

Full-scale hybrid constructed wetland wastewater treatment plant – efficiency and reliability of operation in the start-up period

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ABSTRACT

A full-scale hybrid constructed wetland (CW) wastewater treatment plant ($Q_{av.d.} = 74 \text{ m}^3 \cdot \text{d}^{-1}$) was analyzed in terms of its operational efficiency and reliability in the start-up period (12 months, from April 2023 to March 2024). The focus was only on the biological part consisting of 2 parallel systems of CW beds – with vertical flow (VF) and horizontal flow (HF). Three sampling points were chosen, i.e. mechanically treated wastewater, effluent from the VF-type beds and effluent from the HF-type beds. Several pollution indicators were measured: BOD_5 , COD, TSS, TP and TN. The studied CW ensured high efficiency of wastewater treatment which reached: 96% for BOD_5 , 89% for COD, 82% for TSS, 41% for TP and 50% for TN. At higher air temperatures in the spring-summer season (the average from April to September was 16.8°C), higher removal rates of pollutants expressed by COD, TP, and TN in the VF bed and TSS reduction in the HF bed were achieved compared to the autumn-winter period, when the average temperature from October to March was 3.9°C . This indicates that large-scale constructed wetland wastewater treatment plants serving entire communities (as opposed to small household systems) are more vulnerable to seasonal fluctuations in air temperature, leading to reduced pollutant removal efficiency during cold periods. In this paper, it was shown that the higher values of the BOD_5/TN and BOD_5/TP did not increase the susceptibility of wastewater to decomposition of nitrogen and phosphorus compounds. Further analyses should be carried out to assess how the functioning of the facility changes over time, after the start-up period.

Keywords: hybrid constructed wetland, wastewater treatment, start-up period, efficiency and reliability of operation.

INTRODUCTION

Water and wastewater management still remains one of the key aspects of municipal management, which is carried out in every commune. In addition to supplying residents with water, it is also necessary to properly manage the wastewater collection and disposal system. In the areas with concentrated development, it is recommended to collect and dispose of wastewater by means of collective sewerage systems, and then the wastewater through the sewerage system goes to a collective treatment plant (e.g. serving a whole commune), which provides a solution to the problem of liquid waste at the same

time from a large number of residents. The classic, most commonly chosen solution for collective wastewater treatment plants in Poland and worldwide is a mechanical-biological system with activated sludge [1–3]. However, in recent years, more and more attention has been paid to alternatives, which are considered more innovative, greener, more cost-effective and more prospective [4–6]. Constructed wetland wastewater treatment plants (CW WWTPs) are an example of the nature-based solutions (NBS) that have become very popular in recent years [7–9]. CW WWTPs can also be considered mechanical-biological wastewater treatment systems, their construction is based on the use of equipment to

mechanically remove the largest pollutants from the wastewater, and then the wastewater is treated biologically in a system of constructed wetland beds. These beds are filled with appropriately selected filter material, and the biofilm is formed on the soil grains (it grows as the wastewater flows through the bed) and becomes a habitat for the microorganisms that remove pollutants from wastewater through a variety of processes, i.e. sedimentation, filtration, adsorption, nitrification or denitrification [10, 11]. The surface of the beds is planted with various types of plants [12] which perform auxiliary functions in wastewater treatment processes – such as supplying oxygen to the bed or protecting the surface layer from excessive transpiration and drying in summer and from excessive cooling in winter [10]. Plant roots offer a surface for microbes to attach and form biofilms, while also creating favorable pH conditions in the rhizosphere that support the microbial communities involved in both nitrification and denitrification [13]. Special attention should be paid to the most commonly used hybrid constructed wetland systems, which combine the use of several soil-plant beds with different wastewater flow directions to achieve the most optimal pollutant removal results [6]. Originally, CW WWTPs were mainly used as small, household facilities serving a few dozen people. Since various long-term studies of such small facilities [14, 15] have shown the high efficiency of such systems, it is now increasingly common to design such facilities on a larger scale [16, 17]. After the construction of wastewater treatment plants, studies are carried out on their efficiency with regard to the removal of pollutants from wastewater in order, among others, to control the fulfillment of the requirements set in the relevant legislation, as well as to find possible inadequacies and inconveniences in the solutions used so far, in order to make improvements aimed at increasing the efficiency of operation of this type of facilities [18].

Constructed wetland wastewater treatment plants are the subject of research by many authors. However, the vast majority of attention is paid to the general evaluation of the efficiency of pollutant removal in this type of facilities, but there are few studies focusing specifically on the period right after putting the facility into operation. It is therefore worth considering whether hybrid constructed wetlands achieve maximum efficiency from the very beginning of their operation, or whether a certain start-up period is needed, i.e., for

example, a few months, when the soil-plant beds need to undergo so-called “work-up” in order to achieve maximum possible efficiency in removing pollutants from wastewater after some time.

Another aspect that still raises many doubts and objections, especially among those who are not permanently involved in constructed wetlands (CWs), i.e., for example, local authorities or private investors willing to invest in this type of solution, is the impact of thermal conditions on the efficiency and reliability of such wastewater treatment plants. It therefore turns out to be necessary to check whether such facilities function similarly, regardless of the seasons, or whether there is a correlation between changes in atmospheric air temperature and the efficiency of removing pollutants from wastewater.

Considering the above, the purpose of this study was to evaluate the performance of a full scale hybrid constructed wetland wastewater treatment plant located in southeastern Poland. The performance of the facility was studied during the early period of its operation, which lasted for the first 12 months after the facility was commissioned, so during the so-called start-up period. Analyses included the quality of wastewater after successive stages of treatment. In addition, the variability of thermal conditions during the study period was also analyzed in order to examine the relationship between seasonality and the efficiency of the operation of the constructed wetland wastewater treatment plant.

MATERIALS AND METHODS

Experimental facility

The analyzed facility was a hybrid constructed wetland wastewater treatment plant (CW WWTP) in Zawadówka in the Rejowiec Commune, Chełm County, Lublin Voivodeship, southeastern Poland. The location of the CW WWTP is shown in Figure 1.

The studied wastewater treatment plant was put into operation in April 2023. The facility was designed for an average daily capacity of $Q_{av.d.} = 74 \text{ m}^3 \cdot \text{d}^{-1}$ and for P.E. = 740 [22]. However, during the analyzed year, the real observed average wastewater flow was $48 \text{ m}^3 \cdot \text{d}^{-1}$, which constituted about 65% of the designed capacity of the facility. The CW WWTP receives domestic wastewater from residents of Zawadówka and several surrounding villages

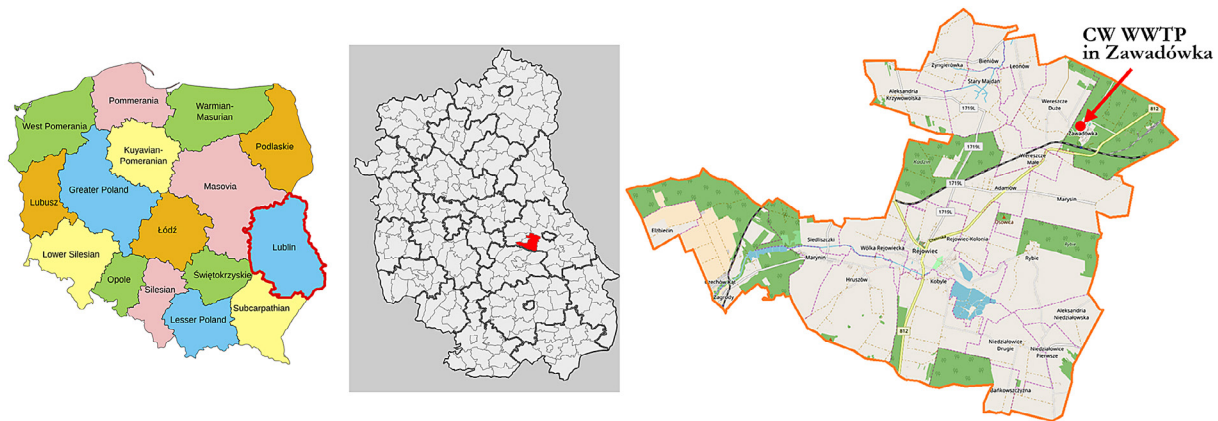


Figure 1. Location of the analyzed facility – Lublin Voivodeship, Chełm County, Rejowiec Commune, Zawadówka village (own elaboration based on [19–21])

via the sewerage system. There is also the possibility of transporting wastewater from septic tanks by a septic tank truck, but over the first year of the facility operation, no imported wastewater was recorded. The treatment plant is automated and computer-controlled, and has been equipped with a photovoltaic installation, thanks to which the electricity produced is used, among others, to power pumps and the wastewater aeration system.

A top view showing the various components of the treatment plant together with the sampling points under study is shown in Figure 2.

The first element into which raw wastewater flowing through the sewerage system goes is the screening and grit separator, where the largest impurities are separated on the screens and sand is removed (no. 1 in Figure 2). Subsequently, further mechanical treatment of wastewater takes place in a 3-chamber primary settling tank through such processes as sedimentation and flotation (no. 2. in Figure 2) [22].

The sludge generated in the primary settling tank is pumped at a set frequency to constructed wetland beds for sludge dewatering (no. 3 in Figure 2), each of which has a surface area of 50 m², two of them are planted with giant miscanthus (*Miscanthus giganteus* × Greef et Deu) and two with common reed *Phragmites australis*. Periodically, once every 3 days (in spring and summer) or 7 days (during autumn and winter), one of the four beds is flooded. The deposits are flooded with sewage sludge, which vertically filters deep into the beds. The solid fraction of the sludge remains on the surface of the beds, and the filtered liquid fraction (filtrate) is collected by a drain and fed back to the first

chamber of the primary settling tank, where it is mixed with the wastewater that goes there after the screening and grit separator [22]. This way of dealing with sewage sludge is economically very profitable, as it deprives the operator of the wastewater treatment plant of the need for frequent and regular removal of sludge from the settling tank with the help of septic tank trucks. The dewatered sewage sludge, after accumulating on the beds for the following years and after passing the required tests, can be used in nature, for example, for fertilizing crops or for the reclamation of soilless land and degraded areas [23–25].

In the next stage, after mechanical treatment, wastewater goes through a pumping station (no. 4 in Figure 2) and then is treated biologically in a system of soil-plant beds (2 parallel systems). In each system, the first bed with vertical wastewater flow (VF) with an area of 408 m² is planted with giant miscanthus (*Miscanthus giganteus* × Greef et Deu) (no. 5 in Figure 2), and a second bed with horizontal wastewater flow (HF) with an area of 408 m² is planted with willow (*Salix viminalis* L.) (no. 6 in Figure 2). Constructed wetland beds are isolated by a tight geomembrane from the surrounding soil, are filled with appropriately selected filter material, are planted with selected plants and equipped with systems of pipelines for distribution and collection of wastewater [22]. Removal of organic and nutrient pollutants occurs during the flow of wastewater through the bed, in which the root system of the plants is a supporting element. Around the roots of the plants, a specific aerobic zone is formed, which makes ideal conditions for nitrification of pollutants. In contrast,

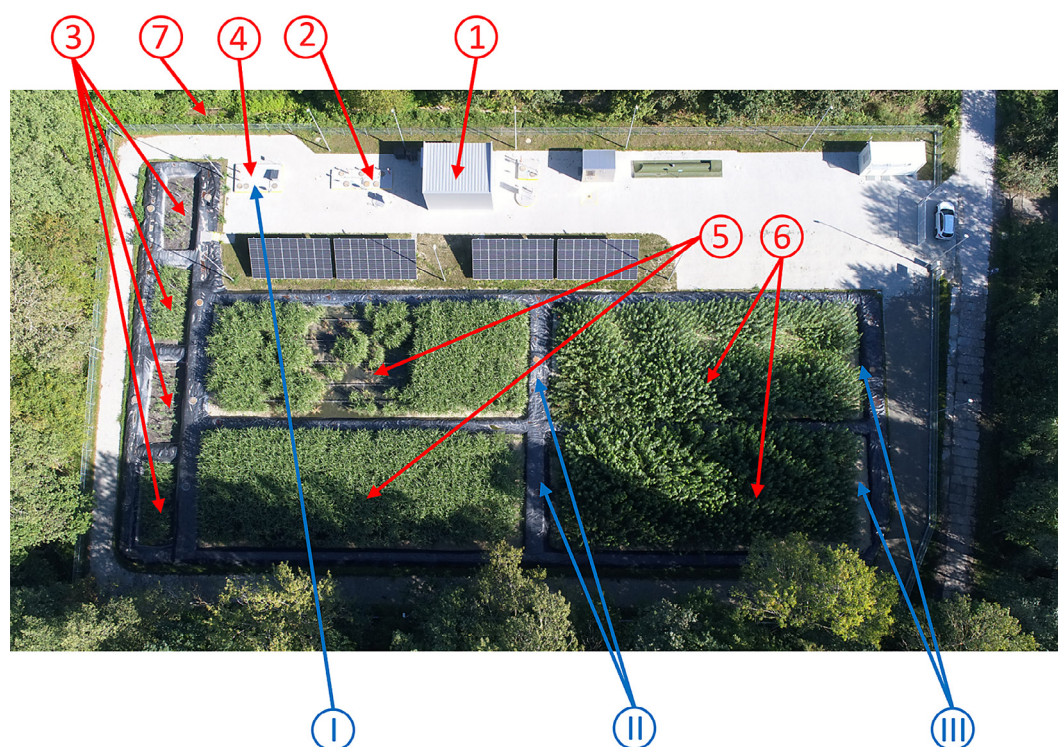


Figure 2. Hybrid constructed wetland wastewater treatment plant in Zawadówka – view from above (photo – Radomir Obroślak). Main components of the facility: 1 – screening and grit separator; 2 – primary settling tank; 3 – sludge dewatering beds; 4 – pumping station; 5 – VF-type CW beds with giant miscanthus; 6 – HF-type CW beds with willow; 7 – recipient of treated wastewater. Sampling points: I - mechanically treated wastewater, after the screening and grit separator, primary settling tank and after mixing with leachate from the sludge dewatering CW beds; II - effluent from the VF-type beds; III - effluent from the HF-type beds

other zones of the bed are poorly oxygenated or anaerobic, that is, denitrification occurs there [15]. Figures 3 and 4 show, respectively, the first (*Miscanthus giganteus* × Greef et Deu) and the second HF-type CW bed with willow (*Salix viminalis* L.) in different seasons. The individual seasons included the following months: spring – March, April, May; summer – June, July, August; autumn – September, October, November; winter – December, January, February. The recipient of treated wastewater is a nearby forest drainage ditch (no. 7 in Figure 2) [22].

Statistical and analytical methods

Wastewater quality

The study was conducted for the first 12 months after the facility was commissioned -from April 2023 to March 2024, during the so-called start-up period of the treatment plant.

The scope of the study was to evaluate the quality of wastewater at different stages of the treatment plant and the efficiency of wastewater

treatment for selected pollution indicators from the basic group – five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and concentration of total suspended solids (TSS). Moreover, concentrations of pollutants from the biogenic group were analyzed – total phosphorus (TP), total nitrogen (TN).

Wastewater was collected at 3 measurement points shown in Figure 2: I – mechanically treated wastewater, after the screening and grit separator, primary settling tank and after mixing with leachate from the sludge dewatering CW beds; II – effluent from the VF-type beds; III – effluent from the HF-type beds. In order to increase readability, in the rest of the paper, sample No. I is called shorter - “mechanically treated wastewater”.

The wastewater samples from the facility were collected, transported and analyzed in compliance with international reference recommendations. The assay methods and the equipment used for each parameter are listed in Table 1.

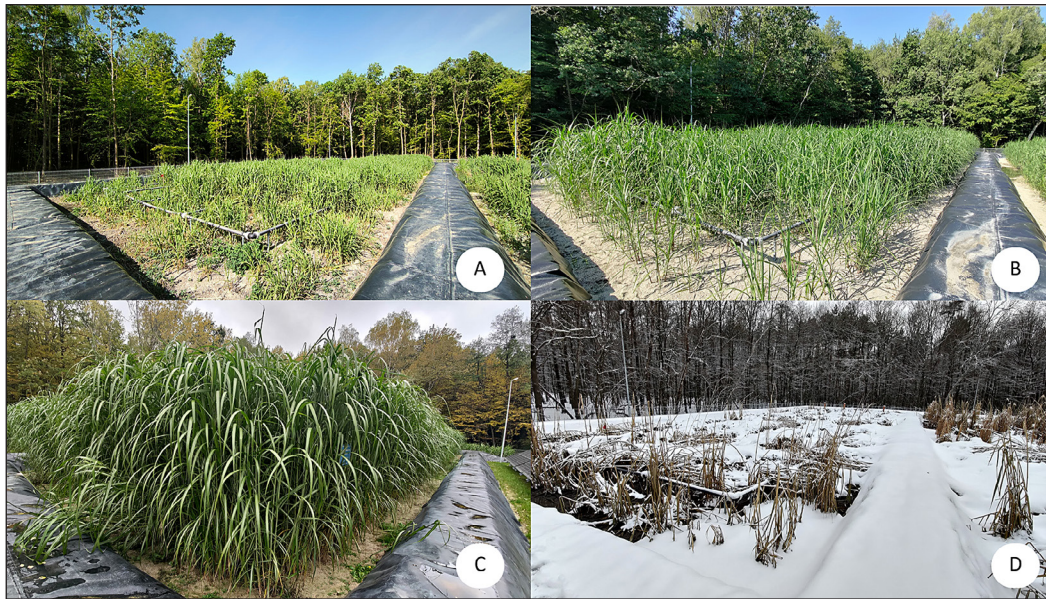


Figure 3. The first VF-type CW bed in different seasons: A – spring, B – summer, C – autumn, D – winter

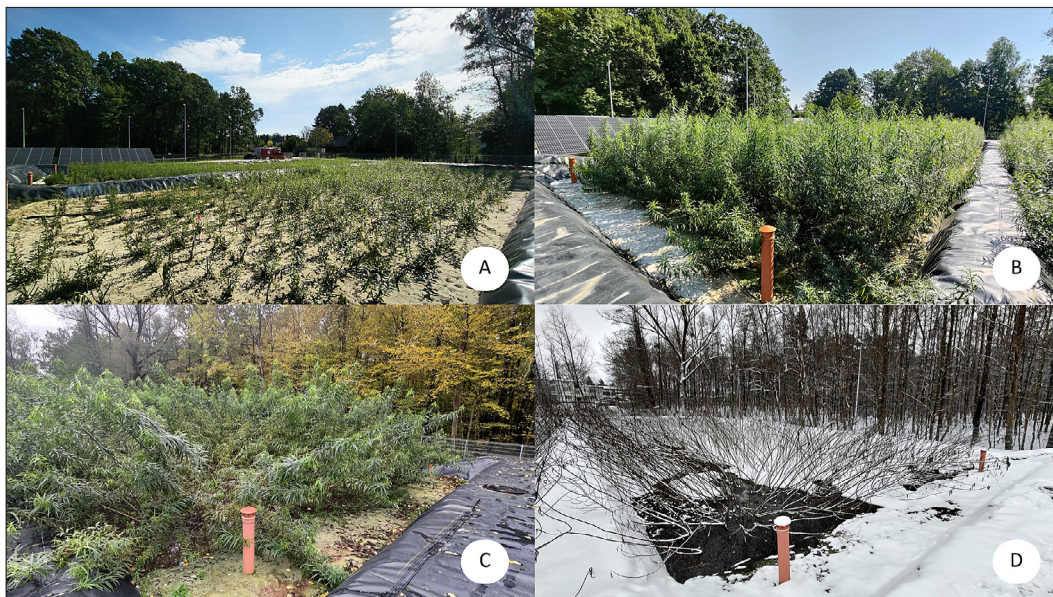


Figure 4. The second HF-type CW bed in different seasons: A – spring, B – summer, C – autumn, D – winter

The tests were carried out at the Laboratory of the Department of Environmental Engineering at the University of Life Sciences in Lublin as part of the implementation of a research project for young researchers in the discipline of environmental engineering, mining and energy.

The studied facility is a wastewater treatment plant designed for 740 P.E. (< 2.000 P.E.), which means that in accordance with Polish guidelines [31], the maximum permissible concentrations of pollutants in the treated wastewater discharged from

this facility may not exceed $BOD_5 - 40 \text{ mgO}_2 \cdot \text{dm}^{-3}$, $COD - 150 \text{ mgO}_2 \cdot \text{dm}^{-3}$, $TSS - 50 \text{ mg} \cdot \text{dm}^{-3}$. Maintaining the pollution parameters at levels lower than the above mentioned allows providing sufficient treatment efficiency, bringing wastewater to a state in which it can be safely discharged into the environment without the risk of contamination. According to the Regulation of the Minister of Maritime Affairs and Inland Navigation of July 12, 2019 on substances particularly harmful to the aquatic environment and conditions to be met when discharging

Table 1. Assay methods used to measure the selected wastewater quality indicators

Item	Parameter	Unit	Assay method	Measuring range and accuracy of the measured value	Equipment used
1	Biochemical oxygen demand (BOD ₅)	[mgO ₂ ·dm ⁻³]	Electrochemical, dilution method PN-EN 1899-1:2002 [26]	3 - 6000 mgO ₂ ·dm ⁻³ ±0.2 mgO ₂ ·dm ⁻³	Cylinders for BOD (Karlsruher), with caps ORION Star A329 SET multi-parameter meter from Thermo Fisher Scientific
2	Chemical oxygen demand (COD)	[mgO ₂ ·dm ⁻³]	Dichromate method with prior oxidation of the sample in a thermoreactor at 148 °C for 2 h ISO 15705:2005 [27]	15 - 160 mgO ₂ ·dm ⁻³ ± 5 mgO ₂ ·dm ⁻³ and 100 - 1500 mgO ₂ ·dm ⁻³ ± 16 mgO ₂ ·dm ⁻³	Thermoreactor from WTW, NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel
3	Total suspended solids (TSS)	[mg·dm ⁻³]	Method using filtration through glass filters and drying at 105 °C PN-EN 872:2007 +Apl:2007 [28]	2 - 5000 mg·dm ⁻³ ± 1 mg·dm ⁻³	Vacuum filtration set, glass microfibre filters GF/A from Whatman, SLW 53 laboratory dryer from Pol-Eko, Ohaus Pioneer PA213CM/1 scale
4	Total phosphorus (TP)	[mgP·dm ⁻³]	Spectrophotometric method with prior oxidation of the sample in a thermoreactor at 120°C for 30 min ISO 6878:2004 [29]	0.30 - 15.00 mgP·dm ⁻³ ± 0.7 mgP·dm ⁻³	Thermoreactor from WTW, NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel
5	Total nitrogen (TN)	[mgN·dm ⁻³]	Spectrophotometric method with prior oxidation of the sample in a thermoreactor at 120°C for 30 min ISO 23697-1:2023-02 [30]	3 - 60 mgN·dm ⁻³ ± 0.31 mgN·dm ⁻³ and 5 - 220 mgN·dm ⁻³ ± 4.79 mgN·dm ⁻³	Thermoreactor from WTW, NANOCOLOR UV/VIS spectrophotometer from Macherey-Nagel

wastewater into waters or into the ground, as well as when discharging rainwater or snowmelt into waters or into water facilities [31] it is necessary to control the content of nutrients in the wastewater discharged from small wastewater treatment plants of up to 2000 PE. While this requirement applies only to the wastewater discharged into lakes, their tributaries, and directly into artificial water reservoirs in flowing waters, this study also analyzed the concentration of selected nutrient compounds in the treated wastewater to assess whether the treatment plant contributed to the pollution of the surrounding environment. Thus, the maximum permissible concentrations of nutrients in treated wastewater are as follows: TN – 30 mgN·dm⁻³ and TP – 5 mgP·dm⁻³ [31].

Assessment of atmospheric air temperature

During the study period the air temperature in the research area was recorded using the EL-USB-1-pro LASCAR electronic sensor, which was equipped with an integrated data recorder housed in a stainless steel case. This setup was used to continuously monitor temperature at a specified time interval. The sensor and recorder were positioned 2 meters above the ground, beneath the roof of a building with a sieve-sand

separator. Located on the northern side of the building, the sensor was shielded from direct sunlight to avoid any measurement distortion. The temperature data collected from April 2023 to March 2024 were analyzed. Temperature was recorded every 6 hours (four times per day), and the average of these four readings was calculated as the daily value.

Statistical analysis

The results were statistically analyzed, graphed, and organized into tables using Microsoft Excel 2016 and Statistica 13.1. To assess the performance of the wastewater treatment plant, a statistical analysis of the initial data was conducted. Basic descriptive statistics were calculated, including: measures of location (mean ($\bar{x}$), median (Me), minimum (min), maximum (max), range (R)), and measures of spread (standard deviation (s) and coefficient of variation (Vs)). The values of the coefficient of variation (Vs) of wastewater composition were interpreted in accordance with Mucha's classification [32], which features the following variation groups: low (0–20%), moderate (20–40%), high (40–100%), very high (100–150%), and extremely high (> 150%) variation.

The operational efficiency and reliability of the facility were evaluated using the following four parameters:

- pollutant removal efficiency η ;
- yreatment plant reliability factor (RF);
- yecnological efficiency of wastewater treatment P_{SW} ;
- risk of a negative assessment of the wastewater treatment plant operation R_s .

The pollutant removal efficiency (= the reduction coefficient) was measured as the ratio of the difference in pollutant concentrations between the wastewater before treatment (influent) and after treatment (effluent) to the pollutant concentration in untreated wastewater (influent). The pollutant removal efficiency was calculated from Equation 1 [33, 34]:

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

where: C_i – concentration of a pollution indicator in influent [$\text{mg} \cdot \text{dm}^{-3}$], C_e – concentration of a pollution indicator in effluent [$\text{mg} \cdot \text{dm}^{-3}$].

The treatment plant reliability factor was calculated according to Equation 2 [33,35]:

$$RF = \frac{\bar{x}}{x_{per}} [-] \quad (2)$$

where: $\bar{x}$ – mean concentration of a pollution indicator in treated wastewater [$\text{mg} \cdot \text{dm}^{-3}$], x_{per} – permissible concentration of a pollution indicator in treated wastewater [$\text{mg} \cdot \text{dm}^{-3}$].

The higher the mean concentrations of the tested pollutants in the treated wastewater and the closer they are to the limit value, the higher the values of the treatment plant reliability factor RF.

The technological efficiency of wastewater treatment shows what part of the pollutant readings obtained at the outflow of the treatment plant are within the permissible limits specified in the regulation that is in force in Poland [31]. This value was calculated according to Equation 3 [33, 36]:

$$P_{SW} = \frac{n_c}{N} [-] \quad (3)$$

where: n_c – number of outflow readings compliant with the Regulation [31] [-], N – number of all the outflow readings [-].

PSW has values in the range [0,1]. The more samples that meet the conditions set in the Regulation [31], the higher the technological efficiency of wastewater treatment.

The risk of negative assessment of the wastewater treatment plant operation is defined as the probability of exceeding the pollutant concentration limits in treated wastewater; it was calculated using Equation 4 [33,37]:

$$P(n_n > N_{per}) [-] \quad (4)$$

where: n_n – number of samples collected at the outflow from the treatment plant in which the concentration limits for the tested pollutant were exceeded [-], N_{per} – the maximum permissible number of samples that, according to the Polish Regulation [31], may exceed the pollutant concentration limits during one year; two exceedances are allowed per 12 samples [-].

A lower RS rate indicates a higher likelihood that the relevant guidelines are met and that the operation of the treatment plant will be positively evaluated.

In order to analyze the quality of wastewater and the efficiency of the wastewater treatment plant some statistical tests at a significance level of $\alpha = 5\%$ were used i.e., Shapiro-Wilk test, Friedman test, Wilcoxon post-hoc test, Spearman correlation analysis.

RESULTS AND DISCUSSION

Conditions during the research conducting -atmospheric air temperature

The performance of the constructed wetland wastewater treatment plant was studied during the early period of its operation, which lasted for the first 12 months after the facility was commissioned, so during the so-called start-up period. Therefore, it turned out to be necessary to check whether the facility can function similarly, regardless of the seasons, or whether there is a correlation between changes in atmospheric air temperature as well as the efficiency and reliability of removing pollutants from wastewater.

Figure 5 shows the range of variation of the air temperature in particular months of the study period, from March 2023 to April 2024. During the whole study period, only January 2024

occurred to be the month when median of daily average values was below 0 °C.

Wastewater quality after different treatment stages

Table 2 shows basic descriptive statistics regarding the values of the tested pollutant indicators recorded after successive stages of wastewater treatment (after mechanical treatment and mixing with sludge bed leachate, after VF beds and after HF beds (i.e., the entire process line) throughout the study period (IV.2023–III.2024).

The normality of the distribution of the analytical results was checked with the Shapiro-Wilk test at a significance level of $\alpha = 0.05$. For most parameters after successive treatment stages, the results showed a normal distribution. However, a normal distribution was not observed for dissolved oxygen and total suspended solids concentrations, or the values of BOD₅ and COD indicators after the VF bed, or the values of COD and TSS concentration after the HF bed. Due to the ambiguity of the distributions, a nonparametric Friedman test was performed to compare the quality of wastewater after successive stages of treatment, which evaluates whether there are differences between at least two successive stages. For indicators such as BOD₅, COD, TSS, TN the differences in their values in the wastewater after successive treatment stages were shown to be statistically significant at the 5% significance

level. The aforementioned pollutant indicators were then analyzed for the significance of changes in their values between each successive treatment stage using the Wilcoxon post-hoc test (with Bonferroni correction). The Wilcoxon post-hoc test showed a statistically significant decrease in the values of the indicators BOD₅, COD, and the concentrations of TSS and TN between most of the successive treatment stages ($p < 0.0083$, after Bonferroni correction). The median values indicate a systematic decrease in the pollutant load, which confirms the effectiveness of the constructed wetland system in terms of the reduction of organic pollutants expressed by the BOD₅ and COD indicators, as well as the removal of total suspended solids and total nitrogen.

Figure 6 demonstrates changes in average values of tested pollutant indicators (from basic group – A and from biogenic group – B) after successive stages of wastewater treatment.

As it can be seen, for all tested pollution indicators the highest values were reached in the sample I, i.e. in mechanically treated wastewater. The greatest decrease in the average values of the tested pollution indicators was recorded after wastewater passed through the VF-type bed. As it can be seen, both VF and HF beds allowed successively reducing the values of the tested pollution indicators and eventually reach minimum values in the outflow from the HF bed - after all the stages of the hybrid constructed wetland wastewater treatment plant.

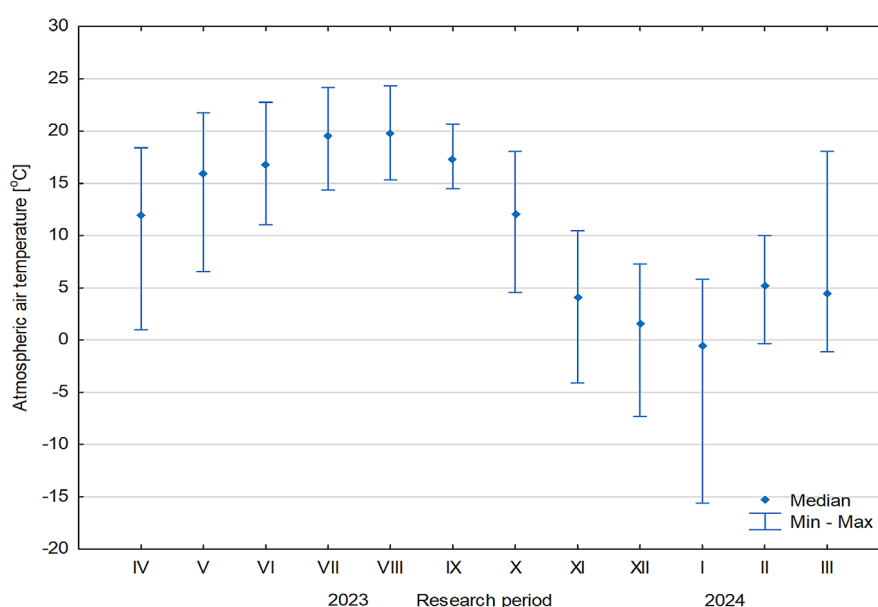


Figure 5. Range of variation of the air temperature during the study period (April 2023–March 2024)

Table 2. Wastewater quality after different treatment stages throughout the study period - basic descriptive statistics

	$\bar{x}$	Me	min	max	R	s	Vs
Mechanically treated wastewater							
BOD ₅	184.58	206.00	53.50	253.00	199.50	57.19	30.98
COD	408.25	414.00	186.00	593.00	407.00	107.80	26.41
TSS	85.83	90.00	40.00	140.00	100.00	30.88	35.98
TP	6.53	6.24	3.59	10.90	7.31	2.49	38.10
TN	63.69	62.25	33.30	95.80	62.50	22.31	35.04
Effluent from the VF-type beds							
BOD ₅	38.62	33.45	10.20	152.00	141.80	38.02	98.44
COD	115.58	94.00	30.10	484.00	453.90	119.19	103.12
TSS	25.94	20.00	12.00	70.00	58.00	16.48	63.52
TP	4.40	4.25	2.43	7.03	4.60	1.50	34.08
TN	35.38	33.95	13.70	64.30	50.60	12.51	35.37
Effluent from the HF-type beds							
BOD ₅	7.55	7.90	0.80	16.00	15.20	5.42	71.74
COD	41.98	32.85	24.20	106.00	81.80	22.89	54.53
TSS	14.53	13.30	6.70	30.00	23.30	7.42	51.07
TP	3.27	2.75	1.38	7.29	5.91	1.76	53.97
TN	28.00	25.90	14.50	48.70	34.20	9.35	33.39

Wastewater before biological treatment in the VF-HF system

In this paper, the first analyzed series of wastewater samples was mechanically treated wastewater, after the screening and grit separator, primary settling tank and after mixing with leachate from the sludge dewatering CW beds. The following mean values of the analyzed pollution indicators were observed during the study period: BOD₅ - 184.58 mgO₂·dm⁻³, COD – 408.25 mgO₂·dm⁻³, TSS – 85.83 mg·dm⁻³, TP – 6.53 mg·dm⁻³, TN – 63.69 mg·dm⁻³.

At this stage, after mechanical but before biological treatment, a very important aspect that should be taken into account is the susceptibility of wastewater to biological degradation. Such assessment was conducted on the basis of the dependencies indicated by some researchers [38,39] describing the biodegradability measures:

- COD/BOD₅ ≤ 2.0 – easy biodegradability
- COD/BOD₅ > 2.0 ≤ 2.5 – average biodegradability
- COD/BOD₅ > 2.5 ≤ 5.0 – poor biodegradability
- COD/BOD₅ > 5.0 – non-degradable matter
- BOD₅/TN ≥ 5 – easy susceptibility of nitrogen compounds to biological degradation
- BOD₅/TP ≥ 25 – easy susceptibility of phosphorus compounds to biological degradation.

Values of the analyzed biodegradability measures in individual months of the tested year (IV.2023–III.2024) are presented in Table 3.

The analysis showed that in such months as: April, May and September, the wastewater after mechanical treatment was described as easy-biodegradable because of the ratio COD/BOD₅ was no more than 2.0. Half of the measurements were the months (June, October, November, December, January, March) were when average biodegradability was observed. July, August and February occurred to be the only three months with poor wastewater biodegradability. Mean value of the COD/BOD₅ ratio in the wastewater after mechanical treatment and before biological treatment during the whole study period amounted to 2.3. It has been shown that the biodegradability of wastewater after mechanical treatment clearly depends on the season. Summer and winter (especially July, August, February) are problematic periods, during which it is especially necessary to control the wastewater load and the efficiency of biological treatment. Spring and early autumn bring the most favorable conditions for further stages of biological treatment (due to a higher content of easily decomposable organic matter, such as plant residues, natural organic matter). Moreover, moderate temperatures support microbial activity and

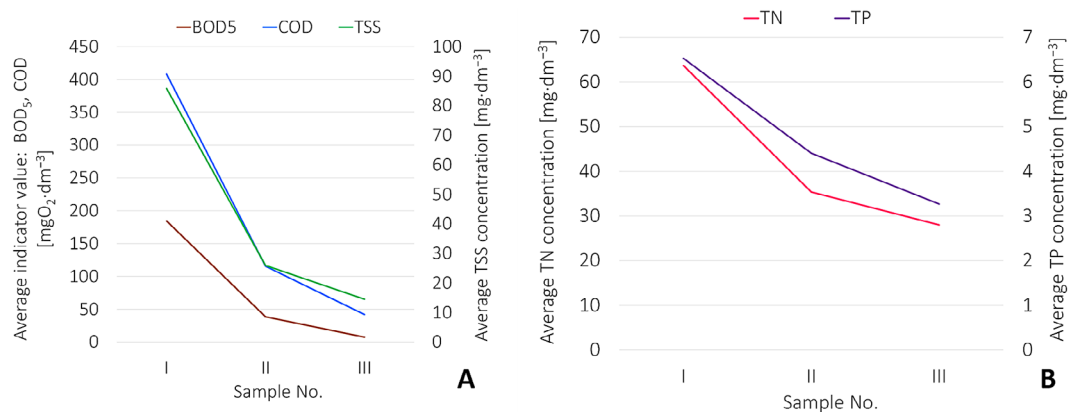


Figure 6. Changes in average values of tested pollutant indicators after successive stages of wastewater treatment: I – mechanically treated wastewater; II – effluent from the VF-type beds; III – effluent from the HF-type beds

Table 3. Values of the biodegradability measures in the analyzed wastewater before biological treatment during the study period

Months	Ratios		
	COD/BOD ₅	BOD ₅ /TN	BOD ₅ /TP
IV	1.5	4.5	41.3
V	2.0	2.6	31.0
VI	2.3	2.8	26.0
VII	3.5	1.6	14.9
VIII	2.6	2.4	21.9
IX	2.0	2.6	20.7
X	2.4	2.4	24.7
XI	2.3	2.5	27.7
XII	2.2	3.3	33.8
I	2.1	5.4	55.8
II	2.6	3.0	29.6
III	2.4	3.1	30.1
mean	2.3	3.0	29.8

preserve organic matter structure. On the other hand, high temperatures (July and August) promote anaerobic decomposition in the sewerage system which causes fewer readily biodegradable compounds reach the treatment plant. In winter (December-February), lower temperatures can slow down biological decomposition processes, but also cause wastewater compaction. It is also possible then that the chemicals used in winter (e.g., de-icing agents, road pollutants) may flow into the sewerage system. In effect of all these, the biodegradation of wastewater is reduced.

When it comes to the susceptibility of wastewater to biological decomposition of biogenic compounds, the mean values of the BOD₅/TN and BOD₅/TP ratios in wastewater after mechanical

treatment and before biological treatment during the whole study period amounted to 3.0 and 29.8, respectively. Thus, in general, the tested wastewater was characterized by poor conditions for biological degradation of nitrogen compounds and favorable conditions for phosphorus compounds biodegradation. Only September was the month with easy susceptibility of nitrogen compounds to biological degradation (BOD₅/TN = 5.4). In September, wastewater may contain more readily biodegradable organic matter (e.g., from plants, gardens, food scraps), which serves as a source of organic carbon for denitrifying bacteria. Good C:N ratios favor the denitrification process. Optimal oxygen and temperature conditions can facilitate nitrogen conversion (e.g.,

from nitrate to nitrogen gas). In other months, the ratio of BOD_5 to TN is lower, which means too little readily available organic matter (carbon deficiency), an increased proportion of mineral nitrogen (nitrates, ammonium nitrogen), more difficult to remove biologically, and a possible decrease in the activity of microorganisms (e.g. in winter - low temperature). At the same time, all the months, except July, August, September and October, were characterized by easy susceptibility of phosphorus compounds to biological degradation ($BOD_5/TP \geq 25$). A possible reason for the easy biodegradation of phosphorus in most months is that there is phosphorus in organic form in the wastewater, which can be easily removed biologically with sufficient organic matter available. On the other hand, high temperatures (in July and August) can cause fermentation in the sewerage system, which depletes wastewater of easy organic matter and less organic carbon means more problems with effective phosphorus accumulation. However, in the autumn months (September, October), temporary increases in phosphorus concentrations are possible (e.g. from fertilizers applied to winter crops that are flushed by rainfall), which disturbs the BOD_5/TP ratio and reduces the susceptibility of phosphorus compounds to biological degradation.

A similar issue has been already tested by some other authors. In the study conducted by Micek et al. [40], the mean COD/BOD_5 ratio in wastewater before biological treatment was 3.1 which was higher than observed in the studied facility and this indicated a poor susceptibility of wastewater to biodegradation. On the other hand, the ratios of BOD_5/TN and BOD_5/TP were much lower in the research of Micek et al. in comparison to the present study and amounted up to 1.1 and 6.7, respectively. This points to very poor susceptibility of nitrogen and phosphorus compounds to biological degradation.

Another study concerning biodegradability measures of mechanically treated wastewater was conducted by Bugajski et al. [41] and in that case about half of the measurements were characterized by average susceptibility to biological decomposition of organic matter which is very similar to the results obtained in the recent research. When it comes to the susceptibility of wastewater to the decomposition of biogenic compounds, Bugajski et al. reached a better situation – in their study, in 17% of the cases the BOD_5/TN ratio was above 5.0, while in wastewater

from the analyzed CW WWTP it was only 8% of the observations (one case). This shows that generally it is not easy to obtain the wastewater after mechanical treatment which has favorable conditions for nitrogen compounds biodegradation. Similar situation was observed in the case of wastewater susceptibility to phosphorus compounds biological degradation. Bugajski et al. had 90% of observations with the value of BOD_5/TN ratio above 25.0, which means easy susceptibility, while in the facility under study there was 67% of all the observations.

Effluent after all the stages of the CW

Figure 7 shows how the concentrations of the analyzed pollution indicators (BOD_5 , COD, TSS, TP, TN) in the wastewater flowing out from the treatment plant changed during the study period. Moreover, the standards in force in Poland [31] (red line) and a trend line (dotted line) are marked. On the basis of the data presented in Figure 7A–E, it cannot be unambiguously stated whether the concentrations of pollutants in the effluent after all the treatment stages increase or decrease with the duration of the operation of the constructed wetland wastewater treatment plant. However, it can be clearly seen that the highest concentrations of the studied pollutants were observed in winter months (mostly December and January) with lowest air temperatures. This indicates that the researched facility was characterized by decreased efficiencies of pollutants removal during cold periods.

Over the first 12 months of the facility operation, no case of exceeding the maximum permissible value was recorded, as far as the indicators of the basic group are concerned (BOD_5 , COD, TSS). However, a problem was demonstrated with the removal of pollutants from the biogenic group, i.e. total phosphorus and total nitrogen, for which there were several exceedances of the permissible value specified in the Polish legal act – one exceedance of the TP concentration and as many as 4 exceedances for the TN concentration. These cases with exceeding permissible values of biogenic parameters in the outflowing wastewater were observed mainly in winter months (November, December, January) so when the atmospheric air temperatures were the lowest. However, no such problem was found in a household CW WWTP functioning in similar climatic conditions but serving much smaller volumes of wastewater. For example,

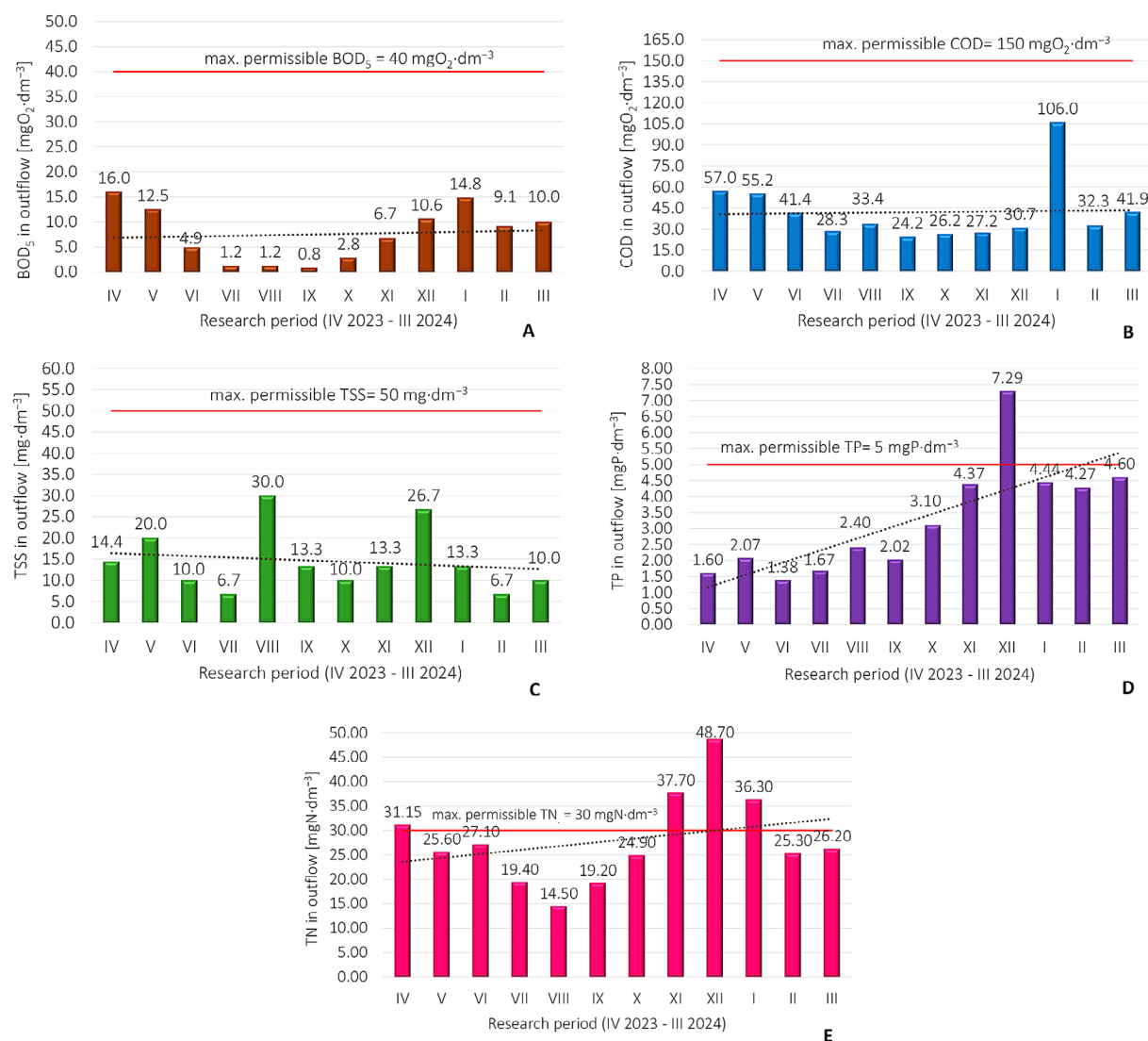


Figure 7. Values of tested wastewater quality indicators in outflowing wastewater after all the treatment stages: (A) – BOD₅, (B) – COD, (C) – TSS, (D) – TP, (E) – TN

Józwiakowska and Bugajski [14] demonstrated that the tested household constructed wetland wastewater treatment plant operated similarly in terms of removal of both basic (BOD₅, COD, TSS) and biogenic pollutants (TP, TN) across seasons regardless of the air temperature. Thus, a hypothesis can be made that full-scale constructed wetland wastewater treatment plants serving whole communities (not small household systems) are less resistant to seasonal changes in air temperature which causes decreased efficiency of biogenic pollutants removal and increased values of these substances in the outflowing wastewater in winter period. For this reason, in the further part of the paper, it was analyzed whether there actually exists a relationship between air temperature changing in following months of year and constructed wetland operation.

Efficiency and reliability of the facility

The operational efficiency and reliability of the biological part of the facility (VF+HF beds together) were evaluated using four different parameters and for this purpose there were chosen all the 5 pollution indicators, for which their maximum permissible values in the outflow are stated in the Polish Regulation [31], namely from the basic group: five-day biochemical oxygen demand (BOD₅), chemical oxygen demand (COD) and concentration of total suspended solids (TSS) and from biogenic group: total phosphorus (TP) and total nitrogen (TN). The results of the efficiency and reliability calculations are presented in Table 4.

On the basis of the conducted analyses it can be seen that during the first year of operation the studied facility ensured high efficiency of wastewater treatment in the case of pollution indicators from the basic group - pollutant removal efficiency in CW beds reached respectively almost 96% for BOD₅, about 89% for COD and 82% for TSS. A slightly greater problem was observed while biogenic contaminants removal -the studied CW eliminated about 41% of total phosphorus and 50% of total nitrogen.

In the case of the treatment plant reliability factor (RF) a smaller value of this reliability indicator mean smaller average concentrations of the tested pollutants in treated wastewater. That is why it can be stated that the analyzed facility performed best in removing the organic pollutants expressed in indicators such as BOD₅ and COD (RF amounted to 0.23 and 0.27, respectively), whereas for the total nitrogen (RF = 0.93) the relatively highest concentrations in the outflowing wastewater were achieved, most close to the maximum permissible value specified in the relevant legal act.

Similar observation was made for the technological efficiency of wastewater treatment (P_{sw}) which can have values in the range [0,1]. The more samples that meet the conditions set in the Regulation [31], the higher the technological efficiency of wastewater treatment. Thus, during the first year of operation the best technological efficiency of wastewater treatment ($P_{sw} = 100\%$) was stated for BOD₅, COD and TSS and the lowest for TN -in this case about one-third of the observations exceeded the maximum permissible concentration of total nitrogen in outflowing wastewater.

Risk of a negative assessment of the wastewater treatment plant operation (R_s) should have the lowest value possible (0) which means no probability of exceeding the pollutant concentration limits in treated wastewater. Such phenomenon occurred in the case of pollution indicators from the basic group (BOD₅,

COD and TSS). According to the Polish Regulation [31], 2 out of 12 samples in one year may exceed the pollutant concentration limits. However, 4 exceedances of TN concentration were observed, which is why the risk of a negative assessment of the wastewater treatment plant operation in the case of total nitrogen removal reached up to 2.0.

Figure 8 shows a box-and-whisker plot illustrating the range of variation in the removal efficiency values of individual pollutants at successive CW beds. The median was chosen as the value marked with points, as it is the most representative of the individual data series and more resistant to outliers than the mean. The boxes show the range between Q1 (25th percentile), and Q3 (75th percentile), which shows the 25% and 75% smallest data, respectively. The interquartile range illustrates how dispersed the data is around the median.

Figure 8 makes it possible to not only compare the removal efficiency of the tested pollutants in the two constructed wetland beds (with vertical flow -VF and horizontal flow -HF) but also to assess the efficiency of the whole biological part of the facility (together VF and HF beds). The first constructed wetland bed with vertical flow was characterized by greater median efficiency of all the tested pollutants removal. The whole biological part of the facility (VF + HF beds together) provided pollutants removal efficiency in the following ranges: BOD₅ 91.95–99.65%, COD 75.80–94.99%, TSS 66.67–92.30%, TP 5.95–84.86%, and TN from -19.03 to 81.47%. The phenomenon of increasing the concentration of TN in wastewater means that additional nitrogen has been released into the wastewater in the constructed wetland bed. Negative values of total nitrogen removal were observed from December to March, i.e. in winter months with low air temperatures. Low temperatures slow down the metabolism of microorganisms responsible for nitrification and denitrification, hinder the nitrogen uptake by

Table 4. Reliability indicators for the analyzed wastewater treatment plant in Zawadówka

Reliability indicators	BOD ₅	COD	TSS	TP	TN
Pollutant removal efficiency (η)	95.76	89.02	82.00	40.89	50.01
Treatment plant reliability factor (RF)	0.23	0.27	0.29	0.65	0.93
Technological efficiency of wastewater treatment (P_{sw})	1.00	1.00	1.00	0.92	0.67
Risk of a negative assessment of the wastewater treatment plant operation (R_s)	0.00	0.00	0.00	0.50	2.00

plants and promote decomposition of dead plant biomass which causes the release of organic nitrogen to surrounding wastewater [42]. The whole biological part (VF + HF beds together) showed a very high total efficiency of pollutants removal and the medians, which were higher than mean values showed in Table 4, amounted about: BOD₅ – 95.89%, COD – 89.16%, TSS – 85.22%, TP – 49.44%, TN – 59.50%.

Similar studies have been carried out by different researchers around the world. For example Vera et al. [43] studied the first year of operation of a facility that in the mechanical part has an Imhoff tank for primary treatment, and in the biological part, like the treatment plant described in this paper, consists of two constructed wetland beds - a VF and a subsequent HF bed planted with *Typha latifolia* L.. Two types of substrate were used: basalt gravel and lapilli, a porous volcanic material local to Gran Canaria. The pollutants removal efficiencies obtained by Vera et al. were significantly lower than the values in the facility in Zawadówka. In the CW WWTP, the mean treatment efficiencies reached the following levels: BOD₅ – 80%, COD – 75%, TSS – 90%, TP – 30% and TN – 50%. This phenomenon may indicate that the filling material (gravel and sand) or plants (*Miscanthus giganteus* × Greif et Deu and *Salix viminalis* L.) used for CW beds in the facility in Poland were more efficient in processes of wastewater treatment than in the case of Spanish WWTP.

Another study from Czech Republic [44] showed that a system consisting of 2 VF

beds and one HF bed enabled a very high pollutants removal, which for BOD₅ and COD amounted to 94.5% and 84.4%, respectively, with respective average outflow concentrations of 10 mg/l and 50 mg/l. The mean values of organic pollution indicators in outflowing wastewater were higher than in the case of the facility in Zawadówka, where they amounted to about BOD₅ – 8 mg/l and COD – 42 mg/l with average coefficient of reduction 95.8% and 89.0%, respectively. On the other hand, phosphorus removal in the facility analyzed by Vymazal and Kröpfelová amounted to 65.4%, with the average outflow concentration of 1.8 mg/l. Therefore, it can be seen that the facility in Czech Republic was more efficient in phosphorus removal than the one in Poland, which ensured the average coefficient of phosphorus reduction up to only about 41%, with mean outflow concentration of 3.3 mg/l (almost 2 times bigger than in Czech Republic). Probably the higher efficiency of phosphorus compounds removal may be the result of an additional VF bed used in the studied WWTP. In addition to high pollutants removal efficiency, the authors pointed out that constructed wetland systems are characterized by the capital cost that is comparable to the conventional on-site treatment plants but the operations and maintenance costs are about one third of the conventional facilities.

Parde et al. [45] published a review of different constructed wetlands and proved that such facilities perform exceptionally well

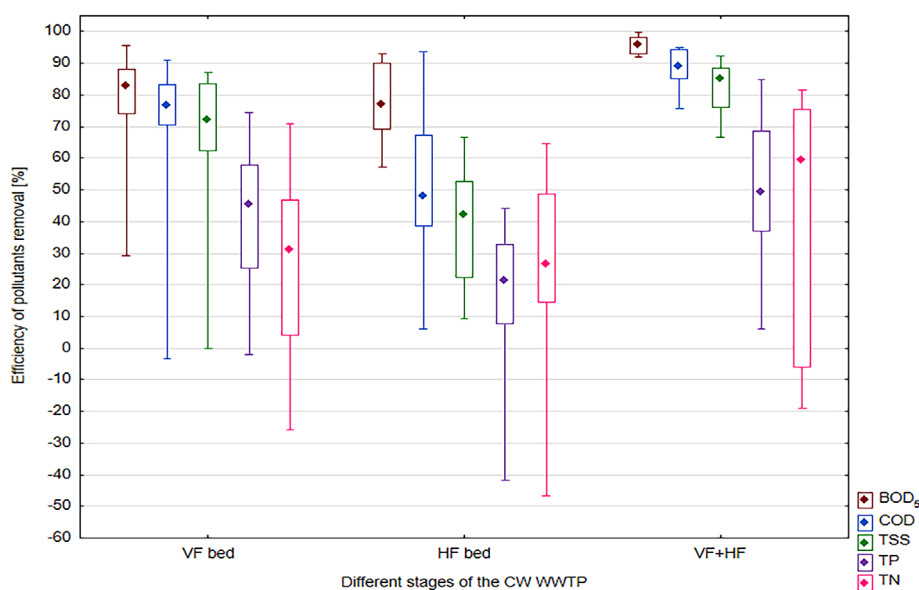


Figure 8. Range of variation of the efficiency of pollutants removal during the study period

and can remove 80–91% BOD₅, 60–85% COD and 80–95% TSS. Thus, only in the case of TSS there was reached a better mean removal efficiency than in the facility analyzed in the present study. Moreover, it was stated that such systems require a very low operation and maintenance than others so should be definitely promoted to use worldwide for wastewater management.

As stated by Vymazal [46], constructed wetlands with horizontal subsurface flow (HF CWs) were the most common type of constructed wetlands used for municipal wastewater during the last 20 years of the 20th century. On the basis of a study which evaluated treatment performance of 114 Czech HF CWs with special attention to 17 systems that have been in operation for at least 20 years, it was observed that treatment efficiency actually increased over the years of operation with outflow concentrations lower as compared to initial phase of operation. Moreover, it was proven that removal of both organic pollution indicators and TSS did not depend on the season. In other paper [47] Vymazal analyzed some constructed wetland systems for wastewater treatment operating in Czech Republic for more than 30 years without any refurbishment. The author indicated that the average treatment efficiencies were 87.5% for BOD₅, 78.5% for COD, 85.7% for TSS, and 41% for TP. The respective average outflow concentrations were as follows (in mg/l): 12.5, 48.5, 11.2 and 3.35. This shows that the hybrid constructed wetland wastewater treatment plant in Zawadówka during the first year of its operation ensured higher average efficiencies of organic pollutants and total phosphorus removal than the old facilities in Czech Republic. On the other hand, only mean TSS concentration in outflowing wastewater was higher in Zawadówka than in the facility studied by Vymazal.

Special attention should be paid to relatively lower efficiency of nutrients removal in the analyzed constructed wetland wastewater treatment plant. Because nitrogen-rich effluents cause numerous environmental issues in receiving water bodies, enhancing nitrogen removal is a key priority [48]. As pointed out by some authors, various measures can be taken to improve the efficiency of nutrients removal in CW systems, e.g. using suitable hydroponic materials – special filter bed substrate such as pumice, cocopeat or mineral wool. Such materials are highly porous which could therefore allow

oxygen diffusion into the filter bed enhancing the microbial activities, nitrification process and that will increase the efficiency of biogenic compounds removal [13]. Moreover, some studies showed that the efficiency of phosphorus and nitrogen compounds removal is strongly correlated with the influent composition and especially C/N ratios. The higher amount of carbon compounds, the smaller nutrients concentrations in the outflow can be reached. Hence, in order to increase the efficiency of biogenic compounds removal the problem of carbon source deficiency should be eliminated, for example by adding some external carbon source supplements [49]. Moreover, some previous studies have indicated that while there is no correlation between the operating time of the treatment plant and the efficiency of nitrogen compound removal, phosphorus removal decreases over time as the sorption capacity of the beds becomes saturated [50]. For this reason, it is suggested to monitor the changes of total phosphorus concentration in the outflowing wastewater in the following years of the system operation.

Influence of selected factors on the operation of the studied CW system

The next step in the analysis was to see how various factors affected the efficiency of the tested wastewater quality indicators reduction in individual beds of the constructed wetland system. The initial research hypothesis was that the removal efficiency of the tested pollutants could depend on atmospheric air temperature and/or wastewater quality indicators such as biodegradability measures (COD/BOD₅, BOD₅/TN, BOD₅/TP). In order to analyze the effect of atmospheric air temperature on the performance of the CW WWTP, a five-day average value was calculated, that is, the average of the five days preceding the day of wastewater sampling.

The normality of the distribution of the analytical results was checked with the Shapiro-Wilk test at a significance level of $\alpha = 0.05$. Due to the ambiguity of the distributions, a nonparametric Spearman correlation test was performed to assess monotonic interrelationships between different variables. Table 5 presents the interrelationships which occurred to be statistically significant at a significance level of $\alpha = 0.05$ ($p < 0.05$) together with the values of Spearman correlation coefficients (R_{Spearman}) and probabilities (p).

All the selected interrelationships that showed statistical significance indicated a strong ($R_{\text{Spearman}} > 0.6$) or very strong ($R_{\text{Spearman}} > 0.8$) correlation between the studied parameters.

There was a clear positive correlations between both increased atmospheric air temperature and the efficiency of the VF-type constructed wetland bed in terms of the removal of organic pollutants expressed by the COD indicator as well as the reduction of total phosphorus and total nitrogen. Higher atmospheric air temperature also strongly affected the efficiency of the HF-type constructed wetland bed in terms of TSS removal. As the temperature increased, the degree of reduction of the mentioned pollutants also increased. Similar results to the ones obtained in in the recent study were previously reached by some other authors [51,52], who also observed that lower temperatures hinder nitrification processes and by that decrease nitrogen compounds removal in constructed wetland systems. On the other hand, the obtained results contradict the previous ones obtained by Józwiakowska and Bugajski [14], where it was demonstrated that the tested household constructed wetland wastewater treatment plant operated similarly across seasons regardless of the air temperature. The authors showed no statistically significant correlation between air temperatures and the efficiency of neither BOD_5 , COD, TSS, TN nor TP removal. Small systems treat much smaller volumes of wastewater inflowing from individual households and are subjected to high unevenness of wastewater flow. Sometimes, at high air temperatures and low wastewater production, the flows in CW beds approach almost zero [53]. This may indicate that large-scale constructed wetland wastewater treatment plants serving entire communities (as opposed to small household systems) with higher capacities and instant wastewater flow are more

vulnerable to seasonal fluctuations in air temperature, leading to reduced pollutant removal efficiency during cold periods.

On the other hand, it was stated that as the values of biodegradability measures (BOD_5/TN and BOD_5/TP) in mechanically treated wastewater increased, decrease in COD and TN removal in the VF bed was observed (negative value of Spearman correlation coefficient). This means that the generally accepted theory that higher values of the BOD_5/TN and BOD_5/TP increase the susceptibility of wastewater to decomposition of nitrogen and phosphorus compounds [38,39], respectively, has not been confirmed in the case of the CW WWTP in Zawadówka.

The correlation of individual predictors was then evaluated. A significant correlation was found between various parameters, such as air temperature, and biodegradability indicators, which could indicate potential collinearity. Since it was impossible to select variables of independent nature, performing a multiple regression analysis proved to be statistically unjustified.

CONCLUSIONS

During the first year of operation of the constructed wetland wastewater treatment plant, the average biodegradability of wastewater subjected to biological treatment was observed for 6 months. Moreover, poor conditions for biological degradation of nitrogen compounds and favorable conditions for phosphorus compounds biodegradation were proven. During the start-up period, no case of exceeding the maximum permissible values specified in the Polish legal act as far as the indicators of the basic group are concerned (BOD_5 , COD, TSS) were observed. However, a problem was demonstrated with the removal of

Table 5. Selected results of Spearman correlation analysis

Variables	R_{Spearman}	p
COD removal in the VF bed & air temperature (average 5 days before)	0.6434	0.0240
COD removal in the VF bed & BOD_5/TN after mechanical treatment	-0.7063	0.0102
COD removal in the VF bed & BOD_5/TP after mechanical treatment	-0.7832	0.0026
TP removal in the VF bed & air temperature (average 5 days before)	0.7762	0.0030
TN removal in the VF bed & air temperature (average 5 days before)	0.8671	0.0003
TN removal in the VF bed & BOD_5/TN after mechanical treatment	-0.8531	0.0004
TN removal in the VF bed & BOD_5/TP after mechanical treatment	-0.8671	0.0003
TSS removal in the HF bed & air temperature (average 5 days before)	-0.6294	0.0283

TP and TN, for which there were noticed 1 and 4 exceedances, respectively.

The studied facility ensured high efficiency of wastewater treatment in the case of pollution indicators from the basic group – the pollutant removal efficiency in CW beds reached respectively almost 96% for BOD₅, about 89% for COD and 82% for TSS, about 41% for TP and 50% for TN.

The CW performed best in removing organic pollutants expressed in indicators such as BOD₅ and COD (RF amounted to 0.23 and 0.27, respectively), whereas for TN (RF = 0.93) the relatively highest concentrations in the outflowing wastewater were achieved, most close to the maximum permissible value specified in the relevant legal act. The best technological efficiency of wastewater treatment ($P_{sw} = 100\%$) was stated for BOD₅, COD and TSS and the lowest for TN – in this case, about one-third of the observations exceeded the maximum permissible concentration of total nitrogen in outflowing wastewater. Simultaneously, the risk of a negative assessment of the wastewater treatment plant operation (R_s) was the highest in the case of TN removal and reached up to 2.0.

Higher atmospheric air temperature strongly (positively) affected both the efficiency of the VF-type constructed wetland bed in terms of the removal of COD, TP and TN and the efficiency of the HF-type constructed wetland bed in terms of TSS removal. This indicates that large-scale constructed wetland wastewater treatment plants serving entire communities (as opposed to small household systems) are more vulnerable to seasonal fluctuations in air temperature, leading to reduced pollutant removal efficiency during cold periods.

In this paper, the generally accepted theory that higher values of the BOD₅/TN and BOD₅/TP increase the susceptibility of wastewater to decomposition of nitrogen and phosphorus compounds, respectively, has not been confirmed.

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