

Article

Influence of the Bed Temperature on the Operational Reliability of a Hybrid Constructed Wetland Wastewater Treatment Plant in South-Western Poland—A Case Study

Karolina Jóźwiakowska ^{1,*}  and Piotr Bugajski ² 
¹ Department of Agricultural, Forestry and Transport Machines, Faculty of Production Engineering, University of Life Sciences in Lublin, 28 Głęboka Str., 20-612 Lublin, Poland

² Department of Sanitary Engineering and Water Management, Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Kraków, 24/28 Mickiewicza Str., 30-059 Kraków, Poland; piotr.bugajski@urk.edu.pl

* Correspondence: karolina.jozwiakowska@up.lublin.pl

Abstract: The aim of this study was to assess the influence of atmospheric air temperature on the efficiency and reliability of pollutants removal from wastewater. The studied facility was a hybrid constructed wetland wastewater treatment plant with vertical and horizontal flow serving a single-family building in the village of Krajanów in south-western Poland. The operation of the facility was evaluated on the basis of studies conducted in 2021–2022. The tests included a physico-chemical analysis of wastewater treated mechanically in a settling tank and effluents from constructed wetland beds with the vertical and horizontal flow. The following parameters were determined: BOD₅, COD, total suspended solids, total nitrogen, and total phosphorus. No statistically significant effect of air temperature on the analyzed pollutants removal levels was found. The temperature in the soil–plant bed never fell below 0 °C, and so the wastewater flowing through the beds never froze. The discussed facility was characterized by high efficiency and reliability of the tested pollutants removal across the seasons. The mean concentrations of pollutants in treated wastewater did not exceed the limit values specified in the currently binding legal act. It was shown that hybrid constructed wetlands can be successfully used for wastewater treatment in the climatic conditions of southern Poland.

Keywords: hybrid constructed wetland system; wastewater treatment plant; domestic wastewater; efficiency and reliability of pollutant removal; air temperature



Citation: Jóźwiakowska, K.; Bugajski, P. 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* **2023**, *15*, 11790. <https://doi.org/10.3390/su151511790>

Academic Editor: Andreas Angelakis

Received: 28 June 2023

Revised: 25 July 2023

Accepted: 26 July 2023

Published: 31 July 2023



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1. Introduction

In today's world, water resources should always be managed in compliance with the principle of sustainable development, which means that the Earth's limited and overexploited water supply must not be depleted either quantitatively or qualitatively [1,2]. It is necessary to maintain water reserves in a proper condition so that they can also be used by future generations [3,4]. This encourages water management that involves both reducing water consumption and recovering water through wastewater treatment [5,6].

The most commonly used and most profitable wastewater management method is treatment in centralized wastewater systems, which serve entire cities or municipalities [7–11]. However, in regions with scattered development, such as rural areas in Poland (which are inhabited by 40% of the country's population), centralized systems cannot be used for economic reasons. Instead, wastewater has to be neutralized and disposed of at the place where it is generated, i.e., in so-called household wastewater treatment plants.

Depending on the type of land and the specific local conditions, various methods of domestic wastewater treatment can be used [12,13]. Nowadays, both domestic and collective wastewater treatment plants most often use technology based on the activated sludge process. However, as research has repeatedly shown, this method is associated with high

operating costs and requires constant maintenance by qualified staff. The answer to the search for uncomplicated and inexpensive alternative treatment technologies is constructed wetlands, which are increasingly used for wastewater treatment all over the world [14,15]. They are used not only for the management of typical domestic wastewater but also for the treatment of stormwater, greywater, overflows, and runoff [16], as well as municipal, industrial, and refinery wastewater, post-mining wastewater, and leachate from landfills [17–19]. Hybrid constructed wetland systems have already been studied for the removal of basic pollutants (organic pollutants and suspended solids), biogenic pollutants (nitrogen and phosphorus) [20,21], as well as additional and emerging contaminants (pharmaceuticals, antibiotics, drugs, etc.) [22].

In comparison to wastewater treatment plants with activated sludge, constructed wetlands are highly resistant to both changes in wastewater inflow rates and the composition of sewage across the year. Moreover, they are characterized by a high efficiency of pollutant removal and low operating costs [23,24].

There are two main groups of constructed wetlands: free-water surface flow wetlands and subsurface flow wetlands, which are most commonly used in Central Europe. Subsurface flow systems can be further divided into those with horizontal and vertical flow [25]. Most often, constructed wetlands are technological systems in which wastewater is passed through an initial settling tank, and beds filled with soil are vegetated with appropriately selected plants. In these facilities, organic and biogenic pollutants are removed by microorganisms that form a biological membrane as wastewater flows through the beds [26]. Initially, systems with only one soil-plant bed were used, but years of research have shown that systems that combine several beds with different wastewater flow regimes are much more efficient, especially when it comes to eliminating nitrogen compounds. Vertical flow (VF) beds provide good (aerobic) conditions for nitrification, while horizontal flow (HF) beds ensure the anaerobic conditions necessary for denitrification. Owing to the use of combined systems, also known as hybrid systems, the wastewater treatment processes taking place in the VF and HF beds can complement each other [27–29]. As reported in the literature, there are many factors that affect the efficiency of pollutant removal in constructed wetlands [30–33]. The most important of them are the type of wastewater flow regime (VF or HF), the number and sequence of beds [26], the surface area and depth of the beds [34,35], the type of material filling the beds [36,37], the hydraulic load and the quantity of inflowing wastewater [37,38], the pollutant load in wastewater [39], and the type of vegetation growing in the bed [37,40]. Another factor that determines the efficiency of the operation of constructed wetlands is the air temperature [37,41]. It was found that the biochemical and microbiological processes in soil-plant beds work properly at air temperatures above 5 °C [41].

The efficiency and reliability of constructed wetlands are the focus of research conducted by a growing number of scientists around the world. The operation of small constructed wetlands (<2000 PE) has been analyzed both in Poland [21,26,42–46] and in other countries worldwide [47–52].

The aim of the present study was to assess the impact of air temperature and soil-plant bed temperature on the efficiency and reliability of organic and biogenic pollutants removal in a household VF-HF constructed wetland wastewater treatment plant serving a single-family building located in south-western Poland.

2. Materials and Methods

2.1. Experimental Facility

The investigated constructed wetland was located at a private household owned by Polish 2018 Nobel Prize Winner Mrs. Olga Tokarczuk. The residential building from which wastewater is discharged into the analyzed treatment plant is situated in the village of Krajanów in the commune of Nowa Ruda, Kłodzko County, the Lower Silesian Voivodeship, in southwestern Poland, as shown in Figure 1. The discussed technological system was designed for a population equivalent (PE) of 8 and an average daily wastewater inflow

$Q_{a,d} = 0.8 \text{ m}^3 \cdot \text{d}^{-1}$. The facility consists of four main parts, as shown in the technological scheme in Figure 2. The construction of the researched wastewater treatment plant has been described on the basis of information provided in the service instruction [53]. A view of the investigated constructed wetland is shown in Figure 3.

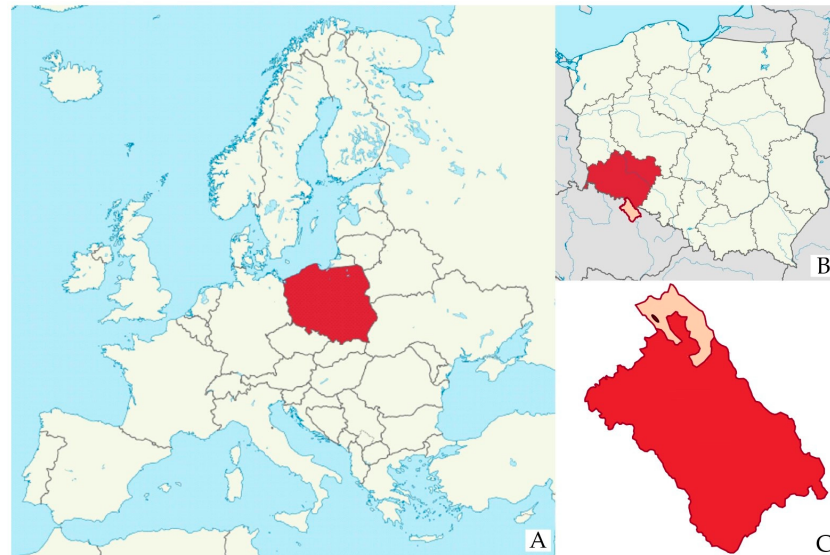


Figure 1. Location of the researched facility: (A)—Poland in Europe; (B)—Lower Silesian Voivodeship and Kłodzko County; (C)—Kłodzko County, Nowa Ruda Commune, and Krajanów Village (own elaboration on the basis of [54–56]).

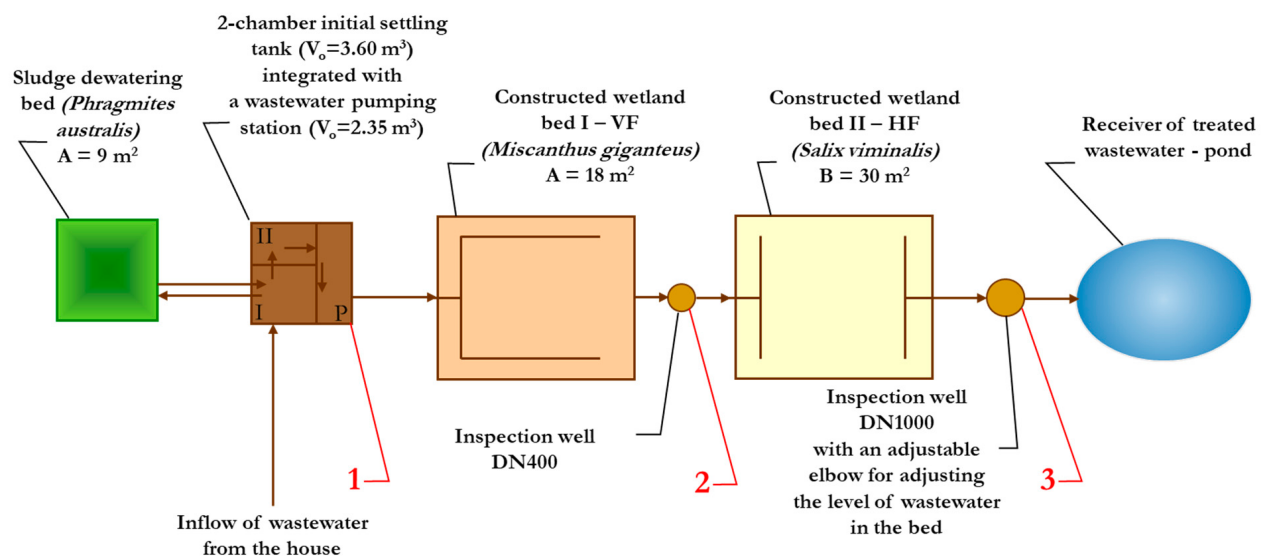


Figure 2. Technological scheme of the household hybrid constructed wetland wastewater treatment plant. Wastewater collection points: 1—mechanically treated wastewater; 2—effluent from bed I (vertical flow—type (VF)); 3—effluent from bed II (horizontal flow—type (HF)).

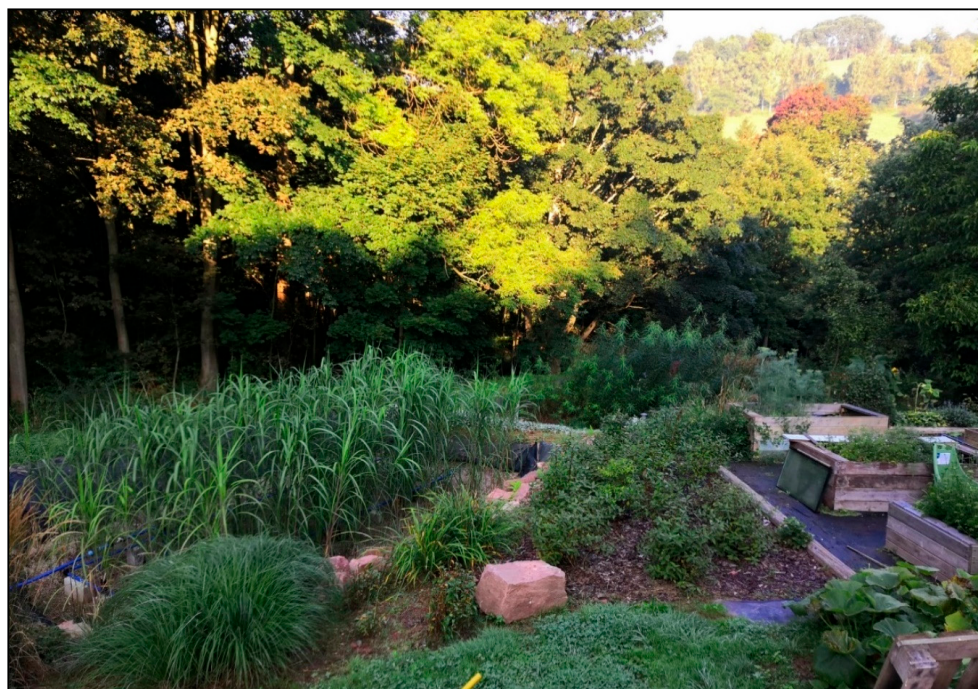


Figure 3. The VF-HF hybrid constructed wetland in Krajanów (summer).

Raw wastewater discharged from the house first flows into the mechanical wastewater treatment system, which consists of a two-chamber initial settling tank integrated with a wastewater pumping station. In the settling tank, the largest solid contaminants are removed by mechanical treatment, which involves sedimentation and flotation processes, as well as biological treatment—fermentation and biochemical processes [57]. The facility under study has a system for dewatering and neutralizing initial sewage sludge at the place of its formation, which means sewage sludge does not have to be removed by a septic tank truck. Sewage sludge is pumped periodically (once a month) from the first chamber of the initial settling tank to the surface of a wetland bed, where it is dewatered. In the 9 m² reed bed, the solid fraction is separated from the wastewater as a result of filtration. The leachate water (filtrate) percolates into the collecting drainage system at the bottom of the bed and then flows back to the first chamber of the settling tank [53].

The biological treatment part of the investigated hybrid constructed wetland is composed of a system of two soil-plant beds. Wastewater from the pumping station is fed periodically, in pulses (after each activation of the pump), into the first 18 m² VF bed planted with giant miscanthus (*Miscanthus giganteus* × Greef et Deu) and distributed over its surface via a drainage system. Next, the wastewater filtered through the VF bed layer is collected by drainage pipes located at the bottom of the bed and discharged gravitationally to the second bed, which is a 30 m² HF bed planted with willow (*Salix viminalis* L.). As indicated in the service instructions for the constructed wetland [53], the VF bed has a wastewater supply control system installed on its surface, which allows for the adjustment of sewage inflow depending on the season (summer/winter). According to recommendations, when low air temperatures (below −10 °C) persist for a longer time, the valve on the pipeline supplying wastewater to the surface of the VF bed should be closed and another valve that directs wastewater flow straight under the surface of the first bed should be opened. Moreover, the inspection well after the HF bed has been equipped with a swivel elbow at the end of the outlet pipe, which is used to bring up the wastewater level in this bed. During warm winters (when the air temperature does not drop below −10 °C), it is recommended that wastewater levels be elevated in the HF bed throughout the year to ensure better wastewater treatment.

The studied wastewater treatment technology based on the use of a hybrid constructed wetland system (consisting of one bed with vertical sewage flow and one bed with horizon-

tal flow) has already been typically applied in an upland area in southeastern Poland under conditions of a temperate transitional climate [45]. In contrast, the area where the studied facility in Krajanów is located is the Sudeten climate region, where conditions are much more diverse. The mountainous landform shapes not only the temperature, cloud cover, and precipitation but also the direction and speed of winds [58]. As altitude rises, precipitation increases, temperature decreases, summer shortens, and winter lengthens. Therefore, it was assumed that it would be worthwhile to perform a case study on the effectiveness of the discussed wastewater treatment technology in other climatic conditions in Poland. Thereby, the research conducted represents a novelty in relation to those previously carried out on this topic.

2.2. Analytical Methods

2.2.1. Wastewater Quality

There were analyses of wastewater treated mechanically in the initial settling tank and wastewater treated biologically in the VF and HF beds. Samples of wastewater from three measuring points were collected and subjected to physico-chemical analyses from the beginning of April 2021 to the end of March 2022. During that period, 12 samples of each type of wastewater were collected at 1-month intervals. Mechanically treated wastewater was collected from the third chamber of the settling tank, i.e., the wastewater pumping station—sampling point 1 (Figure 2). Effluent from the VF bed, after the first stage of biological treatment, was sampled from the inspection well located behind this bed—sampling point 2 (Figure 2). Samples of wastewater from the second stage of biological treatment were collected from the inspection well behind the HF bed—sampling point 3 (Figure 2). Wastewater samples from the facility were collected, transported, and analyzed in compliance with international reference recommendations [59,60]. The physico-chemical analyses included the measurement of basic pollution parameters (five-day biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSS), and biogenic pollutants (total nitrogen (TN) and total phosphorus (TP)). The assay methods for each parameter are listed in Table 1. The tests were carried out at the Water and Wastewater Quality Testing Laboratory, Department of Sanitary Engineering and Water Management, University of Agriculture in Kraków.

Table 1. Assay methods used to measure the selected pollution parameters.

Item	Parameter	Unit	Assay Method
1	BOD ₅	[mgO ₂ ·dm ⁻³]	manometric method using the Oxi Top IS-6 kit
2	COD	[mgO ₂ ·dm ⁻³]	spectrophotometric method using the PhotoLab 7100 VIS spectrophotometer
3	TSS	[mg·dm ⁻³]	weight method using ashless filter strainers after drying in a laboratory dryer of type SLW 32 Smart
4	TN	[mgN·dm ⁻³]	spectrophotometric method using Merck-certified cuvette assays with a PhotoLab 7100 VIS spectrophotometer
5	TP	[mgP·dm ⁻³]	spectrophotometric method using Merck-certified cuvette assays with a PhotoLab 7100 VIS spectrophotometer

BOD₅—five-day biochemical oxygen demand, COD—chemical oxygen demand, TSS—total suspended solids, TN—total nitrogen, TP—total phosphorus.

The constructed wetland under study is a domestic wastewater treatment plant designed for 8 PE (<2000 PE), which means that in accordance with Polish guidelines [61], the maximum permissible concentrations of pollutants in treated wastewater discharged from this facility may not exceed BOD₅—40 mgO₂·dm⁻³, COD—150 mgO₂·dm⁻³, TSS—50 mg·dm⁻³, TN—30 mgN·dm⁻³ and TP—5 mgP·dm⁻³. These reference values should be used each time the parameters of the effluent from the investigated treatment

plant are evaluated. A comparison of the effluent parameters with the reference values allows one to determine whether the facility provides sufficient treatment efficiency, bringing sewage to a state in which it can be safely discharged into the environment without the risk of contamination. The Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 [61] stipulates that it is necessary to control the content of nutrients in sewage discharged from small wastewater treatment plants of up to 2000 PE. However, this requirement only pertains to wastewater discharged into lakes and their tributaries and directly into artificial water reservoirs located on flowing waters. Despite the fact that there is no obligation to monitor nitrogen and phosphorus concentrations in the effluent from facilities such as the one investigated in this paper, the content of these nutrients in treated wastewater was determined to see whether or not the treatment plant contributed to the eutrophication of the nearby pond, which is the recipient of the treated wastewater from this facility.

2.2.2. Assessment of Atmospheric Air Temperature and Temperature Inside the HF Bed

The air temperature and temperature inside the HF bed were measured using EL-USB-1-pro LASCAR electronic sensors. A sensor integrated with a data recorder (set in a stainless steel case) was used to continuously measure temperature at a pre-set time interval. The air temperature sensor integrated with the recorder was placed 2 m above ground level under the ceiling beam of the patio on the northern side of the house. The sensor was not exposed directly to sunlight to prevent interference with the measurements. The sensor and recorder for measuring bed temperature were put in a perforated casing pipe and placed in the HF bed at a depth of 0.5 m below ground level. Readings from the period between the beginning of April 2021 and the end of March 2022 were analyzed. Air temperature and bed temperature were measured continuously at 6-h intervals (4 measurements per day), and the arithmetic mean of 4 measurements was calculated as a reliable daily value.

2.3. Statistical Analysis

The results were analyzed statistically, graphed, and tabulated using Microsoft Excel 2016 and Statistica 13.1. The tables and graphs show changes in the levels of the investigated wastewater pollution parameters after each stage of treatment.

In order to analyze and evaluate the operation of the wastewater treatment plant, a statistical analysis of the initial data was performed. The most important descriptive statistics were determined: measures of location (mean ($\bar{x}$), minimum (min), and maximum (max)), 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 [62], which features the following variation groups: low (0–20%), moderate (20–40%), high (40–100%), very high (100–150%), and extremely high (>150%) variation.

Pearson's linear correlation analysis was carried out to determine the effect of the air temperature and the constructed wetland bed temperature on the pollutant removal efficiency.

The operational reliability of wastewater treatment plants is commonly assessed using a method based on the Weibull distribution, which allows for the assessment of the risk of exceeding pollutant limits for treated wastewater discharged into the environment [9,10,63–65]. This method also permits determining the time for which a facility operates at reduced efficiency, which may be used as an indication that some modernization is required [66]. This study reported in this paper was carried out in the first year of operation of the treatment plant, during its start-up. Hence, only 12 series of data concerning the composition of wastewater samples from the three stages of treatment were available for statistical analyses. Due to the scarcity of data, the reliability analysis method based on the Weibull distribution could not be accurately applied to assess the functioning of the wastewater treatment plant in Krajanów. Instead, the operational efficiency and reliability of the studied facility were measured on the basis of the following four parameters:

- Pollutant removal efficiency η ;

- Treatment plant reliability factor (RF);
- Technological 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 defined as the ratio of the difference in pollutant concentrations between sewage before treatment (influent) and after treatment (effluent) to the pollutant concentration in untreated sewage (influent). The pollutant removal efficiency was calculated from Formula (1) [67,68]:

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

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 Formula (2) [67,69]:

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

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 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 [61]. This value was calculated according to Formula (3) [67,70]:

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

where:

n_c —number of outflow readings compliant with the Regulation [-],

N —number of all the outflow readings [-].

P_{SW} has values in the range [0, 1]. The more samples that meet the conditions set in the Regulation, 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 Formula (4) [67,71]:

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

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 [61], may exceed the pollutant concentration limits during one year; two exceedances are allowed per 12 samples [-].

The lower the value of the R_S rate, the more likely it is that the relevant guidelines are met and that the operation of the treatment plant will be assessed positively.

3. Results and Discussion

3.1. Wastewater Quality

Table 2 presents the basic descriptive statistics for the individual pollution parameters measured in wastewater after mechanical treatment in the settling tank, wastewater after biological treatment in the VF bed, and biologically treated effluent from the HF bed.

Table 2. Basic descriptive statistics for pollution parameters in the effluent from the successive stages of treatment.

Parameter	$\bar{x}$ [mg·dm ^{−3}]	min [mg·dm ^{−3}]	max [mg·dm ^{−3}]	s [mg·dm ^{−3}]	Vs [%]
Mechanically treated effluent from the settling tank					
BOD ₅	125.3	44.0	350.0	93.3	74.4
COD	336.0	140.0	636.0	168.5	50.1
TSS	67.3	9.0	128.0	42.6	63.3
TN	56.7	24.0	131.0	30.5	53.8
TP	10.9	5.1	16.1	3.5	32.1
Effluent from the VF bed					
BOD ₅	20.6	1.0	105.0	30.2	146.9
COD	71.7	30.0	137.0	32.9	46.0
TSS	27.1	2.4	100.0	28.8	106.1
TN	27.3	12.0	71.0	15.3	56.1
TP	4.1	1.8	7.0	1.7	41.7
Effluent from the HF bed					
BOD ₅	5.2	0.5	15.0	5.5	105.9
COD	33.8	6.0	118.0	31.0	91.9
TSS	12.7	2.0	33.6	12.6	99.1
TN	17.4	8.0	35.0	8.2	47.1
TP	2.5	1.5	4.0	0.8	32.9

3.1.1. Mechanically Treated Wastewater

The concentrations of organic pollutants in mechanically treated effluent from the two-chamber initial settling tank ranged from 44.0 to 350.0 mgO₂·dm^{−3} for BOD₅ and from 140.0 to 636.0 mgO₂·dm^{−3} for COD. The mean values of the indicators were: for BOD₅—125.3 mgO₂·dm^{−3} and for COD—336.0 mgO₂·dm^{−3}. The concentration of total suspended solids in mechanically treated wastewater ranged from 9.0 to 128.0 mg·dm^{−3}, with a mean of 67.3 mg·dm^{−3}. The concentrations of biogenic compounds in the effluent from the settling tank ranged between 24.0 and 131.0 mgN·dm^{−3} of total nitrogen, mean 56.7 mgN·dm^{−3}, and from 5.1 to 16.1 mgP·dm^{−3} for total phosphorus, mean 10.9 mgP·dm^{−3}. High standard deviation values were recorded for all the pollution parameters: BOD₅—93.3 mgO₂·dm^{−3}, COD—168.5 mgO₂·dm^{−3}, TSS—42.6 mg·dm^{−3}, TN—30.5 mgN·dm^{−3}, TP—3.5 mgP·dm^{−3}. This indicates that the individual observations were heavily scattered and did not cluster around the means. The values of the coefficient of variation interpreted according to Mucha's scale [62] additionally confirmed the high variation and diversity of the values of BOD₅, COD, TSS, and TN, as well as the moderate variation in the concentrations of TP in mechanically treated wastewater.

As experiences from the operation of wastewater treatment plants show, the efficiency of pollutants removal processes depends not only on the values of the individual parameters but also on the ratios between them [72,73]. Literature reports indicate that in order to ensure the proper biodegradability of wastewater, it is important to maintain these ratios at the following levels [44,74]: COD/BOD₅ ≤ 2.2; BOD₅/TN ≥ 4.0; BOD₅/TP ≥ 25.0. The calculations conducted showed that, in the mechanically treated effluent, the mean COD/BOD₅ ratio was 3.0, the mean BOD₅/TN ratio was 2.2, and the mean BOD₅/TP ratio was 11.1. The obtained values indicate that the investigated facility did not provide proper conditions for biodegradation, which could potentially adversely affect the removal of

organic and biogenic compounds (nitrogen and phosphorus) from the wastewater in the constructed wetland beds.

3.1.2. Effluent from the VF Bed

The organic pollutant concentrations in the effluent from the VF bed ranged from 1.0 to 105.0 $\text{mgO}_2 \cdot \text{dm}^{-3}$ for BOD_5 and from 30.0 to 137.0 $\text{mgO}_2 \cdot \text{dm}^{-3}$ for COD. The mean values were BOD_5 —20.6 $\text{mgO}_2 \cdot \text{dm}^{-3}$ and COD—71.7 $\text{mgO}_2 \cdot \text{dm}^{-3}$. The concentrations of total suspended solids in samples collected at the outflow from the VF bed ranged from 2.4 to 100.0 $\text{mg} \cdot \text{dm}^{-3}$, with a mean of 71.7 $\text{mg} \cdot \text{dm}^{-3}$. The standard deviations for wastewater sampled after the first stage of biological treatment were as follows: BOD_5 —30.2 $\text{mgO}_2 \cdot \text{dm}^{-3}$, COD—32.9 $\text{mgO}_2 \cdot \text{dm}^{-3}$, TSS—28.8 $\text{mg} \cdot \text{dm}^{-3}$, TN—15.3 $\text{mgN} \cdot \text{dm}^{-3}$, TP—1.7 $\text{mgP} \cdot \text{dm}^{-3}$. The individual observations were highly varied and did not cluster around the means. The values of the coefficient of variation interpreted by Mucha's scale [62] additionally confirmed the high variation and diversity of COD, TN, and TP values, as well as the very high variation of BOD_5 and TSS values in the effluent from the VF bed.

3.1.3. Effluent from the HF Bed

The values of BOD_5 and COD in the wastewater discharged from the HF bed, i.e., wastewater that has gone through all the stages of the technological line, ranged from 0.5 to 15.0 $\text{mgO}_2 \cdot \text{dm}^{-3}$ and from 6.0 to 118.0 $\text{mgO}_2 \cdot \text{dm}^{-3}$, respectively. The mean value of BOD_5 was 5.2 $\text{mgO}_2 \cdot \text{dm}^{-3}$ and the mean COD value was 33.8 $\text{mgO}_2 \cdot \text{dm}^{-3}$. The concentration of total suspended solids in the effluent from the HF bed ranged from 2.0 to 33.6 $\text{mg} \cdot \text{dm}^{-3}$, with a mean of 12.7 $\text{mg} \cdot \text{dm}^{-3}$. Standard deviations in the wastewater after the second stage of biological treatment differed considerably among the individual pollution parameters: 5.5 $\text{mgO}_2 \cdot \text{dm}^{-3}$ for BOD_5 , 31.0 $\text{mgO}_2 \cdot \text{dm}^{-3}$ for COD, 12.6 $\text{mg} \cdot \text{dm}^{-3}$ for TSS, 8.2 $\text{mgN} \cdot \text{dm}^{-3}$ for TN, and 0.8 $\text{mgP} \cdot \text{dm}^{-3}$ for TP. Figure 4 shows changes in the concentrations of the studied parameters (BOD_5 , COD, TSS, TN, and TP) in wastewater outflowing from the treatment plant throughout the study period in relation to the standards in force in Poland [61] (red line), together with a trend line (dotted line). From the data presented in Figure 4A–E, it can be seen that the concentrations of pollutants in the outflow from the analyzed wastewater treatment plant usually decrease with the duration of the facility's operation.

The relatively low standard deviation values show that the individual observations were only slightly scattered and were mostly clustered around the means. According to Mucha's scale [62], these values showed that the variation of total phosphorus concentrations was moderate, whereas COD, TSS, and TN concentrations displayed a high variation, and BOD_5 had a very high variation.

The mean concentrations of the researched pollutants in treated wastewater were many times lower than the limits stipulated in the relevant Polish Regulation [61]. The facility provided sufficient treatment efficiency, bringing wastewater to a state in which it could be safely discharged into the environment without the risk of contamination.

The performance of hybrid constructed wetlands with the same bed configuration (VF-HF) has also been analyzed by other authors. Jóźwiakowski [26] and Marzec et al. [44] obtained similar or slightly higher mean values of the basic pollution parameters in wastewater discharged from the treatment plants they investigated than those reported in this study. The researchers achieved the following results: BOD_5 —11.1 $\text{mgO}_2 \cdot \text{dm}^{-3}$, COD—36.9 $\text{mgO}_2 \cdot \text{dm}^{-3}$, TSS—16.4 $\text{mg} \cdot \text{dm}^{-3}$ [26], and BOD_5 —6.6 $\text{mgO}_2 \cdot \text{dm}^{-3}$, COD—31.8 $\text{mgO}_2 \cdot \text{dm}^{-3}$ and TSS—18 $\text{mg} \cdot \text{dm}^{-3}$ [44]. At the same time, their readings for nutrients were substantially different from those obtained in this paper. They observed significantly higher mean concentrations of total nitrogen and total phosphorus in wastewater samples from each treatment stage (effluent from the settling tank, the VF bed, and the HF bed). The mean concentrations of TN and TP in treated wastewater discharged into the environment were respectively 53.0 $\text{mgN} \cdot \text{dm}^{-3}$ and 6.4 $\text{mgP} \cdot \text{dm}^{-3}$ [26] and

56.4 mgN·dm⁻³ and 6.7 mgP·dm⁻³ [44], i.e., they were several times higher than those recorded in Krajanów. It can be surmised that the lower concentrations of nutrients observed in this study were an effect of the ecological attitude of the owners of the building in which the sewage was produced. They declared that they paid special attention to the quality of the cleaning products they used and chose detergents with a reduced content of phosphorus compounds.

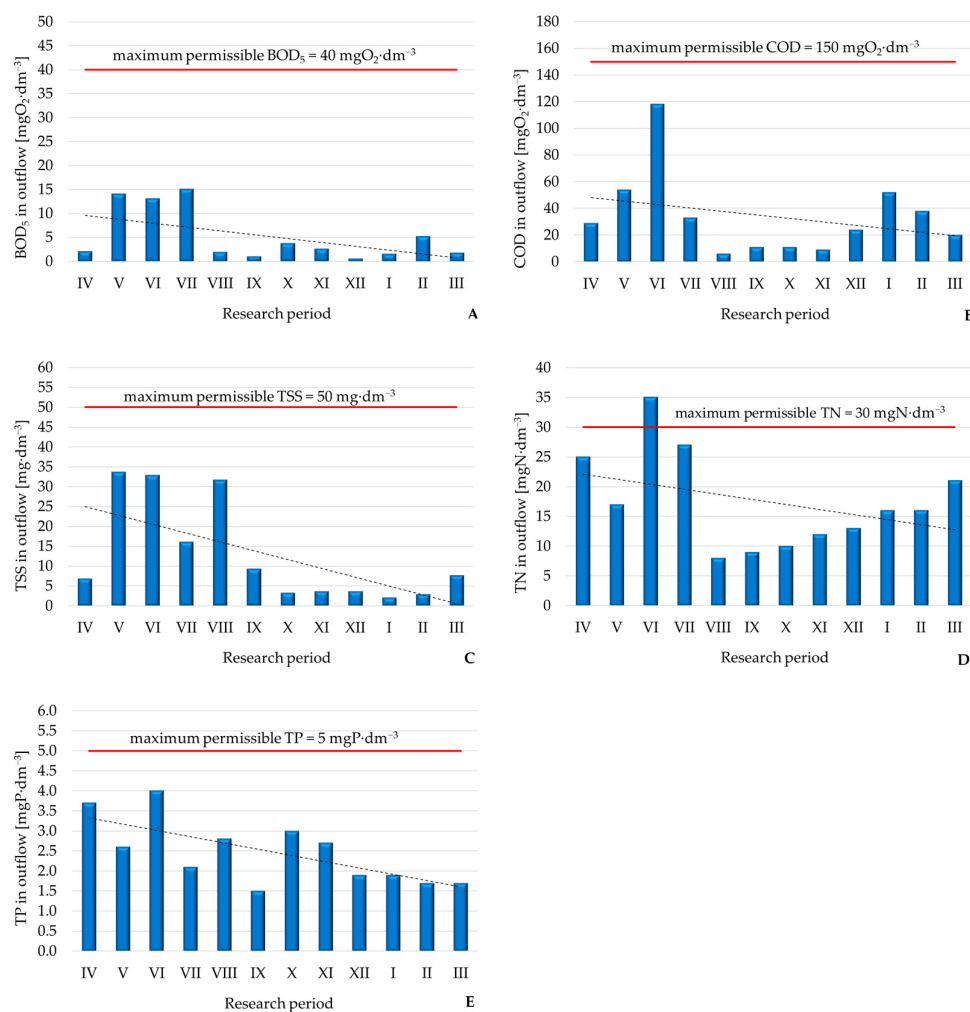


Figure 4. Values of pollution indicators in the outflow from the studied facility during the study period (April 2021–March 2022): (A)—BOD₅, (B)—COD, (C)—TSS, (D)—TN, (E)—TP.

Different observations were made by Lavrić et al. [75], who investigated a VF-HF hybrid constructed wetland located in Italy. Despite the fact that in their study, the wastewater supplied to the wetland beds had higher contents of nutrients in comparison to the wastewater discharged from the treatment plant in Krajanów, the wastewater discharged from that Italian treatment plant contained lower concentrations of total nitrogen and total phosphorus, i.e., on average 4.0 mgN·dm⁻³ and 0.75 mgP·dm⁻³. The VF and HF beds in the facility investigated by Lavrić et al. [75] were vegetated with a different plant species (*Phragmites australis*) and filled with a different material than the beds in Krajanów. This could have contributed to the better removal of nutrients from wastewater in the Italian treatment plant.

3.2. Pollutants Removal Efficiency

As shown in the previous sections, the efficiency of the removal of the analyzed pollutants from wastewater varied depending on the wastewater flow regime in the soil–

plant bed (vertical flow or horizontal flow). Figure 5 compares the mean removal efficiencies for the individual pollution indicators recorded in the two wetland beds of the investigated facility. In addition, the chart illustrates the values of the standard error of the mean, that is, the deviation of individual measurement results from the mean values.

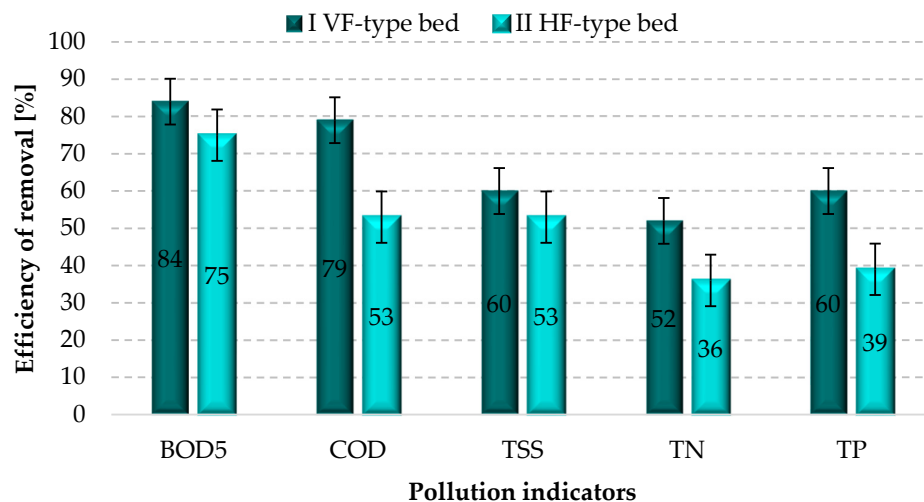


Figure 5. Mean pollutants removal efficiencies for the VF and the HF beds.

The pollutant removal efficiency in the VF bed was assessed by comparing the values of the pollution parameters measured in this bed with the values of these parameters in the mechanically treated effluent. The VF bed enabled the elimination of 84% BOD₅, 79% COD, 60% TSS, 52% TN, and 62% TP.

The quality of wastewater treated in VF beds has been analyzed, among others, by Brix and Arias [35]. They recorded the following levels of the reduction coefficient: 92% BOD₅, 91% TSS, 43% TN, and 25% TP. The differences in the efficiency of organic pollutants removal between the facility studied by Brix and Arias [35] and the one analyzed in the present study may be due to differences in the depth of the wetland beds: the bed in the Danish study was 1.4 m deep, and the bed in Krajanów was 0.8 m deep. The thickness of the filtration layer in Krajanów was smaller, and so the time when sewage had contact with the material filling the bed was shorter, which is probably why the bed had a lower efficiency of organic pollutants removal.

The pollutants removal efficiency in the second HF bed was calculated by comparing the values of the pollution indicators in the effluent from this bed to the corresponding values obtained in the effluent of the VF bed. It was observed that the HF bed, on average, ensured the following reduction coefficients: BOD₅—75%, COD—53%, TSS—53%, TN—36%, and TP—39%. All the pollutants analyzed, both the basic ones (BOD₅, COD, total suspended solids) and the biogenic ones (total nitrogen and total phosphorus), were more efficiently removed in the first wetland bed with the vertical sewage flow regime than in the second, in which wastewater flow horizontally (Figure 5).

Other authors have also studied hybrid systems with the same bed configuration (VF-HF). Marzec et al. [44] reported that the average level of elimination of the individual pollutants in the HF bed they tested was: BOD₅—64%, COD—54%, TSS—54%, TN—32%, TP—44%. These results were similar to those obtained for the treatment plant in Krajanów. In the study carried out by Józwiakowski [26], the HF bed allowed to reduce the levels of basic pollutants by 36%—BOD₅, 31%—COD, and 26%—TSS. The efficiency of that bed was then nearly twice smaller than that of the HF bed in Krajanów, which was probably due to the smaller depth of the wetland bed [26]. The mean nutrient removal efficiencies in Józwiakowski's study [26] were similar to the ones recorded in Krajanów, i.e., 28% TN and 36% TP.

Lavrnić et al. [75], who also investigated a VF-HF hybrid constructed wetland wastewater treatment plant, showed that the first bed with vertical sewage flow ensured the elimination of 70.4% COD, 80.4% TSS, 49.3% TN, and 47.3% TP, i.e., it was much more efficient than the first VF bed in the treatment plant described in this study. The same situation was also observed in the second bed, with horizontal sewage flow. In the study of Lavrnić et al. [75], the HF bed allowed of the removal of 40.1% of COD, 72.7% of TSS, 88.8% of TN, and 88.5% of TP. The authors investigated the facility after a 4-month start-up period and not immediately after it had been constructed, as was the case with the treatment plant in question. It can be presumed that the wetland beds in Krajanów had not been fully run-in yet, which resulted in a slightly lower pollutant removal efficiency. Probably, had the observations of the treatment plant been continued, there would have been an improvement in the efficiency of its operation in successive years.

Many years of studies of various constructed wetlands in Poland and around the world have demonstrated that systems with several soil-plant beds and different wastewater flow regimes show a higher efficiency of pollutants removal, both organic and biogenic, than single-stage systems [26,27,43,45,46,48,50,51].

The final evaluation of the performance of a wastewater treatment plant is assessed for the facility as a whole, i.e., the elimination of individual pollutants is measured in samples of wastewater that have passed through all the stages of treatment. Figure 6 shows the removal efficiency ranges for the individual pollutants during the entire study period for wastewater that was processed through the entire technological line of the analyzed facility. The points indicate the mean level of individual pollutant removal efficiency; additionally, the minimum and maximum efficiency values are shown. In the present study, very high basic contaminant removal efficiency values were obtained at all stages of treatment. The reduction coefficient for BOD₅ ranged from 75 to 99.5%, and the mean value was 95%. Similar results were obtained for COD, whose value decreased by 73 to 98%, with a mean of 89%. The efficiency of total suspended solids removal ranged from 54 to 95%, with a mean of 81%. Biogenic pollutants were removed at a slightly smaller level, but still satisfactory. The level of total nitrogen removal ranged between 29 and 81%, with a mean of 66%. Total phosphorus was eliminated more efficiently; the removal efficiency ranged from 59 to 91%, with a mean of 76%.

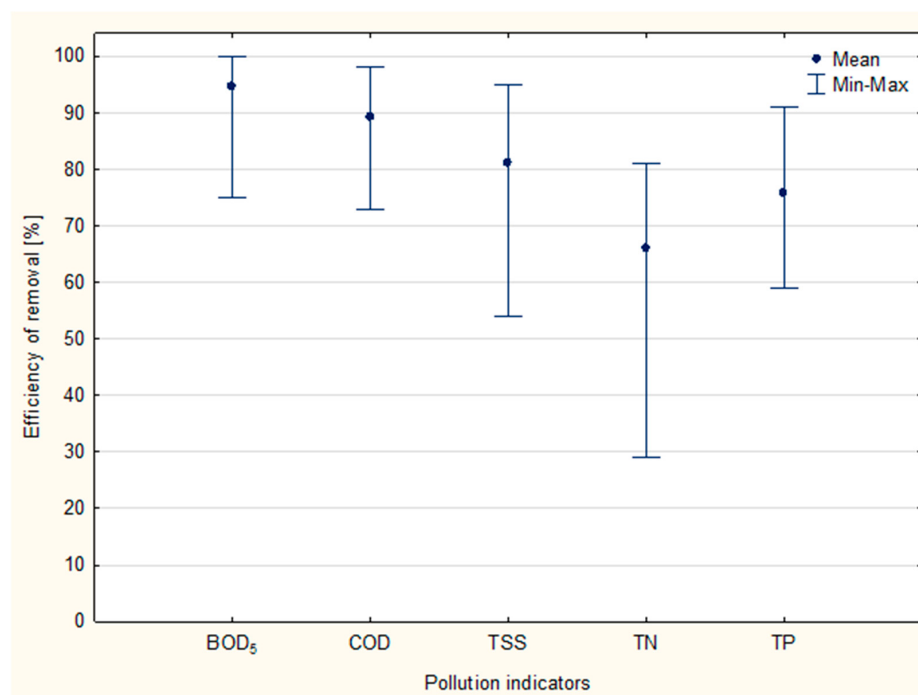


Figure 6. Pollutants removal efficiency in the wastewater treatment plant in Krajanów.

The tests conducted showed that the constructed wetland wastewater treatment plant in Krajanów treated wastewater with a high efficiency, similar to that obtained in some other facilities of this type (hybrid VF-HF systems) operating in Poland and around the world. Table 3 summarizes the mean values of removal efficiencies for the individual basic and biogenic pollutants in various VF-HF hybrid constructed wetlands.

Table 3. Mean pollutant removal efficiencies in some VF-HF hybrid constructed wetlands described in literature.

A VF-HF Constructed Wetland	Mean Pollutants Removal Efficiency [%]				
	BOD ₅	COD	TSS	TN	TP
Paistu, Estonia [49]	91	-	78	63	89
South Korea [50]	99	98	99	68	72
Gran Canaria, Canary Islands, Spain [51]	86	80	86	88	24
Tylicz, Poland [42]	97	95	84	67	-
Janów, Poland [26]	96	94	89	66	95
Skorczyce, Poland [44]	99	98	94	64	68
Florianka, Poland [46]	98	96	87	86	94
various VF-HF facilities, Poland [45]	97	94	92	65	89
KRAJANÓW, POLAND	95	89	81	66	76

When the pollutants elimination levels obtained in the present study are compared to those recorded in other facilities, it should be noted that the constructed wetland in Krajanów seems to be slightly less efficient in individual pollutants removal than most wastewater treatment systems operating in Poland and around the world. It is worth emphasizing, however, that unlike in most of the articles reviewed, in this study, the quality of treated wastewater discharged from the treatment plant was not compared to the quality of raw sewage but to sewage that had been treated mechanically in a settling tank before it was supplied to the first VF bed. Hence, the smaller differences in the pollution parameter values/concentrations of pollutants between the influent and the effluent wastewater in the studied facility. The lower pollutant removal efficiency in the treatment plant in Krajanów may also have been due to the fact that it had only been put into use for a short time before the study. The analyses of wastewater from this facility were conducted in the first year of its operation, immediately after it had been built, i.e., in the so-called start-up period. Literature reports show that in order to achieve their maximum pollutant removal efficiency, constructed wetlands require a longer “run-in” period during which the plants growing in the beds can fully develop their root systems [76].

3.3. Atmospheric Air Temperature and Temperature in the HF Bed

The main goal of the present study was to determine the effect of the air temperature and the temperature in the HF bed on the efficiency of organic and biogenic pollutants removal. To this end, the variability of bed temperature as a function of air temperature was analyzed. Figures 7 and 8 show diagrams of monthly variations of the air temperature and the temperature in the second HF bed during the study period. Median values are marked with dots, and the ranges between the minimum and maximum values recorded in each month of the study are shown. Additionally, the red line marks the temperature of 0 °C.

Over the twelve months of the study, significant fluctuations in average daily air temperature and much smaller monthly temperature amplitudes in the HF bed were observed. During that whole year, there was not a single day with an average daily bed temperature below 0 °C, which means that the wastewater flowing through the bed was never directly exposed to freezing.

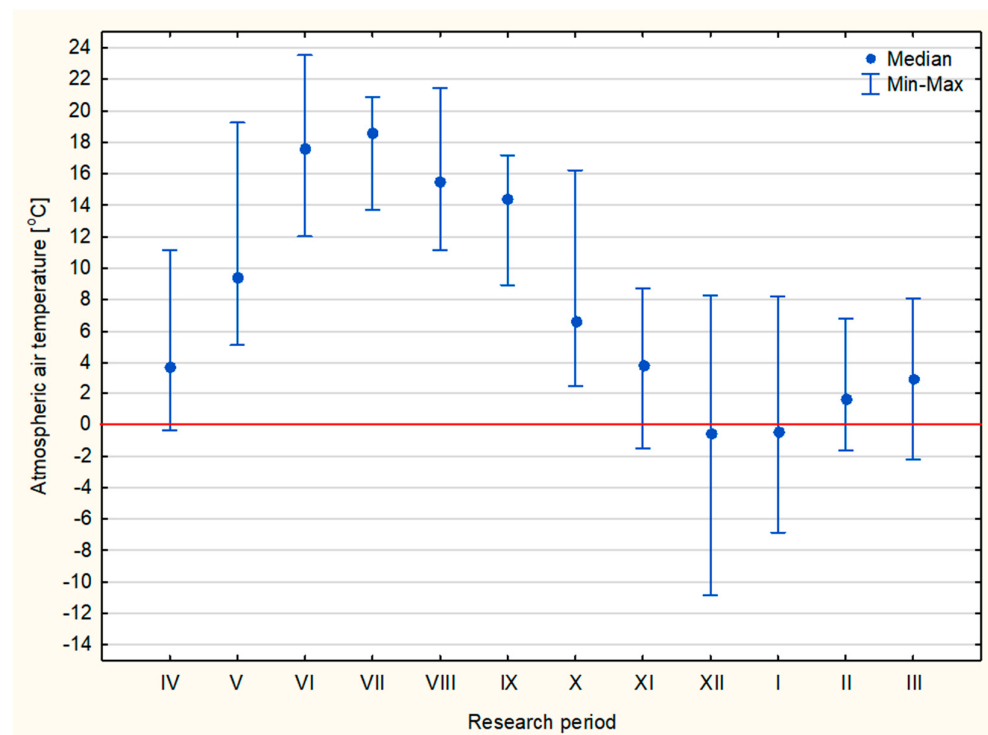


Figure 7. Range of variation of the air temperature during the study period (April 2021–March 2022).

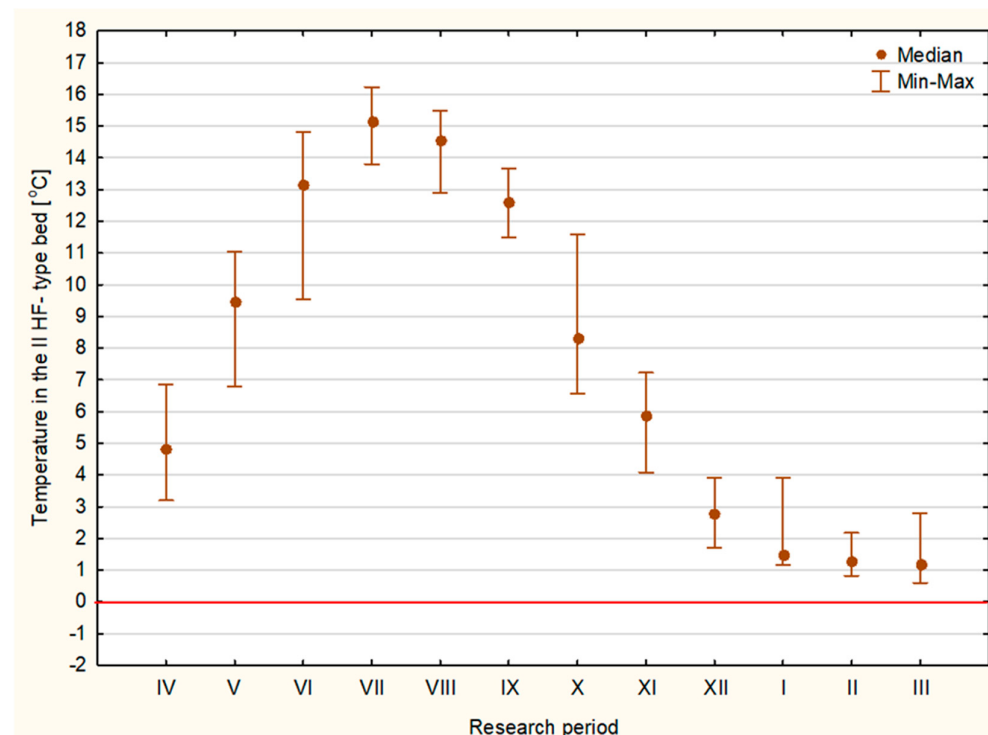


Figure 8. Range of variation of the temperature in the HF bed during the study period (April 2021–March 2022).

To determine the effect of the air temperature (an independent variable) on the temperature of the HF bed (a dependent variable), a correlation between the two parameters was calculated. The conducted analysis indicated there was a strong association, as evidenced by the value of the Pearson's linear correlation coefficient ($r_{x,y} = 0.91$). The Student's *t*-test demonstrated that the correlation was statistically significant at the significance level α

= 0.05. The scatterplot in Figure 9 shows the individual data points, the regression line (solid line), and the confidence interval range (significance level $\alpha = 0.05$) (dashed line). A linear regression equation was also generated, which showed that as the air temperature increased by 1 °C, the temperature inside the HF bed also grew by 0.64 °C. The coefficient of determination, R^2 , was 0.82, which means that the regression line fit the data very well. These findings demonstrate that one can effectively predict the temperature in the wetland bed on the basis of the air temperature using the generated regression equation.

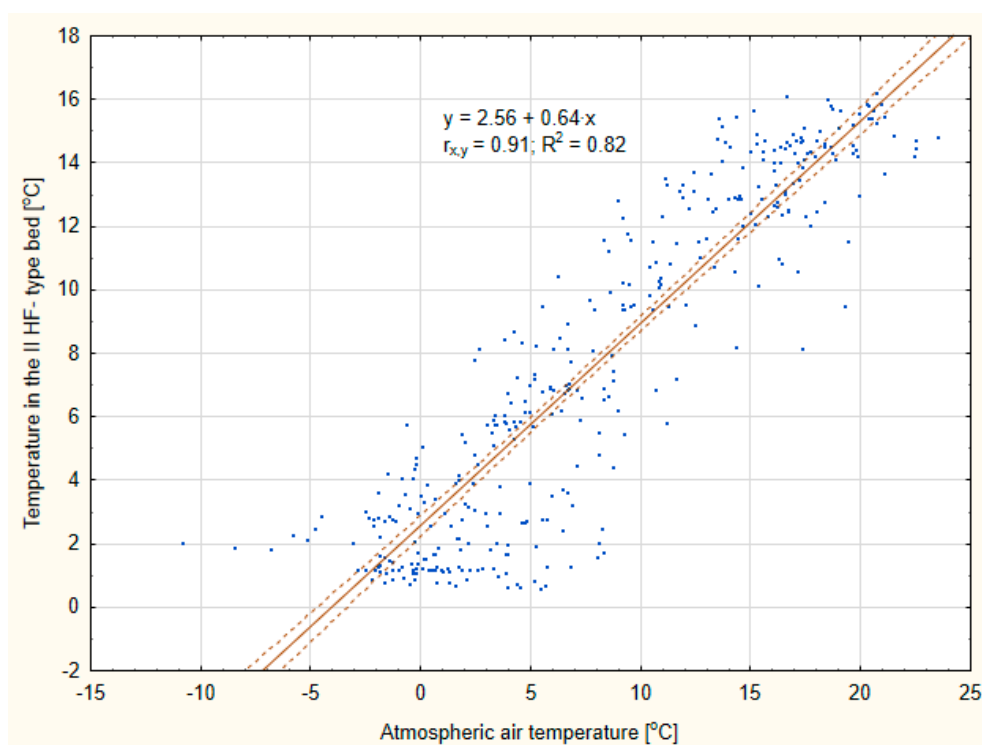


Figure 9. Scatter plot and correlation between the air temperature and the temperature inside the HF bed.

Table 4 shows Pearson's linear correlation coefficients $r_{x,y}$, which represent the correlation relationships between the efficiency of the investigated pollutants removal with the air temperature and the temperature in the HF bed.

Table 4. Pearson's linear correlation coefficients measure the dependency of the values of the analyzed pollution parameters on the air temperature and the temperature of the HF bed.

Removal Efficiency for Individual Pollution Indicator	Temperature [°C]	
	Atmospheric Air	HF Bed
BOD ₅	−0.13	−0.22
COD	0.14	0.29
TSS	−0.03	0.12
TN	0.07	0.17
TP	0.05	−0.01

The absolute values for all the correlation coefficients $r_{x,y}$ were lower than 0.30, which means that the correlations were weak. Also, they were statistically non-significant at the significance level $\alpha = 0.05$. These findings demonstrate that the removal efficiency of both basic (BOD₅, COD, and total suspended solids) and biogenic pollutants (total nitrogen and total phosphorus) in the investigated treatment plant did not depend either on the air temperature or the temperature of the soil-plant bed. Thus, the research hypothesis was

disproven, and it was demonstrated that the tested and constructed wetland wastewater treatment plant operated similarly across seasons regardless of the air temperature.

Other authors have also analyzed the influence of air temperature on the operation of constructed wetlands in Poland [26,42,57,77–83]. They did not notice a clear effect of low temperatures in the winter season on the efficiency of reducing the values of BOD₅ and COD or the removal of total suspended solids. However, as some experiments demonstrate, at lower air temperatures, sewage treatment plants based on various technologies show poorer performance when it comes to the removal of nutrients. It has been observed that the processes of nitrogen removal from sewage are more efficient in warmer periods of the year as the wastewater temperature increases [84–86]. Mietto et al. [87] explored seasonal changes in the rate of elimination of various forms of nitrogen in a VF-HF hybrid constructed wetland. They observed a linear relationship between air temperature fluctuations and the efficiency of the processes of nitrification and nitrogen compound removal. The reduction coefficient was clearly lower in the winter months (January, February, and March). Kuslu [88] examined a constructed wetland with a VF bed operating in cold climate conditions in Turkey. In winter, the wastewater distribution pipelines froze, which prompted a search for solutions to protect the bed against the adverse influence of weather conditions. Güneş [89] pointed out that in a cold climate, a HF wetland bed should be properly insulated against the cold. The bed achieved a higher pollutant removal efficiency when it was covered with a layer of plant waste (e.g., straw), dead leaves of the plants growing in the bed, and snow cover.

3.4. Pollutants Removal Reliability

In order to fully assess the operation of a wastewater treatment plant, it is necessary to determine not only its efficiency, but also its operational reliability. Table 5 lists the values of three parameters that were used to describe the operational reliability of the hybrid constructed wetland wastewater treatment plant.

Table 5. Reliability indicators for the hybrid constructed wetland in Krajanów.

Indicator	RF [-]	P _{SW} [-]	R _S [-]
BOD ₅	0.13	1.00	0.00
COD	0.23	1.00	0.00
TSS	0.25	1.00	0.00
TN	0.58	0.92	0.50
TP	0.50	1.00	0.00

As the calculations show, the hybrid constructed wetland in Krajanów ensured very high reliability in the removal of the basic pollutants from wastewater. The best reliability (the lowest value of the reliability factor RF) was achieved for BOD₅, with the mean value of this parameter in treated wastewater discharged into the environment being almost 8 times lower than the limit stipulated in the relevant legal act. The highest value of the RF factor was obtained for total nitrogen (RF = 0.58), i.e., the mean concentration of TN in the wastewater discharged from the treatment plant was the closest to the limit value specified in the regulation in force in Poland [61].

As for wastewater treatment performance, the facility in Krajanów achieved the maximum level of wastewater treatment technological efficiency (P_{SW} = 1.00) when it came to the elimination of all the basic pollutants (BOD₅, COD, and total suspended solids) and total phosphorus, i.e., all the tested samples of treated wastewater met the conditions for discharging treated sewage to a receiver. In the case of total nitrogen, one exceedance of the concentration limit was recorded, which corresponded to a slightly lower technological efficiency level of 0.92.

An analysis of the risk of negative assessment of the wastewater treatment plant operation showed that for all the basic pollutants values (BOD₅, COD, total suspended solids) and for the concentrations of total phosphorus, the probability of exceeding the permissible limit in

treated wastewater discharged into the environment was zero ($R_S = 0.00$). For total nitrogen, only one case of exceedance of the limit concentration in treated wastewater was recorded, which meant the risk of negative assessment of the wastewater treatment plant operation in the case of this biogenic contaminant was 0.50.

4. Conclusions

The researched hybrid VF-HF constructed wetland wastewater treatment plant showed high mean rates of pollutants removal efficiency: BOD₅—95%, COD—89%, total suspended solids—81%, total nitrogen—66%, and total phosphorus—76%. The mean values/concentrations of pollution indicators in treated wastewater were as follows: BOD₅—5.2 mgO₂·dm^{−3}, COD—33.8 mgO₂·dm^{−3}, TSS—12.7 mg·dm^{−3}, TN—17.4 mgN·dm^{−3}, TP—2.5 mgP·dm^{−3}. These values were much lower than the required limits stipulated in the legal act currently in force in Poland.

In the analyzed facility, no statistically significant effect of the air temperature or the constructed wetland bed temperature on the pollutant removal efficiency was found. This indicates that treatment plants of this type can be successfully used in the climatic conditions of southern Poland. During the research period, the temperature in the HF bed did not fall below 0 °C, and so the wastewater flowing through the bed did not freeze. This shows that it is not necessary to lower the level of wastewater in soil-plant beds in winter. The unchanging wastewater flow conditions in the beds allow of high rates of pollutant removal efficiency throughout the year.

It was found that the analyzed wastewater treatment plant had no risk of exceeding (R_S) concentration limits in treated sewage when it comes to the pollutants from the basic group (BOD₅, COD, total suspended solids) and total phosphorus and achieved the maximum level of technological efficiency of wastewater treatment (P_{SW}) in terms of elimination of these pollutants. In the one-year study period, only one case of exceedance of the limit concentration of total nitrogen in the effluent from the facility was observed. The reliability factor RF reached the following values: BOD₅—0.13, COD—0.23, TSS—0.25, TN—0.58, and TP—0.50.

Given their high efficiency and reliability in removing organic and biogenic pollutants from wastewater, hybrid constructed wetland systems can be successfully used as household wastewater treatment systems in areas where no centralized sewage systems are planned to be built. Also, their specific features and low operating costs make them a perfect wastewater treatment option. This paper indicated that the studied wastewater treatment technology can also be used in the climatic conditions of mountainous areas.

Author Contributions: Conceptualization, K.J. and P.B.; methodology, K.J. and P.B.; software, K.J. and P.B.; validation, K.J. and P.B.; formal analysis, K.J. and P.B.; investigation, K.J.; resources, K.J. and P.B.; data curation, K.J. and P.B.; writing—original draft preparation, K.J.; writing—review and editing, K.J. and P.B.; visualization, K.J.; supervision, K.J. and P.B.; project administration, K.J. and P.B.; funding acquisition, K.J. and P.B. All authors have read and agreed to the published version of the manuscript.

Funding: The study was conducted with a subsidy from the Ministry of Science and Higher Education in Poland for the University of Agriculture in Kraków in 2021–2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to cordially thank the Polish 2018 Nobel Prize Winner, Olga Tokarczuk, for making the research object available for experiments. Moreover, special thanks go to Karolina Hap, an employee of the Department of Sanitary Engineering and Water Management at the University of Agriculture in Kraków, for her support in analyzing the samples during the study, which was carried out at the Water and Wastewater Quality Testing Laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

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