakis, 2019; Wu et al., 2015). These systems are particularly effective in treating domestic wastewater; in addition, their efficiency can be further enhanced through appropriate design and the use of specialized filter materials. One of the greatest challenges in the domestic wastewater treatment process is the removal of phosphorus, which, in excess, leads to eutrophication of surface waters and the degradation of aquatic ecosystems (Abdoli et al., 2024; Di Capua et al., 2022; Zheng et al., 2023).

Contemporary methods for removing phosphorus from wastewater include biological and physicochemical methods. Biological phosphorus removal from wastewater utilizes the ability of polyphosphate bacteria to capture and store phosphorus compounds within their cells. This process is environmentally friendly, but it requires a constant inflow of wastewater and a high BOD_5 to total phosphorus concentration. Therefore, its effectiveness may not be high in small wastewater treatment plants, where the quantity and quality of influent wastewater fluctuates greatly. Chemical phosphorus removal from wastewater in conventional treatment plants involves precipitation using PIX, PAX, or lime, followed by the formation of struvite, hydroxyapatite, etc. (Rayshouni and Wazne, 2022; Soares et al., 2017). This gives the possibility of phosphorus recovery (Kasprzyk and Gajewska, 2019; Muys et al., 2021; Soares et al., 2017; Wang et al., 2021; Zhang et al., 2019) or agricultural use (Kataki et al., 2016).

An innovative solution for removing phosphorus from municipal wastewater is the use of activated bed filtration (Jucherski et al., 2017; Jucherski et al., 2022). This mechanism is based on sorption (Letshwenyo and Mokokwe, 2021) and ion exchange, which retains phosphorus primarily in the form of phosphates. This technology is implemented at the final stage of the wastewater treatment process, after organic contaminants have been removed. Numerous materials have been described in the literature that could be used in process lines to remove phosphorus from wastewater (ÁdÁm et al., 2007; Bacelo et al., 2020; Ezzati et al., 2019; Grace et al., 2016; Gubernat et al., 2020; Penn et al., 2017; Pytka-Woszczyło et al., 2022; Vohla et al., 2011; Westholm, 2010). Among them, a significant group consists of the materials manufactured from carbonate-silica rock – opoka (Brogowski and Renman, 2004; Bus and Karczmarczyk, 2014; Ezzati et al., 2019; Jóźwiakowski et al., 2017; Jucherski et al., 2022; Pytka-Woszczyło et al., 2022; Zawadzka et al., 2024a; Zawadzka et al., 2023; Zawadzka et al., 2024b). One of the most frequently mentioned sorption materials from this group in the literature is Rockfos® – a specially modified granulate characterized by a high phosphate binding capacity (Pytka-Woszczyło et al., 2022; Zawadzka et al., 2024a; Zawadzka et al., 2023; Zawadzka et al., 2024b). So far, most published studies have only referred to the effectiveness of the Rockfos® material in removing phosphorus under laboratory conditions (Jucherski et al., 2017). The studies on the use of Rockfos® material in full-scale filters confirm its high efficiency in phosphorus removal under real-world conditions (Zawadzka et al., 2023). The effectiveness of the process depends not only on the material properties and sorption parameters, but also on the filter design, which determines the flow pattern and the contact time of wastewater with the sorption material (Zawadzka et al., 2023). Vertical filters are considered the optimal solution, in which forced flow through the entire filter bed ensures uniform utilization of its volume. However, their use is limited to facilities with low throughput (Pytka-Woszczyło et al., 2022). However, in the case of classic horizontal filters, there is a risk of preferential flow paths, which leads to reduced filter bed efficiency (Zawadzka et al., 2023). To mitigate these effects, Zawadzka and co-authors (Zawadzka et al., 2023) proposed a modified design for horizontal filters that enforces a meander flow. This results in an extended wastewater flow path through the filter bed and increased contact time with the sorption material. Preliminary studies conducted on a full-scale meander filter showed an increase in phosphorus removal efficiency from wastewater, from 9.4% to 40.6%, compared to a classic horizontal filter (Zawadzka et al., 2023). However, these were short-term studies (8 months), so an attempt was made to continue them.

The aim of this study was to evaluate the effectiveness of phosphorus removal from wastewater in a meander-flow filter filled with Rockfos® material over several years of full-scale operation. This study is a continuation of short-term preliminary studies conducted at the same facility and described in the publication by Zawadzka et al.(Zawadzka et al., 2023). The same batch of sorption material was analyzed to determine the ability of the filter to maintain high phosphorus removal efficiency over three years of operation. Additionally, the effectiveness of the filter in removing organic pollutants, measured by BOD_5 and COD, total suspended solids, and nitrogen compounds, was analyzed.

MATERIALS AND RESEARCH METHODS

Rockfos® material characteristics

The Rockfos® filter material is made from opoka obtained in the Piaski area (Lublin Voivodeship). Its production process involves decarbonizing the raw material through high-temperature thermal treatment. Rockfos® is characterized by a significant content of calcium oxide (CaO 43.336% by mass) and silica (SiO_2

36.047% by mass). The detailed chemical composition of this material has been extensively described in the literature (http://www.ceramika-kufel.pl/rockfos/; Pytka-Woszczyło et al., 2022; Zawadzka et al., 2023).

Characteristics of the research object

A meander filter filled with Rockfos® material operates in Białka (Dębowa Kłoda commune, southeastern Poland). It is part of the technological system of a hybrid constructed wetland treatment plant, designed to treat domestic sewage supplied both through the sewer system from Białka and transported by septic tankers. The average daily throughput of the facility is 180 m³/d. Due to the large number of summer resorts located around the surrounding lakes, the facility is characterized by significant fluctuations in wastewater flow, especially during the summer season. The wastewater treatment process in the analyzed facility is carried out in six hybrid systems of soil-plant beds, operating in vertical and horizontal flow systems. An integral element of the process chain is a meander filter, composed of three parallel chambers, designed to remove phosphorus from wastewater after the biological treatment stage. The final recipient of the treated wastewater is a drainage ditch. The phosphorus removal filter chambers are constructed as rectangular reinforced concrete tanks. Each tank measures 6.0 m in length, 2.0 m in width, and 2.0 m in height. In March-April 2022, the P-filter was modified by installing three transverse baffles in each tank, forcing a meandering flow of wastewater (Figure 1). The entire filter modification process is described in detail in the paper (Zawadzka et al., 2023).

Analytical methods and statistical analysis

The evaluation of total phosphorus removal efficiency during the passage of biologically treated wastewater through a full-scale filter filled with Rockfos® material was conducted based on the data collected between 2023 and 2025. Wastewater samples were collected monthly from two control points: at the filter inlet and outlet. The effectiveness assessment and statistical analysis also used preliminary research results from May 2022 to December 2022, described in another publication (Zawadzka et al., 2023). Throughout the study period, the wastewater samples were analyzed for total phosphorus concentration and pH. From August 2024 to July 2025, the wastewater samples were also analyzed for total suspended solids, COD, BOD_5, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen, total nitrogen, electrical conductivity, turbidity, and alkalinity. A total of 39 measurement series were performed, including 12 series with an extended scope of testing.

Basic physicochemical parameters (pH and total phosphorus) were determined using reference methods: (PN-EN ISO 6878:2006 Water quality – Determination of phosphorus – Spectrometric method with ammonium molybdate; PN-EN ISO 10523 :2012 Water quality – Determination of pH; PN-ISO 5667-10:2021-11 Water quality – Sampling – Part 10: Guidance on waste water sampling). The pH was measured using an ORION Star A329 Set meter (Thermo Scientific, Waltham, USA). Total phosphorus content was determined spectrophotometrically after oxidizing the samples in a thermoreactor at 120 °C for 30 minutes. Wastwater quality analyses were conducted in accordance with Polish standards at the

Figure 1. Meander flow filters in Białka (Dębowa Kłoda commune)

accredited Research Services Laboratory of the Lublin Cooperative of Dairy Services in Lublin (Laboratorium Usług Badawczych Lubelskiej Spółdzielni Usług Mleczarskich w Lublinie), Poland. Poland. All markings were performed in accordance with applicable Polish standards. A detailed list of the standards and testing procedures used is presented in the Table 1.

To accurately represent the obtained results, selected statistical measures were calculated, including the arithmetic mean, median, standard deviation, coefficient of variation, as well as maximum and minimum values. The coefficient of variation is defined as the ratio of the standard deviation to the mean value. The average concentrations of the analyzed pollutant indicators in the wastewater flowing into the P-filter from the hybrid constructed wetland system (C_{in}) and in the wastewater after treatment by the P-filter (C_{out}) were used to calculate the average pollutant removal efficiency (η), according to Equation 1:

$$\eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

The measurement series were tested for normality using the Shapiro-Wilk model. The effect of the P-filter was statistically determined using the Student's t-statistic for the normally distributed series, and the Wilcoxon test (a nonparametric test for dependent samples) for the non-normally distributed series. Both the Wilcoxon test and the Student's t-test were performed using Statistica NIBCO v. 13. All statistical tests were considered significant at $\alpha = 0.05$. The linear correlation coefficient between the wastewater flow rate through the P-filter and the removal efficiency of selected pollutants was also determined using Statistica NIBCO v. 13.

Table 1. Standards and procedures used in wastewater analysis

Parameter	Research method	Polish standards numbers	Unit
–	Sampling	PN-ISO 5667-6:2016-12 (PN-ISO 5667-10:2021-11 Water quality – Sampling – Part 10: Guidance on waste water sampling)	-
pH	Potentiometric method	PN-EN ISO 10523:2012 (PN-EN ISO 10523 :2012 Water quality -- Determination of pH)	-
Total suspended solids (TSS)	Weight method	PN-EN 872:2007 + Ap1:2007 (PN-EN 872:2007/Ap1:2007 Water quality - Determination of suspended solids - Method by filtration through glass fibre filters)	mg/l
COD	Spectrophotometric method	PN-ISO 15705:2005 (PN-ISO 15705:2005 Water quality - Determination of the chemical oxygen demand index (ST-COD) - Small scale sealed-tube method)	mg O_2/l
BOD_5	Electrochemical method	PN-EN 5815-1:2019-12 (PN-EN 5815-1:2019-12 Water quality -- Determination of biochemical oxygen demand after n days (BODn) -- Part 1: Dilution and seeding method with allylthiourea addition)	mg O_2/l
Total phosphorus (TP)	Spectrophotometric method	PN-EN ISO 6878:2006 p.7 + Ap1: 2010 + Ap2:2010 (PN-EN ISO 6878:2006 Water quality -- Determination of phosphorus -- Spectrometric method with ammonium molybdate)	mg/l
Ammonium nitrogen	Spectrophotometric method	PN-ISO 7150-1:2002 (PN-ISO 7150-1:2002 Water quality - Determination of ammonium - Part 1: Manual spectrometric method)	mg/l
Nitrate nitrogen	Spectrophotometric method	PN-82/C-04576.08 (PN-82/C-04576.08 Water and waste water -- Tests for content of nitrogen compounds -- Determination of nitrate nitrogen by colorimetric method with sodium salicilate)	mg/l
Nitrite nitrogen	Spectrophotometric method	PN-EN 26777:1999 (PN-EN 26777:1999 Water quality - Determination of nitrite - Molecular absorption spectrometric method (ISO 6777:1984))	mg/l
Total nitrogen (TN)	Calculation method	PB/POŚ/06 wyd.1 z 01.07.2011 r.	mg/l
Turbidity	Nephelometric method	PN-EN ISO 7027-1:2016-09 (PN-EN ISO 7027-1:2016-09 Water quality -- Determination of turbidity -- Part 1: Quantitative methods (ISO 7027-1:2016))	NTU
Electrical conductivity	Conductometric method	PN-EN 27888:1999 (PN-EN 27888:1999 Water quality - Determination of electrical conductivity)	μS/cm
Total alkalinity	Titration method	PN-EN ISO 9963-1:2001+Ap1:2004 (PN-EN ISO 9963-1:2001+Ap1:2004 Water quality - Determination of alkalinity - Part 1: Determination of total and composite alkalinity (ISO 9963-1:1994))	mmol/l

RESULTS

Phosphorus removal efficiency

Total phosphorus concentrations in the wastewater flowing into and out of the full-scale filter at the Białka wastwater treatment plant were measured from January 2023 to July 2025. These results were supplemented with those from 2022, following filter modernization (Zawadzka et al., 2023), when the impact of the filter on changes in phosphorus concentrations was tested. Selected statistical results are presented in Table 2, while Figure 2 presents the variation in total phosphorus concentrations in the wastewater flowing into and out of the filter throughout the study period.

During the study period (May 2022–July 2025), the wastewater flowing into the filter filled with Rockfos® material was characterized by a mean total phosphorus concentration of 3.66 mg/l. The observed values ranged from 0.13 to 7.04 mg/l. In the analyzed case, the median was 3.26 mg/l, slightly deviating from the mean. Despite the high variability of the data within the set, extreme values did not significantly impact the mean value; the data distribution was nearly symmetrical. However, a standard deviation (SD) of 2.82 mg/l and a coefficient of variation (CV) of 77.06% still indicate moderate variability in the composition of raw sewage with respect to phosphorus content. These indicators confirm that, despite the lack of significant deviations from the average values, the influent wastewater was not homogeneous. In the case of effluent sewage, a significant improvement was noted – the mean concentration of total phosphorus was 2.10 mg/l, with a standard deviation of 1.72 and a CV of 81.91%. The median (1.80 mg/l) was close to the mean, confirming the lack of significant deviations from a symmetrical distribution.

There is little research in the literature regarding the use of Rockfos® material at full technological scale. The achieved level of phosphorus

Table 2. Basic statistical parameters of total phosphorus concentrations in wastewater at the inlet and outlet of the filter filled with the Rockfos® material (V 2022-VII 2025)

Parameter	Statistical measures						Average efficiency [%]
	Average	Median	Min	Max	SD	CV [%]	
	[mg/l]						
Inflow	3.66	3.26	0.13	7.04	2.82	77.06	42.59
Outflow	2.10	1.80	0.11	12.20	1.72	81.91	

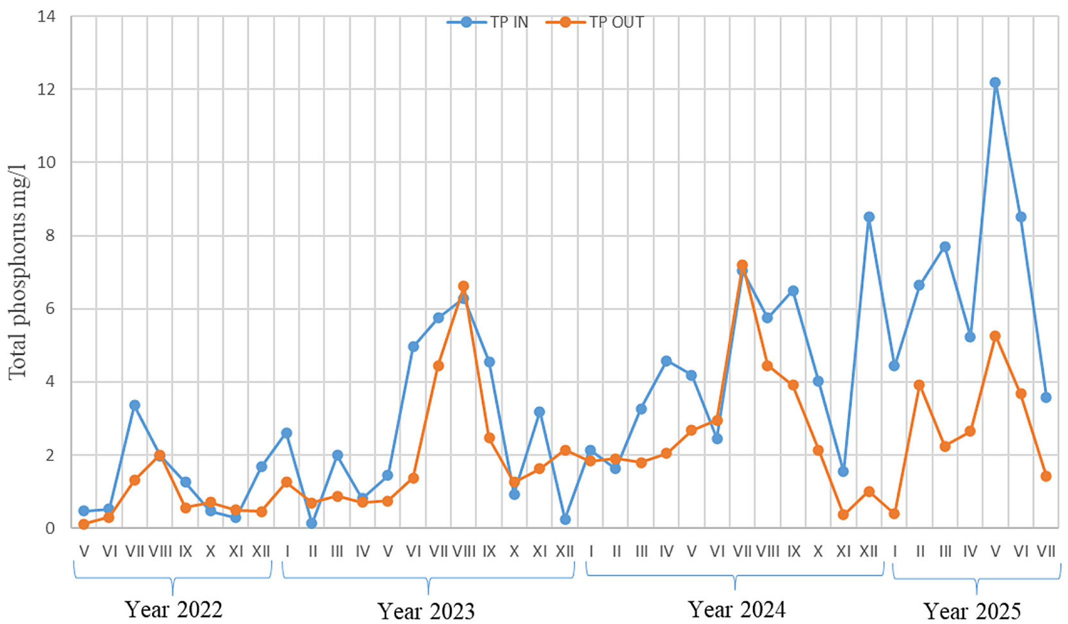

Figure 2. Total phosphorus concentrations in wastewater at the inlet and outlet of the Rockfos® filter across all months of the study period

removal efficiency of the P-filter (42.59%) during its 3-year operation was significantly lower compared to field studies conducted by other authors using filter media made of opoka (Nilsson et al., 2013; Renman, 2008; Renman and Renman, 2010; Vidal et al., 2018). Pytka-Woszczyło et al. (2022) analyzed the performance of filters with the Rockfos® material under real-world conditions in two wastewater treatment plants. The achieved total phosphorus removal efficiency ranged from 34% to 45% at the Kosobudy wastewater treatment plant. At the Stare Załucze wastewater treatment plant, the same authors observed significantly higher phosphorus removal efficiency in the first year of operation, reaching 82%. However, in the second and third years, this value dropped to 36-40%. In Kosobudy and Stare Załucze, classic gravity-flow filters were used, while in Białka, a variable, meander-flow filter was used. These results are slightly higher than those obtained during the initial period of meander filter operation, described by Zawadzka et al.(2023). It is worth noting that the tests were conducted on the same meander filter, with the filter bed unchanged. This indicates that the filter design, which forces a meander flow, provides a real and stable effect on phosphorus removal from wastewater. Extending the flow path through the filter bed, and thus the contact time with the filter bed, creates favorable conditions for phosphorus binding and utilizes the sorption capacity of the Rockfos® material to a greater extent. The tests also demonstrated the good durability of the Rockfos® material over many years of filter operation. The filter bed in the analyzed filter has been operating since 2020. Initially, it operated as a horizontal-flow bed, and in May 2022, as a meander-flow bed. The efficiency of the meander filter remained stable throughout its operation, and even increased above average in the last year (Table 3).

Statistical analysis of total phosphorus concentrations in the wastewater entering the Rockfos® filter using Student's t-test indicated that the differences between the compared parameters were statistically significant ($p<0.05$). This result demonstrates the impact of the P-filter on reducing phosphorus content in wastewater and supports its use in reducing eutrophication of receiving waters.

Seasonal variability of total phosphorus concentrations

Due to the touristic nature of the commune and the significant increase in the wastewater flowing into the treatment plant during the summer holidays, the effectiveness of the Rockfos® filter in removing total phosphorus was analyzed in different seasons. Characteristic statistical values were calculated for the months of spring, summer, autumn, and winter, including: minimum, maximum, mean, median, SD, CV, and total phosphorus removal efficiency (Table 4). Three measurement series were assigned for each season, performed on the appropriate dates between August 2024 and July 2025. The spring period covered the months of March-May, the summer period: June-August, the autumn period: September-November, and the winter period: December-February. To highlight the impact of sewage inflow variability and evapotranspiration rates, the average sewage flow rates entering the P-filter in individual months were taken into account (Figure 3), which enabled the assessment of the impact of hydraulic conditions on the efficiency of treatment processes.

During the spring period, the mean concentration of total phosphorus in the influent to the P-filter was 6.78 mg/l, with a range from 6.26 to 7.70 mg/l. The median was close to the mean (6.39 mg/l), suggesting a relatively symmetrical data distribution. The standard deviation was 0.65 mg/l, and the CV was 9.62%, indicating low variability in the wastewater composition. In the treated wastewater, the mean concentration decreased to 1.70 mg/l, and the treatment efficiency during this period was 74.86%, which resulted from moderate wastewater flows (approximately 5.9–7.3 m^3/d). The coefficient of variation of phosphorus concentration in the effluent was high

Table 3. Basic statistical parameters of total phosphorus concentrations in wastewater at the inlet and outlet of the Rockfos® filter (VIII 2024-VII 2025)

Parameter		Min	Max	Average	Median	SD	CV [%]	Average efficiency [%]	t-Student
Total phosphorus [mg/l]	In	1.54	12.2	6.22	6.13	2.69	43.24	57.87	z = 2.803 p = 0.005 *
	Out	0.37	5.26	2.62	2.45	1.56	59.58		

Table 4. Basic descriptive statistics of total phosphorus concentrations in wastewater at the inlet and outlet of the Rockfos® filter, depending on the season

Season	Parameter	Min	Max	Average	Median	SD	CV [%]	Average efficiency [%]
		mg/l						
SPRING	Inflow	6.26	7.70	6.78	6.39	0.65	9.62	74.86
	Outflow	0.69	2.24	1.70	2.18	0.72	42.06	
SUMMER	Inflow	3.58	8.51	5.75	5.75	2.02	33.93	46.52
	Outflow	1.48	4.45	3.67	3.67	1.28	40.40	
AUTUMN	Inflow	1.54	6.50	4.02	4.02	2.02	50.37	46.77
	Outflow	0.37	3.91	2.14	2.14	1.45	67.53	
WINTER	Inflow	4.43	8.50	6.64	6.64	1.66	25.50	72.82
	Outflow	0.39	3.92	1.01	1.01	1.54	86.78	

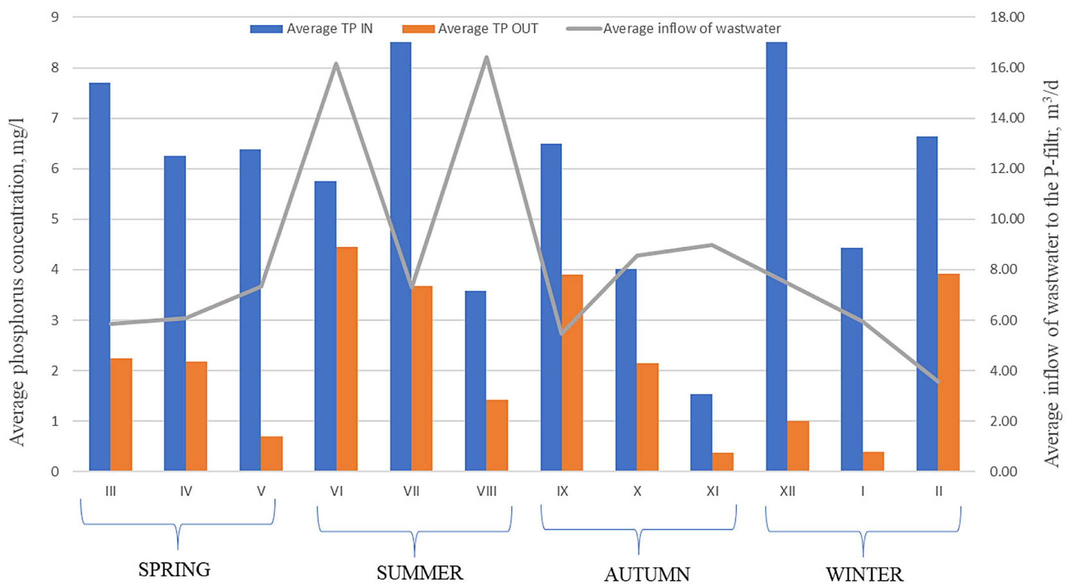

Figure 3. Average monthly concentrations of total phosphorus (TP) at the inflow and outflow from the P-filter and the average sewage inflow intensity in individual months (VIII 2024 -VII 2025)

(42.06%), indicating some variability in system performance, but overall high efficiency.

During the summer period, higher total phosphorus concentrations were observed in the influent wastewater, with both the mean and median values equal to 5.75 mg/L, indicating a symmetrical distribution of the data. The standard deviation reached 2.02 mg/l, and CV was 33.93%, indicating moderate variability in wastewater composition. The outflow wastewater contained an average of 3.67 mg/l of phosphorus, and treatment efficiency during this period was lower -46.52%. The high coefficient of variation in the outflow (40.40%) is worth noting, indicating instability of the treatment process under summer conditions, which may be the result of high temperatures, intense evaporation, or variable inflow characteristics. This was likely caused by high flow rates (up to 14–15 m³/d), which reduced the contact time of the wastewater with Rockfos® material and consequently decreased the phosphorus sorption efficiency.

In autumn, lower phosphorus concentrations were recorded in the influent – an average of 4.02 mg/l, with a large scatter of data (CV = 50.37%). The median was equal to the mean (4.02 mg/l), indicating a relatively symmetrical distribution, although the high CV suggests the occurrence of individual outliers. After treatment, the concentration decreased to 2.14 mg/l, and the efficiency was 46.77%. The coefficient of variation in the effluent was very high (67.53%), indicating high process instability in autumn.

Under winter conditions, the mean concentration of total phosphorus in the influent was 6.64

mg/l, with moderate variability (CV = 25.50%). The median was equal to the mean (6.64 mg/l), confirming the symmetrical data distribution. In the outflow, the phosphorus concentration decreased to 1.01 mg/l, and the treatment efficiency was 72.82%. The CV in the outflow was high (86.78%), indicating high process variability during winter; however, the treatment efficiency remained high.

The obtained results indicate that both seasonality and hydraulic conditions have a significant impact on the performance of the P-filter with Rockfos® material.

Phosphorus sorption isotherm tests on the Rockfos® material conducted under laboratory conditions showed a high sorption capacity of the material at higher temperatures (under the suggested summer conditions) (Zawadzka et al., 2024b).

pH variability

The Rockfos® material used in this research is a burnt opoka under appropriate temperature conditions (Bus and Karczmarczyk, 2014; Cucarella et al., 2007). Due to the high content of CaO, as presented in chapter 2.1, the rock is characterized by a strong alkalization of the solution, which results in an increase in pH to high values, above 10 and even above 11 (Brogowski and Renman, 2004; Cucarella et al., 2007; Gubernat et al., 2020; Kasprzyk and Gajewska, 2019; Kasprzyk et al., 2018b; Pytka-Woszczyło et al., 2022; Vohla et al., 2011). Despite its high phosphorus removal efficiency, raising the pH to such high levels weakens the potential of the material for wastewater treatment. Legislative requirements (Regulation of the Minister of Maritime Economy and Inland Navigation of July 12) require the wastewater discharged into the environment to have a pH of 6.5 –9.0. Previous publications (Kasprzyk and Gajewska, 2019) show that pH decreases with time. Kasprzyk and Gajewska (2019) showed that with an initial pH value of approximately 12.5, after approximately 120 hours of the experiment, the pH decreased to a value below 10, and after approximately 240 hours to below 9.0, showing occasional small fluctuations.

For this reason, this study paid particular attention to the pH changes under natural conditions, taking into account any variability resulting from wastewater treatment plant operation. Measurement results throughout the study period are shown in Figure 4.

The locations of the measurement points shown in Figure 4 indicate that an increase in pH was indeed observed during flow through the tested material. Initially (May 2022) it reached a value of approximately 10.5, but during subsequent tests the pH decreased significantly (Zawadzka et al., 2023). By June, the pH had already dropped to approximately 9.7, and by October 2022, it had permanently decreased to below 9.0. From that month until the end of the study, the pH was within the acceptable range for the wastewater discharged into the environment. From mid-2023, the pH measurement points before and after

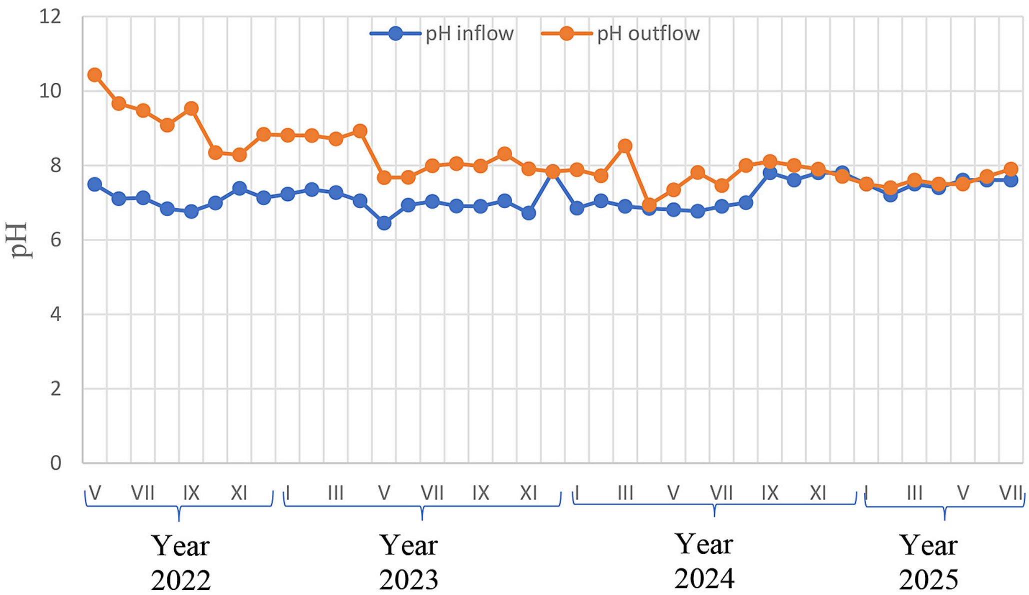

Figure 4. Monthly pH values of wastewater at the inlet and outlet of the Rockfos® filter

the filter became significantly closer together, and from mid-2024, the impact of the filter on pH changes was so negligible that it can be considered unchanged.

Most scientific publications indicate the existence of a positive relationship/correlation between the efficiency of phosphorus removal from wastewater and the pH of the filtrate (Pytka-Woszczyło et al., 2022; Renman and Renman, 2010; Vidal et al., 2018; Zawadzka et al., 2023). Analysis of the results of this long-term study indicates that strong alkalization of the environment is not a necessary condition for effective phosphorus removal. A decrease in filtrate pH did not reduce phosphorus removal efficiency, and in the last year of the study, it was even higher than the average for the entire period. In this situation, it can be concluded that the increased contact time between wastewater and the sorption material may have been more significant, as also suggested by Vidal. et al. (2018). In the case of this study, this effect could be caused by the meandering flow of wastewater in the filter. Nilsson et al. (2013) found no correlation between phosphorus removal rate and pH under low BOD_5 conditions of the wastewater entering the filter.

In terms of pH, a slight increase was observed between August 2024 and July 2025. The average pH at the inlet to the P-filter was 7.46, while at the outlet it was 7.67 (Table 5). The average pH was calculated as the negative logarithm of the average hydrogen ion concentration [H^+], taking into account the logarithmic nature of the pH scale. The normality of the distribution of results was verified using a paired Student's t-test, which showed that the pH differences between the filter inlet and outlet were statistically significant ($p = 0.038$).

Contaminant removal efficiency of the P-filter under operating conditions

Table 6 presents basic descriptive statistics (minimum, maximum, median, mean, standard deviation, and coefficient of variation) as well as the treatment efficiency for selected pollutant indicators in the influent and effluent of the filter, based on the data collected from August 2024 to July 2025. Additionally, the table includes the results of the Student's t-test for dependent samples, used to assess the statistical significance of the impact of the filter on wastewater quality parameters. Figure 5 presents the dynamics of the concentrations of the physicochemical pollutants studied during the aforementioned study period.

During the study period, the wastewater flowing into the Rockfos® filter contained total suspended solids (TSS) at an average concentration of 17.25 mg/l with observed values ranging from10–30 mg/l, while the outflowing effluent from the treatment plant ranged from 5.6–17 mg/l, with an average of 10.89 mg/l. The median for TSS was 15.50 mg/l for the effluent before the filters and 10.00 mg/l for the effluent after the filters. The P-filter achieved a 37% reduction efficiency for TSS. A similar effect was observed for turbidity, which decreased on average from 10.89 to 7.02 NTU, with an efficiency of 35.51%. This indicates the ability of the P-filter to retain suspended and colloidal particles, which positively impacts effluent clarity.

Chemical oxygen demand (COD) in the wastewater entering the P-filter ranged from 39 to 82 mg O_2/l, while in the wastewater outlet from the treatment plant it ranged from 44 to 95 mg O_2/l. Average COD concentrations were 63.13 and 58.75 mg O_2/l, respectively. The values of biological oxygen demand (BOD_5) upstream of the P-filter ranged from 8 to 30 mg O_2/l and 7 to 16 mg O_2/l downstream. Average BOD_5 concentrations for wastewater before and after the P-filter were 16.29 and 10.46 mg O_2/l, respectively. The average efficiency of reducing biological oxygen demand by the filter filled with Rockfos® material was 35.81%, while for chemical oxygen demand it was only 6.93%. This is a relatively low value, but since the P-filter is designed to remove phosphorus compounds, its low efficiency in reducing organic pollutants is expected. This indicates that the P-filter is not designed to eliminate organic substances, although some improvement in wastewater quality in this regard was observed. The effects on nitrogen compounds were variable. Ammonium nitrogen did not show significant

Table 5. Basic statistical parameters of pH in wastewater at the inlet and outlet of the Rockfos® filter. (VIII 2024-VII 2025)

Parameter		Min	Max	Average	Median	SD	t- Student
pH	In	7.00	7.80	7.46	7.60	0.23	z = 2,073 p = 0.038 <0.05
	Out	7.40	8.10	7.67	7.70	0.23	

Table 6. Basic descriptive statistics of physicochemical parameters in wastewater at the inlet and outlet of the Rockfos® filter

Parameter		Min	Max	Average	Median	SD	CV [%]	Average efficiency [%]	t-Student p-Value
Total suspended solids [mg/l]	In	10	30	17.25	15.50	6.19	35.90	36.86	z = 2.803 p = 0.005*
	Out	5.6	17	10.89	10.00	3.23	29.67		
COD mg O_2/l	In	39	82	63.13	62.25	12.47	19.75	6.93	z = 0.561 p = 0.575
	Out	44	95	58.75	55.50	13.71	23.34		
BOD_5 mg O_2/l	In	8	30	16.29	13.50	6.56	40.26	35.81	z = 2.449 p = 0.015
	Out	7	16	10.46	10.00	2.39	22.88		
Ammonium nitrogen [mg/l]	In	12.70	41.60	24.82	23.05	8.18	32.95	-	-
	Out	12.00	37.30	24.20	23.95	7.30	30.16		
Nitrite nitrogen [mg/l]	In	0.01	0.98	0.33	0.22	0.33	102.08	11.56	-
	Out	0.15	0.46	0.29	0.30	0.08	27.72		
Nitrate nitrogen [mg/l]	In	0.21	29.40	8.86	8.48	7.96	89.85	-	-
	Out	1.32	27.40	10.64	8.89	7.48	70.33		
Total nitrogen [mg/l]	In	25.90	103.00	54.90	53.75	18.90	34.42	18.37	z = 0.255 p = 0.799
	Out	21.30	83.70	44.82	44.30	15.68	34.98		
Electrical conductivity [μS/cm]	In	1264.0	2198.0	1861.1	1915.3	268.11	14.41	19.75	z = 2.803 p = 0.005 *
	Out	1013.0	1901.0	1493.6	1493.5	243.27	16.29		
Turbidity [NTU]	In	6.21	16.7	10.89	10.45	3.92	35.97	35.51	z = 2.497 p = 0.013
	Out	4.78	9.4	7.02	7.08	1.34	19.07		
Total alkalinity [mmol/l]	In	7.00	16.30	12.50	12.95	2.52	20.16	39.57	z = 2.803 p = 0.005 *
	Out	4.70	10.00	7.55	8.25	1.82	24.14		

Note: *Statistically significant differences between parameter values for wastewater before and treated wastewater. Student's t-test for paired observations – critical area R= $(-\infty, -2{,}764)\cup(2{,}764, \infty)$.

changes, and its average concentration remained similar (approximately 24.2–24.8 mg/l). Nitrite nitrogen, on the other hand, was reduced by only about 12%, from 0.33 to 0.29 mg/l, which may indicate partial transformation of this compound under filtration conditions. Nitrate nitrogen was not effectively reduced; the average concentration increased slightly (from 8.86 to 10.64 mg/l). Total nitrogen decreased only by 18.37%, indicating that the P-filter is not an effective tool for reducing total nitrogen content in wastewater.

The literature lacks the results analyzing the effect of P-filters on the physicochemical parameters of wastewater. The obtained values of total suspended solids, COD, and BOD_5 are within the limits specified in the Regulation of the Polish Minister of Maritime Economy and Inland Navigation of 2019 (Regulation of the Minister of Maritime Economy and Inland Navigation of July 12). According to the regulation, the pollutant concentrations for domestic sewage discharged from wastewater treatment plants <2000 RLM cannot exceed 50 mg/l for total suspended solids, 150 mg O_2/l for COD, and 40 mg O_2/l for BOD_5. According to these standards, the results obtained for both wastewater before and after P-filters are within the limits, with average values significantly lower than the maximum possible values.

Analysis of the results showed that the P-filter affected wastewater quality. A paired t-test showed statistically significant differences for total suspended solids (p = 0.005), BOD_5 (p = 0.015), conductivity (p = 0.005), turbidity (p = 0.013), and alkalinity (p = 0.005). However, no statistical differences were found for COD and total nitrogen. Nitrogen fractions, i.e., $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, and NO_3^-, were not analyzed because nitrogen transformations occur during wastewater treatment processes, causing the concentrations of individual forms to change. Ammonification processes transform organic nitrogen into ammonium nitrogen, which, under favorable oxygen conditions, can be converted into nitrite nitrogen and then nitrate nitrogen. These processes depend on other parameters, so their concentrations may increase or decrease in different months.

Between August 2024 and July 2025, low correlations were found between wastewater flow

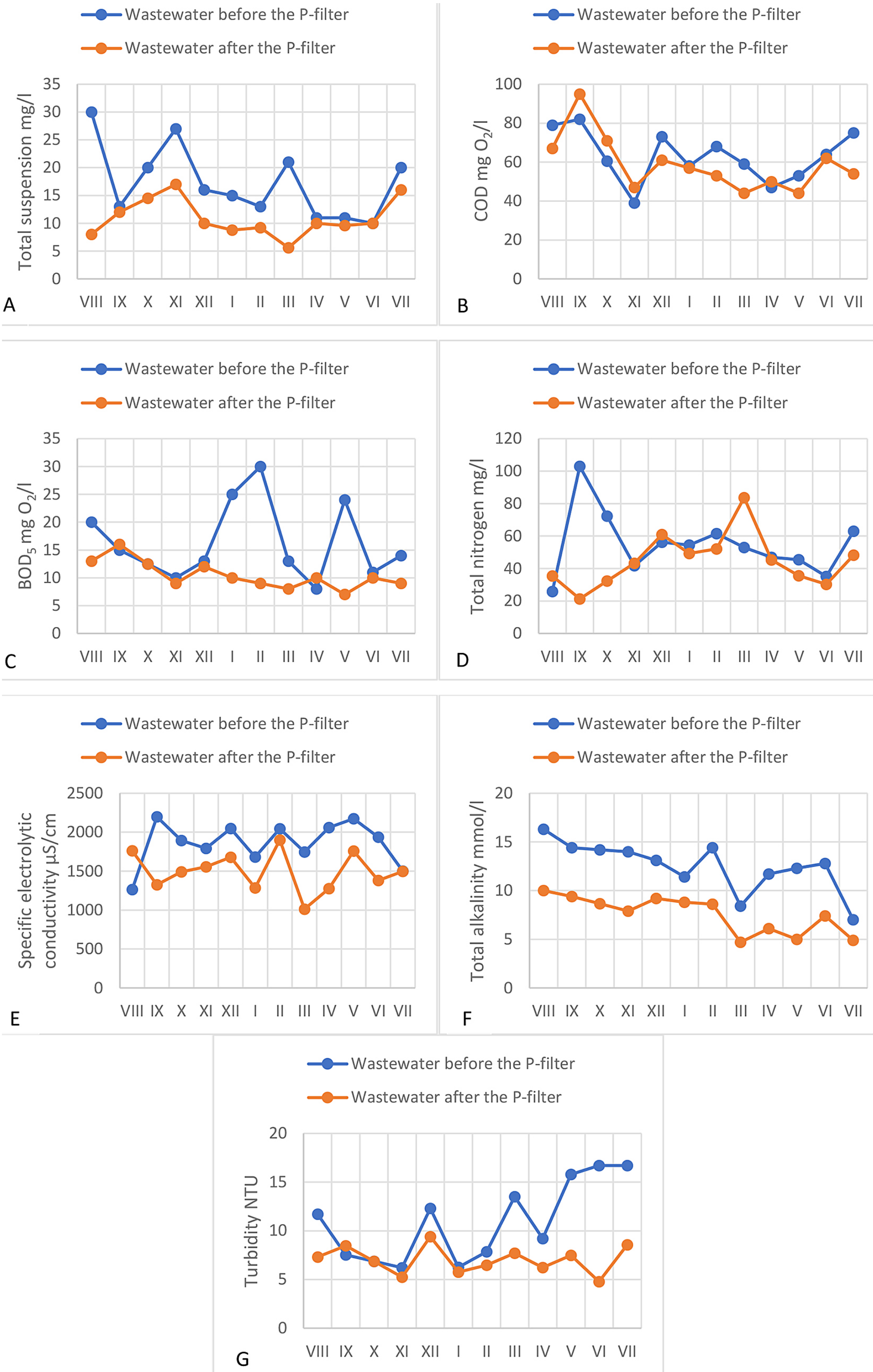

Figure 5. Dynamics of changes in the values of the tested physicochemical parameters (A-G) at individual stages of purification throughout the entire study period

rate through the filter and pollutant removal efficiency. For total phosphorus, the correlation coefficient was -0.250, for total nitrogen -0.176, and for suspended solids 0.264; for BOD_5 0.019 and COD 0.236. A particularly important parameter that guided this study was phosphorus removal. Removal of this indicator exhibits a relatively low negative correlation, which indicates that increasing wastewater flow during tourist periods negatively impacts phosphorus retention, resulting from the shorter retention time of wastewater within the filter bed.

The significance of the correlation coefficients was checked by verifying the null hypothesis of non-absence of correlation by determining the critical value of the linear correlation coefficient for the two-sided critical region. For $\alpha = 0.01$ and the number of measurements n = 12, the critical value is 0.708. This indicates that the absolute value of the correlation coefficient is greater than the critical value, and therefore the null hypothesis is rejected, meaning that the correlation is statistically significant.

DISCUSSION

The location of the tested P-filter at the final stage of the technological process in the treatment plant is, in the classical sense, the final stage of wastewater treatment, allowing for the best possible final effect. The filtration process using Rockfos® material was designed to reduce the phosphorus concentration in treated wastewater. This material contains a significant proportion of elements potentially reactive to phosphorus, including calcium, silicon, aluminum, and magnesium (Walczak et al., 2025), it has a non-homogeneous structure (Pinińska, 2008); therefore, subsequent batches of material may have different adsorption efficiency (Bus and Karczmarczyk, 2014; Karczmarczyk et al., 2017; Zawadzka et al., 2024a; Zawadzka et al., 2024b). The effectiveness of phosphorus binding has been confirmed by many empirical studies (Bus and Karczmarczyk, 2014; Józwiakowski, 2012; Pytka et al., 2013; Renman and Renman, 2010; Zawadzka et al., 2023).

Research in real facilities is particularly important, as the overall efficiency of wastewater treatment is influenced by fluctuations in the quantitative and qualitative parameters of influent wastewater, temperature resulting from natural seasonal changes, the research phase, and, in the case of constructed wetlands, also rainfall. This is confirmed by the research of Kasprzyk et al. (Kasprzyk et al., 2018a), who in their studies of the LMB – Phoslock® mineral showed that the mineral absorption capacity under laboratory conditions was 4.31 mg P/g, and under real conditions – 2.09 mg P/g, i.e. it was about 50% lower. The phosphorus removal efficiencies obtained in these studies are variable; in spring, the efficiency was 61.89%, in summer 19.46%, in autumn 40.55%, and in winter 51.44%. The lower phosphorus removal efficiency achieved by the P-filter under summer conditions may be due to two phenomena. Due to the touristic nature of the commune, recreational centers intensify their activity during the summer, which contributes to increased sewage inflow. The average daily sewage flow through the P-filter in the spring is 4.3 m^3/d, while in summer it reaches 10.1 m^3/d. The impact of this phenomenon is possible and relatively easy to identify, but the second phenomenon in technical-scale facilities is much more difficult to precisely determine. In constructed wetlands, with intensive plant growth and high temperatures, high evapotranspiration results in a significant decrease in the amount of sewage discharged from the treatment plant and its concentration. This effect is compounded by the influence of more or less intense rainfall, as studied by Myka-Raduj et al. (2024). As a result, these phenomena may contribute to demonstrating a lower degree of pollutant reduction. The increase in electrolytic conductivity values between June–August 2025 may confirm the reasoning above. The specific nature of constructed wetland operation, and particularly the dependence on seasonal conditions, does not correlate with the observations of Jucherski et al. (2022), who noted that a decrease in air temperature resulted in an increase in phosphate concentration in wastewater flowing from the filter. They demonstrated that a 1 °C decrease in wastewater temperature caused a 0.30 mg/l increase in $P\text{-}PO_4^{-3}$ concentration in the treated wastewater filtered through Rockfos® material. These observations seem logical, as temperature undoubtedly influences the chemical and biological processes occurring in filter beds. However, these studies used wastewater treated in a biological bed, so the influence of evapotranspiration and rainfall was not present in this case. Dissolved phosphorus compounds, particularly orthophosphates, react with calcium ions, resulting in the formation and precipitation of calcium phosphate minerals. The phosphorus removal mechanism involves two main processes: adsorption and precipitation, which are significantly influenced by pH, and sorption efficiency increases with increasing temperature (Bouamra et al., 2018).

The pH of the wastewater entering the filter was neutral, with a range of 6.33 to 7.8, while the pH in the outlet wastewater was significantly higher. Initially, it increased to 10.5, but after a month, it dropped to 9.7 (Zawadzka et al., 2023) and continued to decline. After five months, the pH dropped permanently to below 9.0, and after a year, pH readings approaching 8.0 were observed, with minor fluctuations. Long-term studies (approximately 6 years) conducted at two different small constructed wetland treatment plants treating domestic sewage show that for an initial period of approximately 1.5 years, pH values showed significant differences between the outlet and inlet, but after that time, they converged, with the pH in the outlet fluctuating within the range of 7–8 (Pytka-Woszczyło et al., 2022). This is likely due to the decreasing share of calcium compounds. This reasoning may be supported by the observed fluctuations in phosphate concentration in the outflow after approximately 3 years, especially since there was a slight upward trend (Pytka-Woszczyło et al., 2022).

Long-term operation of mineral-filled filters will always promote the growth of microorganisms on the grain surface, which facilitates the decomposition of organic compounds. In the case of final filters, as in this case, this phenomenon is not very significant, as biologically treated domestic sewage in constructed wetlands does not exhibit high BOD_5 and COD values, and therefore, significant changes in nitrogen compound concentrations are not expected. As reported Kończak et al. (2020) effective denitrification occurs at a high COD to total nitrogen ratio $COD/N_{tot}>7$, while $BOD_5/N_{tot}<2.5$ a clear inhibition is observed, so the supply of easily decomposable compounds is particularly important.

The analysis of various literature reports focusing on the research on the effect of temperature (seasons) on the performance of phosphorus removal filters, especially filters with opoka-based media, allows concluding that the research phase is of significant importance. In the initial period, easily accessible calcium in the surface layers of the opoka causes very rapid binding with phosphates, resulting in significant decreases in phosphorus compounds in the sewage flowing from the treatment plant. This is such a strong effect of the opoka that regardless of the season, the phosphorus removal effects are high, which also results in significant increases in the pH of these wastewaters. Only after several months, and sometimes even a year, a gradual reduction in the pH difference between the inlet and outlet of the P-filter becomes noticeable, which may be influenced by, among others, temperature, microorganism activity and other factors. Therefore, the results obtained in the initial period of research, depending on the date of commencement, are not always consistent with the literature reports.

CONCLUSIONS

The use of a meander filter with Rockfos® media demonstrated an increase in the overall efficiency of wastewater treatment in the analyzed treatment plant. A particularly significant reduction in pollutant concentrations in the treated wastewater was observed for phosphorus, which is bound in the media through adsorption and ion exchange processes. The average phosphorus removal efficiency in the meander filter with Rockfos® media was 44.43%, slightly higher than that observed during the initial tests (Zawadzka et al., 2023). This indicates a significant filter lifespan and the ability to maintain high efficiency during long-term operation, especially since the phosphorus removal efficiency in the last year of testing was approximately 60%. As a result of flow through a porous material (Rockfos®), the operation of such a filter also resulted in a reduction in the concentrations of certain indicators, such as suspended solids, some organic compounds measured by COD and BOD_5, and the transformation of nitrogen compounds. A reduction in wastewater turbidity and conductivity was also observed. The increase in pH and total alkalinity resulted from the influence of the Rockfos® material components, which was also demonstrated in previous publications.

Statistical analysis showed a significant effect of P-filter on pH, turbidity, conductivity, and changes in phosphorus concentrations, total alkalinity, and BOD_5. No significant effect was found on total nitrogen and COD.

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