

Efficiency of Operation a Hybrid Constructed Wetland Located in the Polesie National Park (Poland) During the Start-Up Period

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ABSTRACT

This study assessed the operational efficiency of a hybrid constructed wetland (CW) in its first year of use. The test facility was put into operation in September 2022 and has since been utilized to treat 0.4 m³/d of wastewater discharged from a forester's lodge located in the Polesie National Park in Poland. The treatment plant consists of a two-chamber primary settling tank integrated with a pumping station, and a system of two beds – a vertical flow (VF) reed bed and a horizontal flow (HF) willow bed. During the research period (October 2022 to December 2023), 14 test runs were performed during which 56 sewage samples were collected for physico-chemical and microbiological assays. The results of these tests were used to determine the pollutant removal efficiency of the CW. The composition of treated wastewater was compared against the current Polish requirements for this type of facilities. The study also included measurements of influent and effluent volumes and the amount of rainwater entering the treatment plant. It was shown that precipitation in each month of the study accounted for between 6–34% of influent volume. The volume of wastewater discharged from the treatment plant during the study period was 11% lower than the volume of incoming wastewater combined with rainwater. It was found that the CW removed an average of over 90% of total suspended solids, BOD₅, COD, *Escherichia coli* bacteria and fecal enterococci from wastewater. Slightly lower removal efficiencies were achieved in the case of total nitrogen and total phosphorus (60–74%). Already during the start-up period, the composition of treated wastewater discharged from the CW met the requirements set out in the current Polish legal regulations. The present study shows that hybrid VF-HF constructed wetlands can be recommended for use in protected areas for wastewater treatment and protection of water against eutrophication.

Keywords: hybrid constructed wetland system, wastewater treatment plant, Polesie National Park, water protection, physico-chemical and microbiological contaminants, pollutants removal.

INTRODUCTION

Untreated wastewater is a source of large amounts of physico-chemical pollutants, but also bacteria, viruses, fungi and protozoa, including pathogenic microorganisms, which, when released into surface waters and groundwater, pose a threat to human and animal health [Korniłowicz-Kowalska et al., 2010]. Current requirements are that the effectiveness of removal

of biological pollutants from wastewater be determined using fecal indicator bacteria, the most important of which are coliform bacteria, including *Escherichia coli*, and enterococci [Anastasi et al., 2012]. These bacteria inhabit human and animal digestive tracts and are excreted with faeces into the natural environment. While the presence of these bacteria in sewage is not uncommon, their presence in drinking water or in surface waters or groundwater may be indicative of fecal

contamination and the presence of pathogenic gastrointestinal bacteria. That is why it is important that wastewater treatment should involve not only the removal of physico-chemical but also microbial contaminants. One type of treatment system that provides very efficient removal of these types of pollutants is the constructed wetland (CW).

CWs have been used as engineering solutions for protecting water resources for about 70 years now. The first paper on wastewater treatment in artificial soil-plant systems was published in Germany in the early 1950s by Seidel [1955] from the Max Planck Institute in Plön. In one of her later works, Seidel [1965] described a vertical flow (VF) CW and a horizontal flow (HF) CW filled with gravel, a filter material with a high hydraulic conductivity. The VF CW was a reed bed, while the HF bed was planted with emergent aquatic macrophytes, such as iris, blacktail, and cattail. Another type of CW referred to as the “Root Zone Method (RZM)” was proposed by Kickuth [1977] from the University of Göttingen. In his experiments, Kickuth used reed (*Phragmites australis*) beds filled with a locally sourced high-clay-content material.

In the 1980s and 1990s, Europe saw extensive development of the CW technology [Haberl et al., 1995]. During this period, Denmark was one of the first countries to implement these wastewater treatment systems [Brix and Schierup, 1989]; the Danes mainly used single-stage HF CWs based on the technology developed by Kickuth [1977]. At the end of the 1980s, the VF and HF CWs proposed by Kickuth and Seidel were also used in other countries, including Austria [Haberl and Perfler, 1990] and Great Britain [Cooper and Green 1995]; in the 1990s, they were built in most European countries [Haberl et al., 1995], including Poland [Gajewska and Obarska-Pempkowiak 2009]. An account of fifty years of experiences with CWs used worldwide for the treatment of various types of wastewater was written by Vymazal [2011]. He reported that initially single-stage CWs had been used in different parts of the world, but research showed that much better wastewater treatment efficiency could be achieved using hybrid CWs, which provided better conditions for removing pollutants. This claim was confirmed by twenty five years of experiments on and experiences with CWs used in south-eastern Poland [Jóźwiakowski et al., 2019]. In recent years, CWs have been classified

as a green technology [Stefanakis 2019] and a nature-based solution [Gonzalez-Flo et al., 2023].

In Poland, hybrid CWs are increasingly used not only to treat industrial wastewater [Bergier and Włodyka-Bergier, 2016] and domestic wastewater in rural areas with a dispersed settlement pattern [Jóźwiakowski et al., 2019, Malinowski et al., 2023], but also to purify small amounts of wastewater in protected areas, such as national parks [Jóźwiakowski et al., 2016, Obroślak et al., 2017, Micek et al., 2020]. To date, however, little research has been published on the functioning and performance of hybrid CWs in the start-up period. This paper fills in this gap in the literature by reporting experimental results obtained during the run-in of a hybrid CW.

In the study, we evaluated the performance of the hybrid CW serving a forester’s lodge in the Polesie National Park (PNP) in Poland during the first 15 months of its operation. The facility we tested is additionally equipped with a water reclamation system that returns reclaimed wastewater to the household for reuse. The results regarding the operation of the system used to water reuse will be presented in another paper.

Characteristics of the facility

The test hybrid CW with a closed water circuit is located in the PNP in Kulczyn, Poland (51°23’7.01”N, 23°17’48.42”E). The PNP was established to protect water and peat ecosystems in areas of high natural value situated in south-eastern Poland, which is located in the central part of Europe (Figure 1). A more detailed description of the PNP can be found in the paper of Myka-Raduj and Jóźwiakowski [2022].

The wastewater treatment plant under study is connected to an employee housing unit in the PNP, which is described in detail in the paper of Myka-Raduj et al. [2023]. The facility is used to treat domestic wastewater discharged from a residential building permanently inhabited by a family of four. A drone’s eye view of the wastewater treatment plant showing the location of its individual elements in the area surrounding the employee housing unit in Kulczyn is shown in Figure 2.

The wastewater treatment plant consists of four main components: a two-chamber primary settling tank with a capacity of 3.2 m³ integrated with a raw sewage pumping station, two CW beds: a 12 m² VF reed bed and a 15 m² HF willow bed, and dry well (Figure 3). The treatment

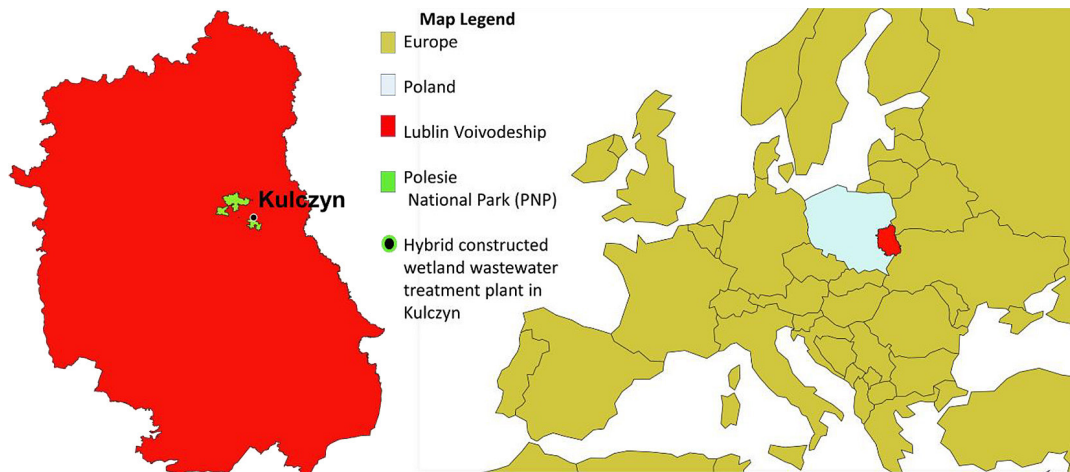


Figure 1. Geographical location of the hybrid closed-water-circuit constructed wetland serving an employee housing unit in the Polesie National Park, south-eastern Poland, Central Europe (data from the websites www.geoportal.gov.pl, www.mapsforeurope.org ©EuroGeographics2024)

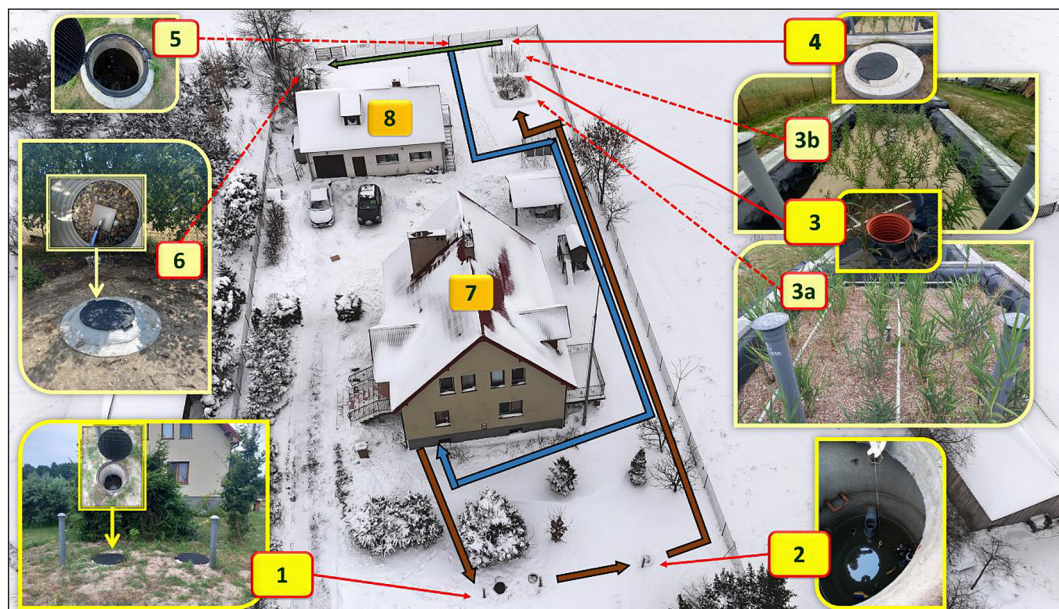


Figure 2. The hybrid constructed wetland with a closed water circuit and the location of its components in the area surrounding the employee housing unit in the PNP, Kulczyn, Poland: 1 – two-chamber primary settling tank; 2 – pumping station for raw sewage; 3a – VF reed bed; 3 – collection/distribution well downstream of the VF bed; 3b – HF willow bed; 4 – collection/distribution well downstream of the HF bed; 5 – pumping station for purified wastewater; 6 – dry well for discharge of excess treated wastewater; 7 – residential building; 8 – outbuilding; brown line – inflow of wastewater to the treatment plant; blue line – inflow of treated wastewater from the treatment plant to the house for re-use; green line – outflow of excess treated sewage to the dry well.

plant was designed to handle 0.4 m³ of influent wastewater per day, with the VF bed operating under a hydraulic load of 0.033 m³/m²/day [Malik et. al., 2021]. Wastewater discharged from the residential building first passes into the primary settling tank (1) for mechanical treatment (Figure 3). Then, it flows by gravity into the pumping station (2) equipped with an Omnigena

WQ 6-10-0.37 submersible pump, which pumps the mechanically treated wastewater into the VF bed with common reed (*Phragmites australis* [Cav.] Trin. ex Steud). Next, the wastewater filtered through the VF bed is collected in the collection/distribution well (3) located between the two beds, from which it passes by gravity into the HF bed planted with willow

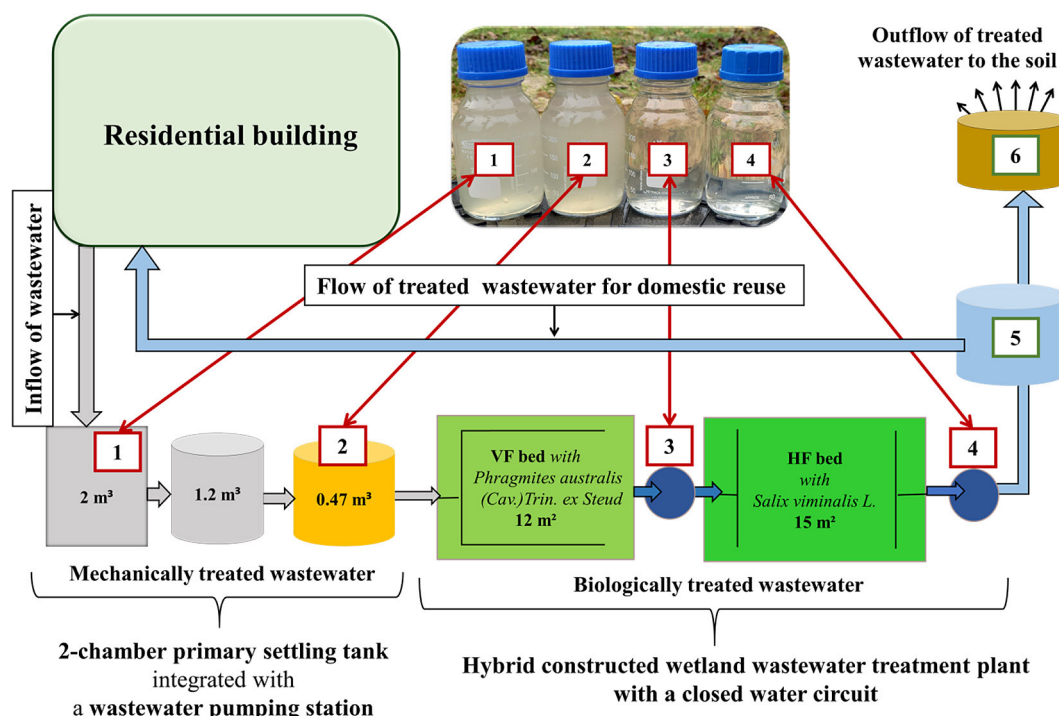


Figure 3. Schematic of the closed water circuit hybrid constructed wetland serving the employee housing unit in the PNP, Kulczyn, Poland. Wastewater sampling sites: 1 – primary settling tank (raw sewage); 2 – pumping station for mechanically treated wastewater; 3 – collection/distribution well downstream of the VF bed; 4 – collection/distribution well downstream of the HF bed, 5 – pumping station for purified wastewater; 6 – dry well – receiver of excess treated wastewater.

(*Salix viminalis* L.). Both beds are rectangular holes in the ground lined with 1 mm thick impermeable waterproofing geomembrane. They are filled with materials that have good filtration properties. The VF reed bed is 80 cm deep and is filled with gravel with a grain size of 2–8 mm. The HF willow bed is 120 cm deep and is filled with 1–2 mm gravel. The beds are used for biological treatment of sewage. Wastewater treated in the HF bed flows by gravity to another collection/distribution well (4), and from there to the pumping station for purified sewage (5). This station is equipped with two submersible pumps. One of them, an Omnigena WQ 1500F sewage and drainage pump, returns treated wastewater into the household for reuse. The other one, an Omnigena WQ 250F submersible sewage and drainage pump, discharges excess purified wastewater to the dry well (6), in which the wastewater passes through two filtration layers to finally seep into the ground. The upper filtration layer consists of crushed stone with a grain size of 30–60 mm, and the lower layer is made of coarse 1–2 mm sand. Table 1 shows the key technological parameters of the tested treatment plant.

$$RT = (L \cdot W \cdot n \cdot d) / Q \quad (1)$$

where: L [m] – bed length, W [m] – bed width, n – porosity of bed material ($n_{\text{sand}} = 0.402$, $n_{\text{gravel}} = 0.431$), d [m] – height of the filter bed filled with wastewater (VF = 0.6 m, HF = 1.0 m), Q [$\text{m}^3 \cdot \text{d}^{-1}$] – average daily influent flow rate in the test period = 0.442 m^3/day .

METHODS

We analyzed the performance of the hybrid CW in the first 15 months of its operation from October 2022 to December 2023. During this time, 14 test runs were performed during which 56 wastewater samples were collected for assessing selected physical, chemical and microbiological parameters of wastewater. The volumes of influent and effluent were also measured. Monthly precipitation totals were used to calculate the share of rainwater (snow) in the total hydraulic load of the CW, and evaporation from the CW in the testing period was determined. Wastewater for physico-chemical and microbiological analyses was sampled from various stages of treatment once a month. During each

Table 1. Technological parameters of the constructed wetland serving the employee housing unit in the PNP, Kulczyn, Poland

Start-of-operation date	2022
Population equivalent	4
Design influent flow rate Q (m ³ /day)	0.4
Active capacity of the primary settling tank V (m ³)	3.2
Wetland surface area	
VF reed bed (<i>Phragmites australis</i> [Cav.] Trin. ex Steud) (m ²)	12
HF willow bed (<i>Salix viminalis</i> L.) (m ²)	15
Total surface area (m ²)	27
Bed depth (m)	VF – 0.8 HF – 1.2
Hydraulic load of the VF bed (m ³ /m ² /day)	0.037
Wastewater retention time in the beds (days)*	VF = 7.0 HF = 13.6
Wastewater receiver	Dry well

Note: Wastewater retention time was calculated by Formula 1 given by Conley et al. [1991]:

test run, four wastewater samples collected from the successive stages of treatment were analyzed (Fig. 3). The following parameters were determined in the samples: dissolved oxygen concentration, total suspended solids (TSS), BOD₅, COD, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen, total nitrogen (TN) and total phosphorus (TP). Moreover, the samples were assayed for the presence of *E. coli* and fecal enterococci.

Samples were collected, transported, processed and tested in compliance with the relevant Polish Standards [PN-EN ISO 5667-1:2022-07, PN-ISO 5667-10:2021-11, PN-EN ISO 19458:2007], which are consistent with APHA protocols [American Public Health Association 1992, American Public Health Association 2005]. Physico-chemical and microbiological assays were performed in compliance with commonly used standards and methods (Table 2) in the laboratories of the Department of Environmental Engineering and Geodesy and the Department of Environmental Microbiology of the University of Life Sciences in Lublin (Poland). The amounts of wastewater influent to and effluent from the treatment plant were recorded using three vane-wheel water meters with pulse generators (1 dm³/pulse). A water meter from BMETERS GSD8 Q3 = 4.0 m³/h T50 (B Meters srl, Via Friuli 3, Gonars 33050, Italy) was installed in the raw sewage pumping station to record the amount of wastewater flowing into the treatment plant. Wastewater discharged from the treatment plant was measured using two other water meters installed (1) in the dry well (a BMETERS GSD8 water meter Q3 = 4.0 m³/h T50; B Meters srl, Via Friuli 3, Gonars 33050, Italy) and (2) downstream

of the hydrophore collecting treated wastewater for reuse in the household (a METRON JS 1.0 17 water meter Qn = 1.0 m³/h; METRON Integrated Systems Factory Sp. z o. o., Torun, Poland). The hydrophore for collecting treated wastewater for reuse in the household is the terminal component of the treated wastewater reclamation installation, the operation of which will be the subject of another article. Data from the water meters installed in the pumping station and the dry well were recorded using two Lascar Electronics EL-USB-5 pulse recorders.

The air temperature in the area of the treatment plant was measured using a Lascar Electronics EL-USB-1-PRO electronic temperature recorder. The temperature recorder was placed 5 cm above the surface of the HF willow bed in a special white housing which protected the device against sunlight and allowed free air flow. The wastewater quantity data and the temperature data were recorded automatically every hour. Downloaded data were read on a PC using EasyLog software (EasyLog USB v. 7.7.0.0, Lascar Electronics Ltd. United Kingdom), which was downloaded by inserting the data logger into the PC's USB port. EasyLog software was used to save, read and export the data to Microsoft Excel 2010 for further analysis. Pulses from the water meter downstream of the hydrophore were registered using a LIW-01 Supla Zamel Wi-Fi pulse counter (Zamel Sp. z o. o. Pszczyna, Poland) with SUPLA software version 24.01.01 [www.supla.org.pl, accessed on 14 January 2024]. Data were saved automatically every 10 minutes in SUPLA CLOUD. Then they were downloaded to a hard drive, stored

Table 2. Testing methods and measuring equipment used for the physico-chemical and microbiological assays of wastewater samples collected from the CW in Kulczyn

No.	Test parameter	Document Standard No.	Measurement method / Measuring equipment
1	Dissolved oxygen	PN-EN ISO 5814:2013-04	Electrometric method / ORION Star A329 Set multiparameter meter from Thermo Fisher Scientific (Waltham, USA)
2	Total suspended solids	PN-EN 872:2007+Apl:2007	Direct gravimetric method used after filtration through filters and drying at 105 °C / SLW 53 laboratory dryer from Pol-Eko (Wodzisław Śląski, Poland)
3	BOD ₅	PN-EN 1899-1:2002, 2:2002	Dilution method. Oxygen was measured before and after 5 days of incubation at 20 °C in complete darkness with the addition of a nitrification inhibitor / ORION Star A329 Set multiparameter meter from Thermo Fisher Scientific (Waltham, USA)
4	COD _{Cr}	PN-ISO 15705:2005	Dichromate method with prior oxidation of the sample in a thermoreactor at 148 °C for 2 h / Thermoreactor from WTW (Weilheim, Germany), NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel (Düren, Germany)
5	Total nitrogen	PN-C-04576-14:1973	Spectrophotometric method with prior oxidation of the sample in a thermoreactor at 120 °C for 30 min / Thermoreactor from WTW (Weilheim, Germany), NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel (Düren, Germany)
6	Total phosphorus	PN-EN ISO 6878:2006 pkt. 7 +Ap1:2010+ AP2:2010	Spectrophotometric method with prior oxidation of the sample in a thermoreactor at 120 °C for 30 min / Thermoreactor from WTW (Weilheim, Germany), NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel (Düren, Germany)
7	<i>Escherichia coli</i> (<i>E. coli</i>)	PN-EN ISO 9308-3:2002P	Miniaturised method (Most Probable Number) for the detection and enumeration of <i>E. coli</i> in surface and wastewater / UV observation chamber (Wood's lamp)
8	Fecal enterococci (<i>Enterococci</i>)	PN-EN ISO 7899-1:2002P	Miniaturised method (Most Probable Number) for the detection and enumeration of <i>E. coli</i> in surface and waste water / UV observation chamber (Wood's lamp)

in Microsoft Excel 2010 and monitored online on mobile devices using the SUPLA app for Android. A Davis Vantage Pro 2 wireless home weather station with WeatherLink Data Logger 6510USB software (Davis Instruments 2019, USA) was installed near the treatment plant to record precipitation data. Gaps in rainfall measurements were supplemented with data from the weather station operated by the Department of Grassland and Landscape Management of the University of Life Sciences in Lublin, which is located near the PNP in the village of Sosnowica. The equipment we used provided very accurate measurements of air temperature, precipitation and the volumes of influent and effluent during the study period. The test results were used to calculate the mean, median, minimum and maximum values of the analyzed pollution parameters, as well as the standard deviation of the mean and the coefficient of variation. The concentrations of pollutants in the effluent from the CW were compared to the limits laid down in the Regulation of the Polish Minister of Maritime Economy and Inland Navigation of 2019. Pursuant to this Regulation [36], the concentrations of pollutants in wastewater discharged from the investigated facility must not exceed 50 mg/L TSS, 40 mg/L BOD₅, and 150 mg/L COD. The pollutant removal

efficiency (η) of the investigated treatment plant was calculated on the basis of the mean concentrations of the analyzed pollution parameters at the inlets (C_{in}) and outlets (C_{out}) of the individual stages of treatment and the entire CW, using Formula 2:

$$\eta = (C_{in} - C_{out}) \times 100 / C_{in} \quad [\%] \quad (2)$$

The average pollutant load (APL) was calculated according to Formula 3:

$$APL = (C_{in} \times Q_{in}) / A \quad [\text{g}/\text{m}^2/\text{day}] \quad (3)$$

where: C_{in} [mg/l] – average influent contaminant concentration; Q_{in} [m³/day] – average daily influent flow rate; A [m²] – surface area of a CW bed.

The mass removal rate (MRR) was calculated according to Formula 4:

$$MRR = [(C_{in} \times Q_{in}) - (C_{out} \times Q_{out})] / A \quad [\text{g}/\text{m}^2/\text{day}] \quad (4)$$

where: C_{in} [mg/l] – average influent contaminant concentration; Q_{in} [m³/day] – average daily influent flow rate; C_{out} [mg/l] – average effluent contaminant concentration; Q_{out} [m³/day] – average daily effluent flow rate; A [m²] – surface area of CW bed.

RESULTS AND DISCUSSION

Influent and effluent volumes

Figure 4 shows monthly rainfall totals and average monthly air temperatures for the CW across the study period. These data demonstrate that during the time of this study, precipitation affected the amount of wastewater flowing into the treatment plant. The data in Figure 4 indicate that the study period was characterized by large fluctuations in rainfall levels across months. The highest rainfall totals of 69 and 70 mm were recorded in the summer months of June and July 2023, respectively; the lowest amount of 20 mm of rainfall was registered in September 2023. The lowest average monthly air temperatures (0.6–2.3 °C) were observed from December 2022 to February 2023 and in December 2023. The highest temperatures of 21.9 and 22.1 °C were recorded in the summer months of July and August, respectively. As the data show, the high temperatures increased evaporation, reducing the amount of wastewater discharged from the treatment plant. Table 3 presents influent and effluent levels for the treatment plant. The influent data include the amount of wastewater discharged from the household plus the amount of rain that fell on the surface of the two CW beds. It was found that in the period from October 2022 to December 2023, a total volume of approximately 201 m³ of wastewater and rainwater entered the treatment plant, and approximately 179 m³ of treated wastewater was discharged from it. This means that despite the inflow of rainwater, the amount

of treated effluent was on average 11% lower than the amount of incoming wastewater. During the test period, approximately 22 m³ of water evaporated from the CW beds. It was calculated that the share of rainwater in the total amount of sewage into the CW ranged from 6.37% in February 2023 to over 35% in July 2023 (Figure 5). On average, then, precipitation accounted for approximately 11% of the total amount of influent wastewater. In another study, investigating a vertical flow CW, the share of rainwater in the influent ranged from 5–45% [Operacz et al., 2023]. Observations of two single-stage and two hybrid CWs reported in [Jóźwiakowski 2012] showed that the share of rainwater in the total amount of incoming sewage ranged from 13 to 33%. Much higher figures were recorded for a CW operating in Glaslough, Ireland, where the average proportion of rainwater in the total hydraulic load was 55.8% [Dong et al., 2011]. Authors who examine the impact of precipitation on the operation of CWs point out that rainwater can significantly dilute wastewater flowing into a treatment plant, thus improving the effectiveness of treatment [Jóźwiakowski 2012, Dong et al., 2011, Jóźwiakowska and Bugajski 2023]. The lowest volumes of influent (7023 m³) and effluent (2292 m³) were recorded in July, when the family living in the household went on vacation and the consumption of water in the household fell (Figure 5). For most of the study period, the amount of effluent was lower than the amount of influent, which was probably due to evaporation from the surface of plants growing in the CW beds. During

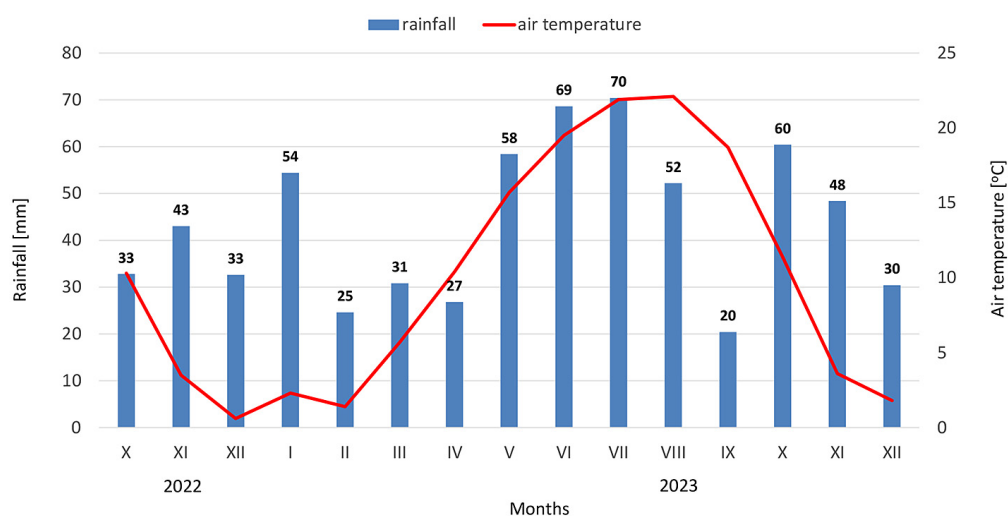


Figure 4. Monthly rainfall totals and average monthly air temperatures in the period from October 2022 to December 2023

Table 3. Influent and effluent levels during the study period

Year/Month		Q [m ³ /d]	Q _{IN+P} [m ³]	Q _{OUT} [m ³]	D [m ³]
2022	Oct	0.402	13.605	12.455	1.150
	Nov	0.413	13.896	13.918	+0.022
	Dec	0.433	14.579	14.973	+0.394
2023	Jan	0.453	15.935	15.873	0.062
	Feb	0.452	13.513	13.422	0.091
	Mar	0.449	15.007	14.820	0.187
	Apr	0.376	12.212	11.698	0.514
	May	0.390	14.145	10.289	3.856
	Jun	0.420	15.002	13.894	1.108
	Jul	0.147	7.023	2.292	4.731
	Aug	0.337	12.277	6.273	6.004
	Sept	0.338	10.844	8.160	2.684
	Oct	0.371	13.609	12.368	1.241
	Nov	0.407	13.904	13.763	0.141
	Dec	0.465	15.484	15.240	0.244
Total volume			201.035	179.438	21.597

Note: Q – average daily influent flow rate; Q_{IN+P} – sum of the amounts of influent wastewater and rainwater feeding the surface of the two CW beds, Q_{OUT} – amount of effluent wastewater, D – difference between the amounts of influent and effluent wastewater.

the winter months, the amounts of incoming and outgoing wastewater were nearly the same, with the exception of November and December 2022. In these two months, the volume of effluent was slightly higher than the volume of influent (Table 3, Fig. 5). This could have been an effect of snow being blown onto the CW beds from the adjacent fields. Once the snow melted, it likely increased the amount of wastewater discharged from the treatment plant. However, the amount of snow could not be registered by the weather station, which only records vertical precipitation.

Wastewater composition at different stages of treatment

Table 4 provides basic descriptive statistics of the tested physico-chemical and microbiological contamination parameters at different stages of purification. Figures 6 and 7, on the other hand, present the dynamics of changes in the concentration of the tested physico-chemical and microbiological contaminants and their average concentrations at individual stages of treatment across the entire study period

Dissolved oxygen

The concentration of dissolved oxygen in raw wastewater ranged from 0.02–0.75 mg O₂/L,

with a mean of 0.16 mg O₂/L. The dissolved oxygen concentration in wastewater that has passed through the primary settling tank was not much higher at 0.36 mg O₂/L. However, a considerable increase in the content of dissolved oxygen was observed in wastewater discharged from the CW beds – 1.52 mg O₂/L (effluent from the VF bed) and 2.88 mg O₂/L (effluent from the HF bed), which testifies to the effectiveness of the biological treatment processes occurring in those beds (Table 4). It was simultaneously observed that the concentrations of dissolved oxygen in wastewater were higher in the winter months and lower in the summer months, when air temperature increased.

Total suspended solids

The concentration of TSS in raw wastewater flowing into the primary settling tank ranged from 85 to 280 mg/L, with a mean of 141 mg/L. After mechanical treatment of wastewater in the tank, the content of TSS decreased to an average of 83 mg/L. A further decrease was recorded in effluents from the VF and HF beds, in which the mean contents of TSS were 16.8 and 11.2 mg/L, respectively (Table 4). Such low TSS levels were recorded in wastewater discharged from the CW beds throughout the study period (Figure 6A). The mean concentration of TSS in wastewater leaving the HF bed was much lower

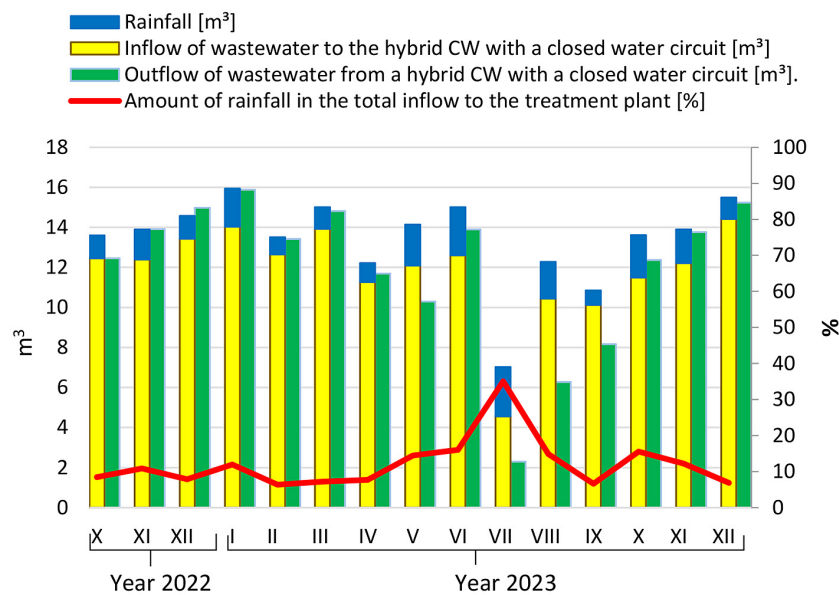


Figure 5. Monthly volumes (m^3) of influent (including rainwater) and effluent, and the percentage of rainwater in influent across the study period

than the limit of 50 mg/L set out in the current Polish Regulation [2019] (Figure 7A).

BOD₅

Raw wastewater influent to the primary settling tank contained an average of 165 to 367 mg O_2/L of organic pollutants expressed as BOD_5 . The mean BOD_5 was 246 mg O_2/L . This value dropped to 183 mg/L when wastewater was treated mechanically in the primary settling tank. Treatment in the VF and HF CW beds led to further reductions in BOD_5 to 19.6 and 6.9 mg O_2/L , respectively. The level of BOD_5 in wastewater discharged from the CW beds was consistently low throughout the period studied (Figure 6B). The mean BOD_5 in wastewater effluent from the HF bed was much lower than the limit of 40 mg/L set out in the current Polish Regulation [2019] (Figure 7B).

COD₃₃₃₃

Raw wastewater flowing into the primary settling tank contained an average of 407 to 800 mg O_2/L of organic pollutants expressed as COD. The mean COD was 606 mg O_2/L . This value dropped to 515 mg/L in wastewater that had passed through the primary settling tank. Further treatment in the VF and HF CW beds caused a reduction in COD to 96 and 40.4 mg O_2/L , respectively. The level of COD in wastewater discharged from the CW beds was consistently low throughout the period studied (Figure 6C). The mean value of COD in

wastewater discharged from the HF bed was lower than 150 mg/L, which means it met the requirements laid down in the current Polish Regulation [2019] (Figure 7C).

Total nitrogen

The assays showed that TN concentration in raw wastewater ranged from 53 to 146 mg/L, with a mean of 87 mg/L. The content of TN did not fall after mechanical treatment of wastewater in the primary settling tank. A gradual decrease in this parameter was observed only in samples of effluent from the VF and HF beds, which contained an average of 50 and 36 mg/L of TN, respectively (Figure 7D). The concentrations of TN in effluent from the HF bed were much lower than those measured in effluent from the VF bed throughout the study period (Figure 6D).

Total phosphorus

The assays showed that the concentration of TP in raw wastewater ranged from 7.1 to 27.9 mg/L, with a mean of 14.3 mg/L. After mechanical treatment of wastewater in the primary settling tank, the content of TP decreased to an average of 13.9 mg/L. Much smaller concentrations were observed in samples of effluent from the VF and HF beds, which contained 6.6 and 4.0 mg/L of TP, respectively (Figure 7E). The concentrations of TP in the effluent from the HF bed were lower than those in wastewater discharged from the VF bed throughout the period studied (Figure 6E).

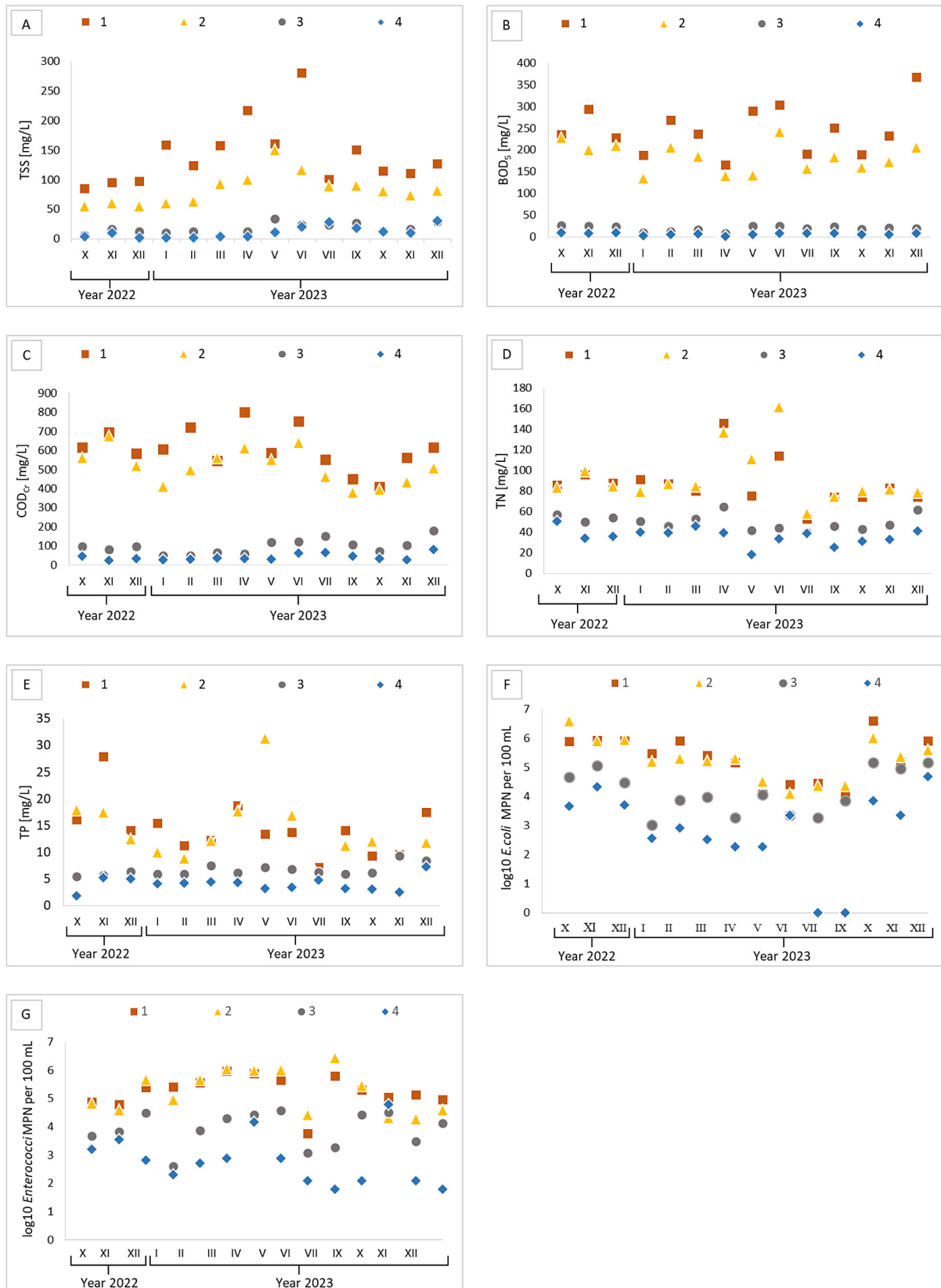


Figure 6. Dynamics of changes in the concentration of the tested physico-chemical (A–E) and microbiological (F–G) contaminants at individual stages of purification over the entire study period. A – total suspended solids (TSS), B – biochemical oxygen demand (BOD₅), C – chemical oxygen demand (COD_{Cr}), D – total nitrogen (TN), E – total phosphorus (TP), F – *Escherichia coli* (*E. coli*), G – Enterococci, 1 – raw wastewater, 2 – wastewater discharged from the primary settling tank, 3 – wastewater discharged from the VF reed bed, 4 – wastewater discharged from the HF willow bed.

Table 4. Descriptive statistics of the pollution parameters of wastewater sampled from different stages of treatment in the study period

Parameter (Unit)	Wastewater type	Min.	Max.	Mean	Median	Standard deviation	Coefficient of variation
Oxygen (mg/l)	1	0.02	0.75	0.16	0.08	0.21	1.30
	2	0.04	1.09	0.36	0.19	0.34	0.97
	3	0.65	2.68	1.52	1.48	0.59	0.39
	4	0.94	4.39	2.88	3.23	1.08	0.37
Total suspended solids (mg/l)	1	85	280	140.9	125.1	53.4	0.38
	2	55	150	83.2	80.5	26.5	0.32
	3	3.6	33.3	16.8	14.7	8.8	0.53
	4	2.0	30	11.2	10.0	9.6	0.86
BOD ₅ (mg/l)	1	165	367	246	236	55	0.22
	2	134	242	183	184	33.9	0.18
	3	8.1	27.0	19.6	20.5	5.9	0.30
	4	0.94	9.98	6.90	7.66	2.61	0.38
COD (mg/l)	1	407	800	606	595	109	0.18
	2	379	675	515	513	91.9	0.18
	3	47	178	96	97	38.2	0.40
	4	22.7	79.0	40.4	33.5	17	0.42
Total nitrogen (mg/l)	1	53	146	87	84	22	0.25
	2	58	162	93	84	27	0.29
	3	40	82	50	49	7.5	0.15
	4	18	50	36	37	8.2	0.23
Total phosphorus (mg/l)	1	7.1	27.9	14.3	13.8	5.1	0.35
	2	5.6	31.3	13.9	12.0	6.2	0.45
	3	5.5	9.3	6.6	6.1	1.1	0.17
	4	1.7	5.2	4.0	4.1	1.3	0.34
<i>E. coli</i> (log ₁₀ MPN)	1	4.08	6.61	5.32	5.45	0.79	0.15
	2	4.09	6.61	5.28	5.30	0.73	0.14
	3	3.02	6.61	4.16	4.02	0.76	0.18
	4	0.00	4.68	2.82	3.14	1.40	0.50
Fecal enterococci (log ₁₀ MPN)	1	3.76	5.97	5.25	5.34	0.57	0.11
	2	4.28	6.44	5.23	5.21	0.74	0.14
	3	2.60	4.84	3.90	3.99	0.61	0.16
	4	1.78	4.78	2.79	2.76	0.89	0.32

Note: 1 – raw wastewater, 2 – wastewater discharged from the primary settling tank, 3 – wastewater discharged from the VF reed bed, 4 – wastewater discharged from the HF willow bed.

Escherichia coli

As our data for the entire study period show (Fig. 6F), the highest concentrations of *E. coli* bacteria were mostly recorded in raw wastewater. The months of October and December 2022 and April, May, September and November 2023 were the only ones in which the number of these bacteria was higher in mechanically treated wastewater than in raw wastewater. In the period from January to April 2023, *E. coli* counts in raw

wastewater and wastewater from the primary settling tank were similar (5.16–5.91 and 5.23–5.30 log₁₀ MPN per 100 mL, respectively); the same situation was observed from May to September 2023, when the respective bacterial counts were in the range of 4.08–4.46 and 4.09–4.52 log₁₀ MPN per 100 mL. In the latter period, however, the counts of this group of microorganisms were lower compared to the period from January to April 2023. *E. coli* counts in effluent from the VF reed bed were considerably lower compared to those recorded

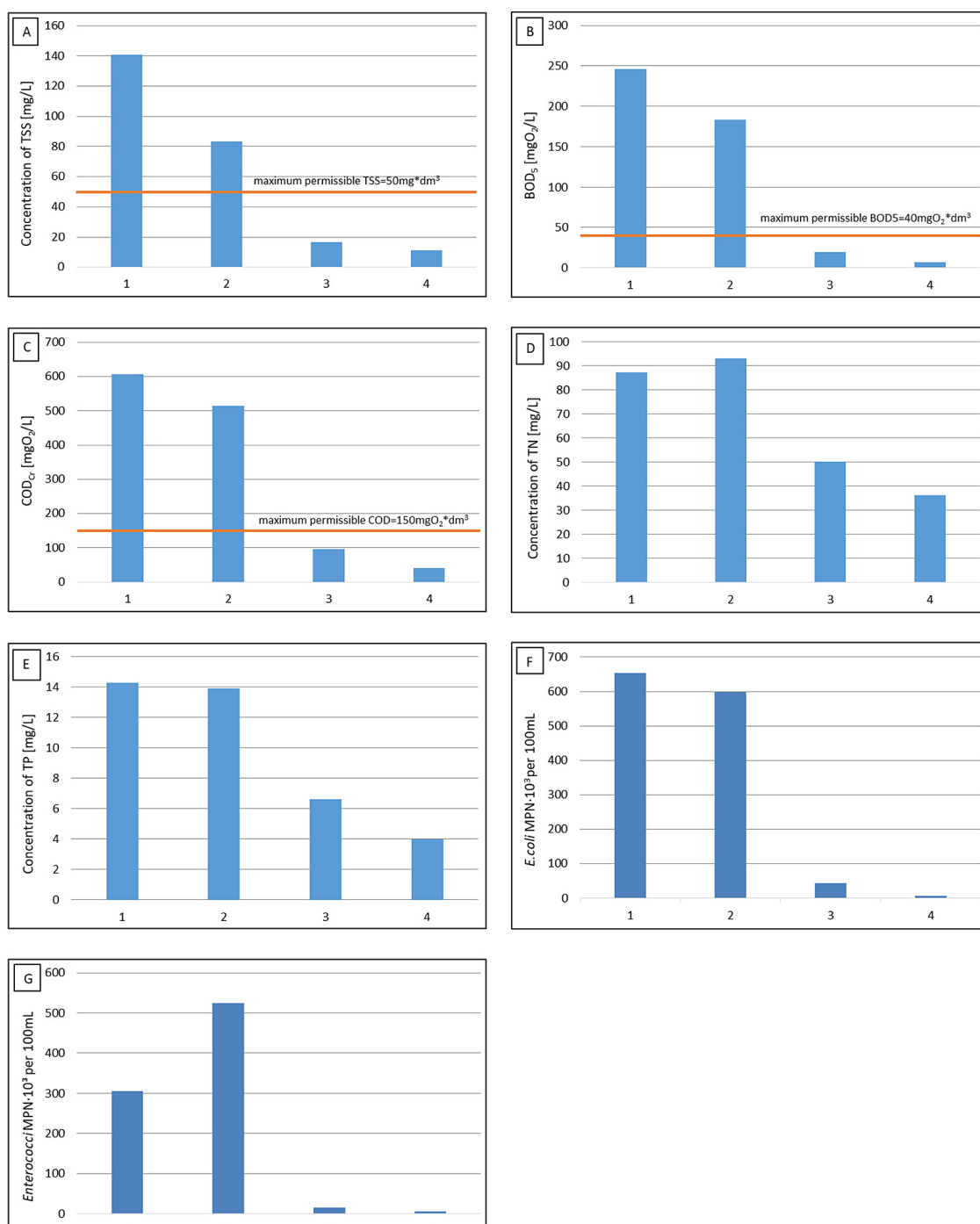


Figure 7. Mean concentrations of physico-chemical (A–E) and microbiological (F–G) contaminants in wastewater sampled from the CW at individual stages of treatment. A – total suspended solids (TSS), B – biochemical oxygen demand (BOD₅), C – chemical oxygen demand (COD), D – total nitrogen (TN), E – total phosphorus (TP), F – *Escherichia coli* (*E. coli*), G – *Enterococci*, 1 – raw wastewater, 2 – wastewater discharged from the primary settling tank, 3 – wastewater discharged from the VF reed bed, 4 – wastewater discharged from the HF willow bed.

in raw wastewater and wastewater treated in the primary settling tank throughout the study period. The lowest concentrations of *E. coli* (log₁₀ MPN per 100 mL) were recorded in January (3.88), April (3.28) and July (3.27) 2023 (Fig. 6F). When data for all the stages of treatment were compared, the lowest levels

of *E. coli* were found in the effluent from the HF willow bed. In July and September 2023, wastewater discharged from this bed was completely free from these bacteria. The highest counts of *E. coli* were recorded in October, November and December of 2022 and 2023 across the sampling sites.

Fecal enterococci

Enterococcal counts (log₁₀ MPN per 100 mL) in raw wastewater were higher than those determined in mechanically treated wastewater discharged from the primary settling tank in November (4.78), January (5.39) and October till December 2023 (4.96–5.05). In the remaining months, effluent from the tank contained higher concentrations of enterococci than raw wastewater. The counts of these bacteria were considerably reduced in wastewater that had passed through the VF reed bed. The lowest enterococcal counts (log₁₀ MPN per 100 mL) in the effluent from this bed were registered in January (2.60), June (3.07) and July (3.26) 2023, and the highest in the period from March to May 2023 (4.30–4.56) and in September (4.41) and October (4.50) 2023. Treated sewage discharged from the HF willow bed contained the lowest numbers of enterococci across the study months. The lowest MPN values per 100 mL (log₁₀) were recorded in the effluent from this bed in the period from June to September 2023 (1.77–2.07) and in November (2.07) and December (1.77) of that year (Fig. 6G).

Wastewater treatment efficiency of the constructed wetland

Table 5 shows the average pollutant loads and mass removal rates for the VF and HF beds and the entire CW system. Figures 8 and 9 present the efficiencies of the individual stages of treatment and the entire CW at removing the tested contaminants.

Total suspended solids removal efficiency

It was shown that the CW's two-chamber primary settling tank had an average TSS removal

efficiency of 40.95% (Figure 8A). This value was lower than that obtained by Micek et al. [2020] during a three-year study of three- and four-chamber primary settling tanks used in CWs and activated sludge treatment plants in the Roztocze National Park (RNP). In their study, the three-chamber settling tanks removed 42–60% of TSS while the four-chamber settling tanks had TSS removal rates in the range of 60–77%. These data indicate that the number of chambers has a strong impact on the efficiency of eliminating TSS from wastewater. Our data showed that the VF reed bed achieved the highest TSS removal rates, eliminating, on average, 79.76% of this contaminant. The TSS removal efficiency of the HF bed was much lower at 33.65% (Figure 8A). The mean TSS removal efficiency of the entire treatment plant was quite high already during the start-up period – 93.33% (Figure 9). In Józwiakowski et al.'s study [2019] of ten hybrid CW systems operating in south-eastern Poland, the mean TSS removal efficiency was 93%, which is similar to that obtained in the tested facility already during the start-up period. Józwiakowski et al. [2019] also found that single-stage CWs provided a lower removal rate for TSS (82%) than hybrid systems.

In the present study, it was shown that in the VF reed bed, the mean mass removal rate (MRR) of TSS was 2.16 g/m²/day, and in the HF bed it was much lower at only 0.15 g/m²/day. The MRR of TSS for the entire treatment plant was 1.04 g/m²/day (Table 4). Lower MRRs for TSS were reported by Micek et al. [2020] for two similar VF-HF CWs used in the RNP. In those facilities, the MRRs of TSS for VF beds were 1.67 and 1.28 g/m²/day, and for HF beds they were 0.36 and 0.17 g/m²/day. The MRRs of TSS for the entire hybrid

Table 5. Average pollutant loads (APL) and mass removal rates (MRR) of the facility under study (in g/m²/day)

Parameter		Bed type		
		VF	HF	VF-HF
TSS	APL	2.70	0.44	1.20
	MRR	2.16	0.15	1.04
BOD ₅	APL	5.96	0.51	2.65
	MRR	5.32	0.33	2.55
COD	APL	16.73	2.51	7.43
	MRR	13.62	1.43	6.85
TN	APL	3.02	1.31	1.34
	MRR	1.40	0.35	0.82
TP	APL	0.45	0.17	0.20
	MRR	0.24	0.07	0.14

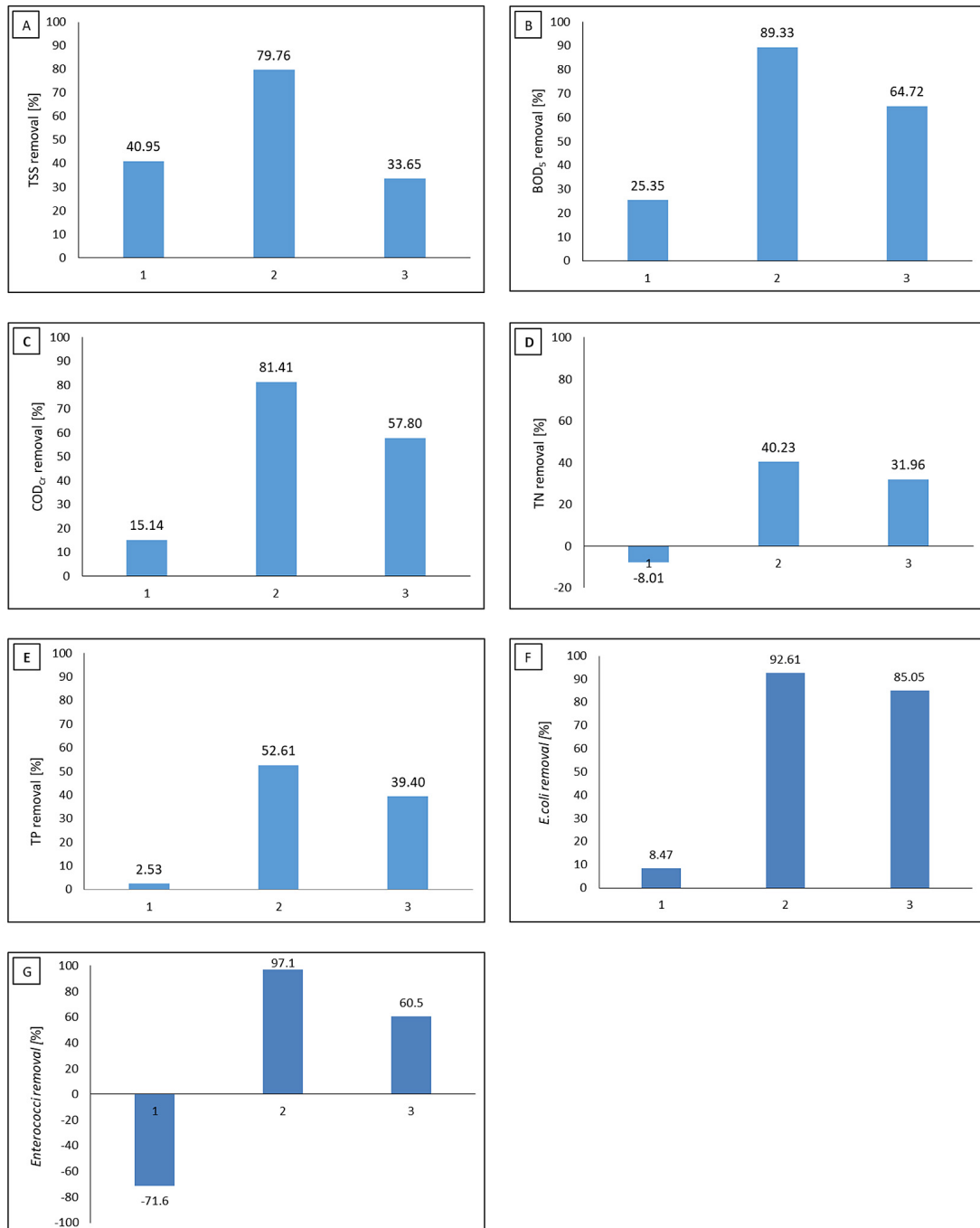


Figure 8. Efficiency of removal of physico-chemical (A–E) and microbiological (F–G) contaminants in the individual treatment stages of the investigated CW: A – total suspended solids (TSS), B – biochemical oxygen demand (BOD₅), C – chemical oxygen demand (COD), D – total nitrogen (TN), E – total phosphorus (TP), F – *Escherichia coli* (*E. coli*), G – Enterococci, 1 – raw wastewater, 2 – removal efficiency of the primary settling tank, 2 – removal efficiency of the VF reed bed, 3 – removal efficiency of the HF willow bed.

CWs operating in the area of the RNP were 0.85 and 0.63 g/m²/day.

BOD₅ reduction rates

In the present study, the two-chamber primary settling tank offered an average BOD₅ reduction rate of 23.25% (Figure 8B). Its efficiency was

comparable to that (8–26%) reported by Micek et al. [2020] for three-chamber primary settling tanks used in the domestic wastewater treatment plants installed in the RNP. In Micek et al. [2020] three-year study, four-chamber settling tanks provided a much higher BOD₅ reduction rate, in the range of 50–51%, which indicates that the

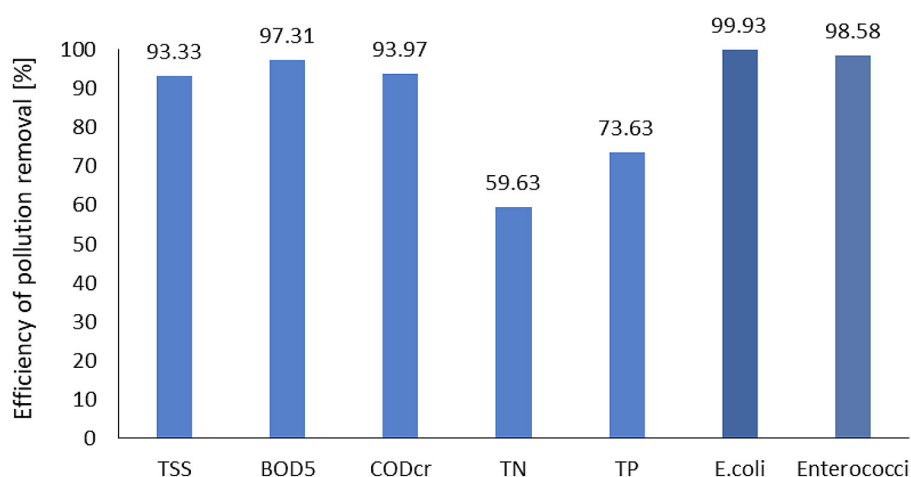


Figure 9. Average pollutant removal efficiency of the investigated CW in the start-up period. TSS – total suspended solids, BOD₅ – biochemical oxygen demand, COD – chemical oxygen demand, TN – total nitrogen, TP – total phosphorus, E. coli – *Escherichia coli*, Enterococci.

number of chambers has a strong impact on the efficiency of a settling tank at reducing BOD₅. The present experiments demonstrated that, just as in the case of TSS, the highest BOD₅ reduction rate (89.33%) was achieved in the VF reed bed. BOD₅ reduction in the HF willow bed was again lower at 64.72% (Figure 8B). The mean BOD₅ reduction rate for the entire treatment plant during the run-in period was 97.31% (Figure 9). In Józwiakowski et al.'s 2019 study of ten hybrid CW systems, the average BOD₅ reduction rate was 97%, which is similar to that obtained in the tested facility already during the start-up period. Similarly to our observations, Józwiakowski et al. [2019] also found that single-stage CWs provided a lower BOD₅ reduction rate (89%) than hybrid systems. In the present study, the mean MRR of BOD₅ for the VF reed bed was 5.32 g/m²/day; This value was much lower for the HF bed at only 0.33 g/m²/day. The MRR of BOD₅ for the entire treatment plant was 2.55 g/m²/day (Table 4). Different MRRs of BOD₅ were obtained by Micek et al. [2020] in their study of the two VF-HF CWs installed in the RNP. In those treatment plants, the MRRs of BOD₅ for the VF beds were 5.77 and 2.66 g/m²/day, and for the HF beds they were 0.16 and 0.24 g/m²/day. The MRRs of BOD₅ for those two hybrid CWs considered as whole systems were 2.26 and 1.25 g/m²/day.

COD reduction rates

In the CW system we investigated, the two-chamber primary settling tank offered an average COD removal efficiency of 15.14% (Figure 8A).

This value was slightly higher than that recorded by Micek et al. [2020] for three-chamber primary settling tanks, but much lower than that obtained by those authors for four-chamber settling tanks (48–51%). These data indicate that the number of chambers has a strong impact on the efficiency of a settling tank at reducing COD. The present study demonstrated that, just as in the case of TSS and BOD₅, the best COD reduction rate (81.41%) was provided by the VF bed. Again, the HF bed had a lower efficiency at 57.80% (Figure 8B). The mean COD reduction rate for the entire treatment plant was 93.97% (Figure 9). This value, which was obtained during the start-up period, is almost identical to the mean COD reduction rate reported by Józwiakowski et al. in their 2019 study of ten hybrid CW systems (94%). In that study [Józwiakowski et al., 2019] single-stage CWs also provided a lower COD removal rate (85%) than hybrid systems. In our experiments, the MRR of COD for the VF reed bed was 13.62 g/m²/day, which was a much higher value that that obtained for the HF bed – 1.43 g/m²/day. The MRR of COD for the entire treatment plant was 6.85 g/m²/day (Table 4). Different MRRs for COD were reported by Micek et al. [2020] in their study of the two VF-HF CWs used in the RNP. In those treatment systems, the MRRs of COD for VF beds were 15.48 and 8.03 g/m²/day, and for HF beds they were 0.71 and 0.96 g/m²/day. The MRRs of COD for the entire hybrid CWs were 6.25 and 13.90 g/m²/day.

Total nitrogen removal efficiency

Our data demonstrated that the two-chamber primary settling tank which was part of the

analysed treatment plant did not ensure an effective removal of TN, as the concentration of this pollutant in the effluent from the tank was 8% higher than in raw wastewater (Figure 8D). A similar observation was made by Micek et al. [2020]. Wastewater discharged from the three-chamber settling tanks they investigated contained 3–14% more TN than raw wastewater. This may have been caused by the release of nitrogen from sewage sludge during the treatment process taking place in the primary settling tanks. The four-chamber primary settling tanks tested by Micek et al. [2020] provided an equally low TN removal efficiency (9–11%). In the present study, the highest TN removal efficiency was achieved in the VF reed bed, which eliminated on average 40.23% of this contaminant. The HF willow bed had a lower TN removal efficiency of 31.96% (Figure 8B). The mean TN removal efficiency of the entire CW system was 59.63% already during the start-up period (Figure 9). This value was only slightly lower than the average TN removal efficiency of 65% reported by Józwiakowski et al. [2019] for ten hybrid CW systems operating in south-eastern Poland. In their study single-stage CWs had a lower TN removal efficiency (53%) than hybrid CW systems. In our experiments, the mean MRR of TN for the VF reed bed was 1.40 g/m²/day, which was a much higher value than that obtained for the HF bed – 0.35 g/m²/day. The MRR of TN for the entire CW was 0.82 g/m²/day (Table 4). These figures are similar to those reported by Micek et al. [2020] in their paper on the two VF-HF CWs used in the RNP. In the facilities they investigated, the MRRs of TN for VF beds were 1.39 and 0.68 g/m²/day, and for HF beds – 0.55 and 1.03 g/m²/day. The MRRs of TN for the entire hybrid CWs were 0.87 and 0.88 g/m²/day.

Total phosphorus removal efficiency

The two-chamber primary settling tank of the treatment plant under study was characterised by a low TP removal efficiency of 2.53% (Figure 8E). Different results were reported by Micek et al. [2020] in their three-year study of three-chamber primary settling tanks used in domestic wastewater treatment plants installed in the RNP. Those authors observed a 26–37% increase in TP concentration in wastewater discharged from the settling tanks compared to raw sewage. This may have been due to the release of nitrogen from sewage sludge during the treatment process occurring in the primary settling tanks. The

four-chamber primary settling tanks investigated by Micek et al. [2020] had an equally low TP removal efficiency.

In our study, the highest TP removal efficiency was achieved in the VF reed bed, which eliminated on average 52.61% of this pollutant. The HF willow bed had a lower TP removal efficiency of 39.40% (Figure 8B). The mean TP removal efficiency of the entire CW system was 73.63% (Figure 9). This value was much lower than the average reported by Józwiakowski et al. [2019] for ten hybrid CW systems operating in south-eastern Poland. Those systems removed an average of 89% of TP from wastewater, but it has to be remembered that the CW we tested was still in its run-in period. In Józwiakowski et al.'s study, [2019], single-stage CWs had a lower TP removal efficiency (65%) than hybrid CW systems.

In our experiments, the mean MRR of TP for the VF reed bed was 0.24 g/m²/day, which was a much higher value than that obtained for the HF bed – 0.14 g/m²/day. The MRR of TP for the entire CW was 0.14 g/m²/day (Table 4). To compare, Micek et al. [2020] reported higher MRR of TP for the two VF-HF CWs operating in the RNP. In those facilities, the MRRs of TP were 0.32 and 0.22 g/m²/day for VF beds, and 0.13 and 0.17 g/m²/day for HF beds. The MRRs of TP for the whole CWs were 0.21 and 0.19 g/m²/day.

E. coli removal rates

The two-chamber primary settling tank in the investigated CW had a low *E. coli* removal efficiency of 8.47% (Figure 8F). The highest concentrations of these bacteria were removed in the VF reed bed – on average 92.61%. The HF willow bed provided a lower mean *E. coli* removal rate of 85.05% (Figure 8F). The mean *E. coli* removal efficiency of the entire CW system was 99.93%, even though it was only the start-up period (Figure 9).

Fecal enterococci removal rates

The two-chamber primary settling tank of the analyzed treatment plant did not ensure effective removal of fecal enterococci, as their concentrations in the wastewater discharged from the settling tank were 71.6% higher than those found in raw wastewater (Figure 8G). The highest removal rates for enterococci were achieved in the VF reed bed, which eliminated on average 97.1% of these bacteria. The HF willow bed had a lower removal efficiency of 60.5% (Figure 8B). The mean

enterococci removal efficiency of the entire CW system during the start-up period was 98.58% (Figure 9).

As pointed out by Rajan et al. [2020], the substrates for hybrid CWs are selected depending on their availability and the design requirements, but it has to be remembered that different substrates have different physical and chemical parameters. These parameters determine the interactions between the plants and the microorganisms inhabiting the CW, as well as their contribution to the treatment of wastewater. Those authors claim that the composition of the microbial communities living in CWs is contingent on temperature, moisture content, pH, presence of macrophytes, type of bed, oxygenation, and the contents of organic matter, organic carbon, $N-NH_4$ and $N-NO_3$. Hernández-Crespo et al. [2022] list the following among the factors that influence the pollutant removal efficiency of a CW: hydraulic loading rate (HLR), hydraulic residence time (HRT), solar disinfection, sedimentation, filtration, adsorption of bacteria on organic and inorganic particles and macrophyte roots, the presence of zooplankton and predatory organisms, depth of the bed, as well as the grain size of the filter medium.

As reported by Anastasi et al. [2012], wastewater treated using the activated sludge method or other biological methods often still contains fecal bacteria and pathogens. *E. coli* bacteria may include uropathogenic strains that can survive after various stages of wastewater treatment. In our study, the presence of *E. coli* and enterococci in wastewater that had passed through the HF bed could be related to the higher resistance of some bacterial strains to adverse physicochemical factors, with enterococci being particularly robust to harsh environmental conditions [Russo et al., 2019, Vymazal 2005].

The pollutant removal efficiency of a wastewater treatment system also depends on how complex the system is. Nan et al. [2020], who analyzed 39 different wastewater treatment solutions, emphasized that the highest efficiency at removing physicochemical and microbiological pollutants could be achieved using hybrid treatment systems. Similar observations were made by Józwiakowski et al. [2019]. Nan et al. [2020] reported that single-stage CWs and hybrid CWs removed from 94 to 99.999% of *E. coli* bacteria during wastewater treatment, but the hybrid systems were the most effective in this respect. Kornilłowicz-Kowalska et al. [2022] found that

when it came to removing fungal propagules from wastewater, a hybrid VF-HF CW was the most efficient type of system while a biological treatment plant was the least efficient one.

The CW we investigated during its start-up period, achieved TSS, BOD_5 and COD removal rates of over 90%, and TN and TP removal rates of 60 and 74%, respectively. The removal rate for *E. coli* was 99.93% and for fecal enterococci – 98.58%, which is consistent with the data reported by Nan et al. [2020]. It has to be remembered, however, as emphasised by Vymazal [2005], that in monitoring contamination with fecal bacteria, it is important not only to assess the efficiency of their removal, but also the mean counts of the bacteria that are still present in treated wastewater. In our study, treated effluent from the HF bed contained 7.103 MPN of *E. coli* per 100 mL and 6.103 MPN of enterococci per 100 mL.

The number of bacterial cells in wastewater fluctuates significantly over time and depends on the size of their population in a given environment [Józwiakowski et al., 2009]. This claim was confirmed by the present results, which showed that *E. coli* counts were lower in the period from May to September, and higher in the period from October to December 2022 and 2023. This can be explained by the fact that the family living in the house spends more time at home during the winter than in the summer. Moreover, as reported by Karathanasis et al. [2003], CWs may be less effective at removing bacteria from wastewater in winter due to persisting low temperatures which reduce the metabolic activity of the bacteria and the activity of predatory organisms. Moreover, limited growth or lack of macrophytes leads to a decrease in root biomass in winter, which decreased the ability of the plants to adsorb microorganisms, thus lowering their filtration potential [Karathanasis et al., 2003]. This may result in bacteria passing unabsorbed through the beds. Vymazal [2005] also emphasizes the role that macrophyte root secretions play in the effective elimination of bacteria. Karathanasis et al. [2003] have shown that in subsurface flow CWs treating domestic wastewater, the effectiveness of fecal coliform removal was influenced by the presence of plants and the season of the year. In their experiments, the highest fecal bacteria removal rates were recorded in the period from May to September in systems with plants, while in systems without plants, the elimination of these bacteria was more efficient in winter and early

spring. Moreover, the high concentrations of oxygen released by the roots of macrophytes promote the formation of oxygen radicals, which damage bacterial cells at high pH. The dead cells are then removed during the operation of the treatment plant [Hernández-Crespo et al., 2022].

Opinions about the influence of temperature on the effectiveness of removing physico-chemical and bacterial contaminants are divided. While some authors report that temperature has a considerable impact on the removal of contaminants [Hernández-Crespo et al., 2022], others claim that the impact of temperature is additionally related to hydraulic load [Rajan et al., 2020, Karathanasis et al., 2003]. In the present study, the efficiency of removal of fecal bacteria, in particular *E. coli* bacteria, was the highest in the period from May to September when the temperatures were high (15.7–22.1 °C).

CONCLUSIONS

This paper reports performance data from the first few months of operation of a hybrid CW. The system under study consisted of a two-chamber primary settling tank integrated with a pumping station and a sequence of two beds: a VF reed bed and a HF willow bed. The facility had been designed to treat 0.4 m³/d of domestic wastewater discharged from a forester's lodge located in the PNP. The tests showed that the actual influent flow rate was the same as the design value. It was observed that rainwater (snow) accounted for 6 to 34% of the amount of wastewater fed to the wetland beds. The amount of effluent from the treatment plant was on average 11% smaller than the amount of influent combined with rainwater. This may indicate that evaporation from the surface of the beds reduced the amount of wastewater discharged into the environment. The tests showed that the two-chamber primary settling tank in the analyzed treatment plant offered lower pollutant treatment performance than three- or four-chamber settling tanks previously used in facilities of this type. This means that three-chamber primary settling tanks are a recommended choice for any hybrid CWs to be built in the future in the PNP and other locations. It was found that the investigated treatment plant on average provided an over 90% removal efficiency for TSS, BOD₅ and COD during the start-up period. This value was similar to those obtained in hybrid CWs that had already been operating for many years. The

CW was less efficient at removing TN (60%) and TP (74%) compared to CWs with a longer operational history, which may indicate that the facility still needs more run-in time to be able to eliminate these pollutants more effectively. At the same time, the treatment plant offered very good performance when it came to reducing the populations of *E. coli* and fecal enterococci (an over 98% removal efficiency). The concentrations of all investigated pollutants in wastewater discharged from the treatment plant met the requirements laid down in the legal provisions currently in force in Poland. This study has shown that hybrid VF-HF CWs can be recommended for use in protected areas as efficient wastewater treatment systems that can help prevent the eutrophication of water bodies.

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REFERENCES

1. American Public Health Association (APHA) 1992. Standard Methods for the Examination of Water and Wastewater. 18th Edition, American Water Works Association (AWWA) and Water Pollution Control Federation (WPCF), Washington DC.
2. American Public Health Association (APHA) 2005. Standard Methods for the Examination of Water and Wastewater. 21st Edition, American Water Works Association/Water Environment Federation, Washington DC.
3. Anastasi E.M., Matthews B., Stratton H.M, Kattoulia M. 2012. Pathogenic *Escherichia coli* found in sewage treatment plants and environmental waters. *Applied and Environmental Microbiology*, 78, 16, 5536–5541. <http://dx.doi.org/10.1128/AEM.00657-12>
4. Bergier T., Włodyka-Bergier A. 2016. Semi-technical scale research on constructed wetland removal of aliphatic hydrocarbons C7–C40 from wastewater from a car service station, *Desalination and Water Treatment* 57, 3, 1534–1542.
5. Brix H., Schierup H.H. 1989. Sewage treatment in constructed wetlands – Danish experience. *Water Science and Technology* 21, 1665–1668.
6. Conley L.M., Dick R.L., Lion L.W. 1991. An assessment of the root zone method of wastewater treatment. *Research Journal WPCF*, 64(3), 239–247.

7. Cooper P., Green B. 1995. Reed bed treatment systems for sewage treatment in the United Kingdom – The first 10 years experience. *Water Science and Technology* 32(3), 317–327. [https://doi.org/10.1016/0273-1223\(95\)00632-X](https://doi.org/10.1016/0273-1223(95)00632-X)
8. Dong Y., Wiliński P.R., Dzakpasu M., Scholz M. 2011. Impact of Hydraulic Loading Rate and Season on Water Contaminant Reductions Within Integrated Constructed Wetlands. *Wetlands* 31, 499–509. doi: 10.1007/s13157-011-0176-5
9. Gajewska, M., Obarska-Pempkowiak, H., 2009. 20 Years of experience of hybrid constructed wetlands exploitation in Poland. *Rocz. Ochr. Sr.* 11, 875–888 (in Polish).
10. Gonzalez-Flo E., Romero X., García J. 2023. Nature based-solutions for water reuse: 20 years of performance evaluation of a full-scale constructed wetland system. *Ecological Engineering* 188, 106876. <https://doi.org/10.1016/j.ecoleng.2022.106876>
11. Haberl R., Perfler R. 1990. Seven years of research work and experience with wastewater treatment by a reed bed system. In: *Constructed wetlands in Water Pollution Control, Advances in Water Pollution Control No. 11*, Cooper P.F. and Findlater B. C. (Eds.), Pergamon Press, Oxford, 529–534.
12. Haberl R., Perfler R., Mayer H. 1995. Constructed wetlands in Europe. *Water Science and Technology* 32(3), 305–315. <https://doi.org/10.2166/wst.1995.0153>
13. Hernández-Crespo C., Fernández-Gonzalvo M.I., Miglio R.M., Martín M. 2022. *Escherichia coli* removal in a treatment wetland - pond system: A mathematical modelling experience. *Science of the Total Environment*, 839, 156237. <http://dx.doi.org/10.1016/j.scitotenv.2022.156237>
14. Józwiakowski K., Bugajski, P. 2023. Influence of the Bed Temperature on the Operational Reliability of a Hybrid Constructed Wetland Wastewater Treatment Plant in South-Western Poland – A Case Study. *Sustainability* 15, 11790. <https://doi.org/10.3390/su151511790>
15. Józwiakowski K., Kornilowicz-Kowalska T., Iglík H. 2009. Estimation of sanitary status of sewage treated in constructed wetland systems. In: *sewages and waste materials in environment* (eds. Wiera Sądej), Wydawnictwo University of Warmia and Mazury in Olsztyn, ISBN 978-83-929462-1-2, 7–22.
16. Józwiakowski K. 2012. Studies on the efficiency of sewage treatment in chosen constructed wetland systems. *Infrastruct. Ecol. Rural. Areas* 1, 232 (In Polish).
17. Józwiakowski K., Gajewska M., Marzec M., Gizińska-Górna M., Pytka A., Kowalczyk-Juśko A., Sosnowska B., Baran S., Malik A., Kufel R. 2016. Hybrid constructed wetlands for the National Parks in Poland - a case study, requirements, dimensioning, preliminary results. *Natural and Constructed Wetlands Nutrients: Heavy Metals and Energy Cycling, and flow*, 247–267.
18. Józwiakowski K., Marzec M., Kowalczyk-Juśko A., Gizińska-Górna, M., Pytka-Woszczyło A., Malik A., Listosz A., Gajewska M. 2019. 25 years of research and experiences about the application of constructed wetlands in southeastern Poland. *Ecological Engineering*, 127, 440–453. <https://doi.org/10.1016/j.ecoleng.2018.12.013>
19. Karathanasis A.D., Potter C.L., Coyne M.S. 2003. Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. *Ecological Engineering* 20, 157–169. [https://doi.org/10.1016/S0925-8574\(03\)00011-9](https://doi.org/10.1016/S0925-8574(03)00011-9)
20. Kickuth R. 1977. Degradation and incorporation of nutrients from rural wastewaters by plant rhizosphere under limnic conditions. In: *Utilization of Manure by Land Spreading*. Comm. Europ. Commun., EUR 5672e, London, UK, 335–343.
21. Kornilowicz-Kowalska T., Józwiakowski K., Iglík H. 2010. Characterisation of the sanitary status of domestic sewage generated in households in rural areas. *Teka Kom. Ochr. Kszt. Środ. Przyr. – OL PAN*, 7, 154–162.
22. Kornilowicz-Kowalska T., Bohacz J., Rybczyńska-Tkaczyk K., Józwiakowski K. 2022. Evaluation of the richness, species diversity, and biosafety of saprotrophic fungal communities in constructed wetlands and biological wastewater ponds. *Water*, 15(1), 31. <https://doi.org/10.3390/w15010031>
23. Malik A., Józwiakowska K., Józwiakowski K., Siwiec T., Myka-Raduj A. 2021. Construction design of a hybrid constructed wetland wastewater treatment plant with a closed water circuit for the forester’s lodge of the Polesie National Park in Kulczyn, Hańsk commune, Maszynopis, Polesie National Park, Manuscript, 29 (in Polish).
24. Malinowski P., Dąbrowski W., Bagińska S., Karolinczak B. 2023. Elimination of bacterial contamination from domestic sewage using vertical flow constructed wetland. *Desalination and Water Treatment* 305, 88–94.
25. Micek A., Józwiakowski K., Marzec M., Listosz A., Malik A. 2020. Efficiency of Pollution Removal in Preliminary Settling Tanks of Household Wastewater Treatment Plants in the Roztocze National Park. *Journal of Ecological Engineering*, 21(5), 9–18. <https://doi.org/10.12911/22998993/122118>
26. Micek A., Józwiakowski K., Marzec M., Listosz A. 2020. Technological reliability and efficiency of wastewater treatment in two hybrid constructed wetlands in the Roztocze National Park (Poland). *Water* 12, 3435. <https://doi.org/10.3390/w12123435>
27. Myka-Raduj A., Józwiakowski K. 2022. Changes in Water Consumption in the Educational-Museum

- Center of Poleski National Park. Journal of Ecological Engineering 23(6), 237–244. <https://doi.org/10.12911/22998993/148136>
28. Myka-Raduj A., Józwiakowski K., Siwiec T., Raduj W. 2023. Changes of Water Consumption in a Forester's Lodge in Polesie National Park (Poland)—Case Study. *Water* 15, 3157. <https://doi.org/10.3390/w15173157>
 29. Nan X., Lavrnić S., Toscano A. 2020. Potential of constructed wetland treatment systems for agricultural wastewater reuse under the EU framework. *Journal of Environmental Management*, 275, 111219. <https://doi.org/10.1016/j.jenvman.2020.111219>
 30. Obroślak R., Mazur A., Józwiakowski K., Dorozhynskyy O., Grzywna A., Rybicki R., Nieścioruk K., Król Ż., Gabryszuk J., Gajewska M. 2017. Using terrestrial laser scanning in inventorying of a hybrid constructed wetland system. *Water Science and Technology* 76, 2664–2671. <https://doi.org/10.2166/wst.2017.436>
 31. Operacz A., Józwiakowski K., Rodziejewicz J., Janczukowicz W., Bugajski P. 2023. Impact of Climate Conditions on Pollutant Concentrations in the Effluent from a One-Stage Constructed Wetland: A Case Study. *Sustainability* 15, 13173. <https://doi.org/10.3390/su151713173>
 32. PN-C-04576-14:1973. Water and sewage - Testing the content of nitrogen compounds - Calculation of total nitrogen.
 33. PN-EN 1899-1:2002, 2:2002. Water quality. Determination of biochemical oxygen demand after n days (BOD_n). Part 1: Dilution and grafting method with the addition of allylthiourea.
 34. PN-EN 872:2007+Apl: 2007. Water quality. Determination of suspensions. Method using filtration through glass fiber filters.
 35. PN-EN ISO 19458:2007. Water quality - Sampling for microbiological analyses.
 36. PN-EN ISO 5667-1:2022-07. Water quality - Sampling - Part 1: Guidelines for the development of sampling programs and techniques.
 37. PN-EN ISO 5814:2013-04. Water quality. Determination of dissolved oxygen -- Electrochemical sensor method.
 38. PN-EN ISO 6878:2006 pkt 7 +Apl:2010+ AP2:2010. Water quality - determination of phosphorus - Spectrometric method with ammonium molybdate.
 39. PN-EN ISO 7899-1:2002P. Water quality - Detection and enumeration of fecal enterococci - Part 1: Miniaturized method for testing surface water and wastewater (most probable number of bacteria).
 40. PN-EN ISO 9308-3:2002P. Water quality - Detection and quantification of *Escherichia coli* and coliforms - Part 3: miniaturized method for the detection and enumeration of E-Coli in surface water and wastewater (most probable bacterial count).
 41. PN-ISO 15705: 2005. Water quality. Determination of the chemical oxygen demand index (SP-COD). Miniaturized method using tight test tubes.
 42. PN-ISO 5667-10:2021-11. Jakość wody - Pobieranie próbek - Część 10: Wytyczne dotyczące pobierania próbek ścieków.
 43. Rajan R.J., Sudarsan J. S., Nithiyantham S. 2020. Efficiency of constructed wetlands in treating *E. coli* bacteria present in livestock wastewater. *International Journal of Environmental Science and Technology*, 17, 2153–2162. <https://doi.org/10.1007/s13762-019-02481-6>
 44. Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on Substances Which Are Particularly Harmful to the Aquatic Environment and the Conditions to Be Met When Discharging Wastewater into Water or Soil and When Discharging Rainwater or Snowmelt into Water or Water Installations, 2019; pos. 1311.
 45. Russo N., Pino A., Toscano A., Cirelli G.L., Caggia C., Arioli S., Randazzo C.L. 2019. Occurrence, diversity, and persistence of antibiotic resistant enterococci in full-scale constructed wetlands treating urban wastewater in Sicily. *Bioresource Technology*, 274, 468–478. <https://doi.org/10.1016/j.biortech.2018.12.017>
 46. Seidel K. 1955. Die Flechtbinse *Scirpus lacustris*. Ökologie, Morphologie und Entwicklung, ihre Stellung bei den Volkern und ihre wirtschaftliche Bedeutung. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, 37–52.
 47. Seidel K. 1965. Neue Wege zur Grundwasseranreicherung in Krefeld, vol. II. Hydrobotanische Reinigungsmethode. GWF Wasser/Abwasser, 831–833.
 48. Stefanakis A.I. 2019. The role of constructed wetlands as green infrastructure for sustainable urban water management. *Sustainability* 11, 6981. <https://doi.org/10.3390/su11246981>
 49. Vymazal J. 2005. Removal of enteric bacteria in constructed treatment wetlands with emergent macrophytes: A review. *Journal of Environmental Science and Health*, 40, 1355–1367. <https://doi.org/10.1081/ESE-200055851>
 50. Vymazal J., 2011. Constructed wetlands for wastewater treatment: five decades of experience. *Environ. Sci. Technol.* 45, 61–69. <https://doi.org/10.1021/es101403q>