

## The efficiency and reliability of pollutant removal in a hybrid constructed wetland with giant miscanthus and Jerusalem artichoke in Poland

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### ABSTRACT

In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of  $1.2 \text{ m}^3 \cdot \text{d}^{-1}$ . The tests were carried out during 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage samples were collected from three stages of wastewater treatment in four seasons (winter – February, spring – May, summer – August, and autumn – November). The following parameters were measured: BOD<sub>5</sub>, COD, total suspended solids, total nitrogen, and total phosphorus. The average effectiveness of organic pollutant removal expressed by BOD<sub>5</sub> and COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids was 93%. The average values of BOD<sub>5</sub>, COD, and total suspended solids in wastewater discharged to the receiver were significantly lower than the limit values required in Poland. The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%, respectively, and the average values of these components in the outflow from the treatment plant exceeded the standard levels. A reliability analysis performed using the Weibull probability model showed that the reliability of pollutant removal in the tested CW system was very high for BOD<sub>5</sub> and COD (100%). It was also demonstrated that the tested CW did not provide effective elimination of biogenic elements (nitrogen and phosphorus), as evidenced by the low reliability values – 32 and 28%, respectively. The investigated hybrid CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic pollutants with a similar efficiency as systems using classic plant species such as reed and willow.

**Key words:** wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal flow, pollutant removal, efficiency and reliability

## 40 **1. Introduction**

41 Domestic wastewater treatment plants are an optimal solution for the disposal of small  
42 amounts of wastewater in areas of dispersed development, where the construction of a sewage  
43 system is economically unjustified (García et al., 2013; Mikosz and Mucha, 2014;  
44 Józwiakowski et al., 2015). Issues related to the operational reliability of low capacity  
45 treatment plants below  $5 \text{ m}^3 \cdot \text{d}^{-1}$  are still rarely brought up due to the lack of precise  
46 requirements regarding the application of various technological solutions for home sewage  
47 treatment plants and their control during operation. Such a situation is not conducive to the  
48 creation and implementation of new, effective technologies. On the contrary, it favours the  
49 cheapest solutions, mainly systems with a leach drain, which are used for discharging  
50 untreated wastewater into the ground, and therefore, their application for waste water  
51 treatment raises serious questions (Józwiakowski et al., 2015, Zhang et al., 2015). Moreover,  
52 many solutions applied in small sewage treatment plants, including those based on  
53 conventional methods, in conditions of high variability of hydraulic load, pollution load and  
54 operating conditions do not guarantee high efficiency of removal of pollutants from sewage  
55 (Marzec, 2017). With a constant increase in the number of ineffective technological solutions  
56 applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawelek  
57 and Bugajski, 2017).

58 Therefore, the reliability of small sewage treatment plants should be an important criterion  
59 in planning the development of technical infrastructure in rural areas, which will enable the  
60 selection of optimal and environmentally safe solutions (Józwiakowski et al., 2015; Jucherski  
61 et al., 2017). There are more and more suggestions that all treatment plants, regardless of their  
62 size and type of receiver, should be placed under the control of competent authorities. At the  
63 same time, the popularity of constructed wetland systems, which can be used in various  
64 conditions, including protected areas and areas of high landscape value, is increasing due to  
65 their high pollutant removal efficiency (Vymazal, 2011; 2013; Józwiakowski, 2012; Paruch et  
66 al., 2011; Józwiakowski et al., 2017; Gajewska et al., 2015).

67 Constructed wetlands, and in particular hybrid treatment plants consisting of at least two  
68 beds with different sewage flows (vertical and horizontal), ensure effective removal of organic  
69 matter ( $\text{BOD}_5$  and COD) (Vymazal, 2011) and slightly less effective removal of nutrients  
70 (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in  
71 constructed wetland systems is related to the functioning of the biological membrane formed  
72 during the flow of wastewater through the material filling the beds. The plants growing in the  
73 wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and



74 Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated  
75 microenvironment, while other layers of the bed provide anaerobic or anoxic conditions.  
76 Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its  
77 structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different  
78 plant species have been used in constructed wetland systems, mainly common reed and  
79 willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite  
80 intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the  
81 possibility of using constructed wetland systems not only for wastewater treatment, but also  
82 for biomass production for energy purposes (Cerbin et al., 2012; Posadas et al., 2014; Lu and  
83 Zhang, 2013). In this respect, research on the use of other plants, e.g. giant miscanthus or  
84 Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al.,  
85 2016). The high energy potential of these plants is a result of high yield and biomass calorific  
86 value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy  
87 et al., 2009; Long et al., 2010). In European conditions, the yield of giant miscanthus in field  
88 cultivation ranges from 10 to 30 Mg DM·ha<sup>-1</sup> (Szulczewski et al., 2018), and Jerusalem  
89 artichoke from 9 to 25 Mg DM·ha<sup>-1</sup> (Baldini et al., 2004; Gunnarsson et al., 2014). The  
90 calorific value of dried biomass of giant miscanthus varies from 14 to 17 MJ·kg DM<sup>-1</sup>, and for  
91 Jerusalem artichoke varies from 15 to 19 MJ·kg DM<sup>-1</sup> (Szulczewski et al., 2018;  
92 Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less  
93 recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used  
94 in constructed wetland systems yet, while research on the use giant miscanthus has been  
95 carried out on a pilot scale and under warm climate conditions. Their results indicate that the  
96 efficiency of pollutants removal in the beds planted with giant miscanthus may be similar to  
97 those found in the case of classical plant species, including common reed (Toscano et al.,  
98 2015; Barbagallo et al., 2014).

99 The aim of the present study is to analyse the reliability and effectiveness of pollutant  
100 removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus  
101 (*Miscanthus giganteus* x Greif et Deu) and Jerusalem artichoke (*Helianthus tuberosus* L.)  
102 during five years of its operation.

103

## 104 **2. Materials and methods**

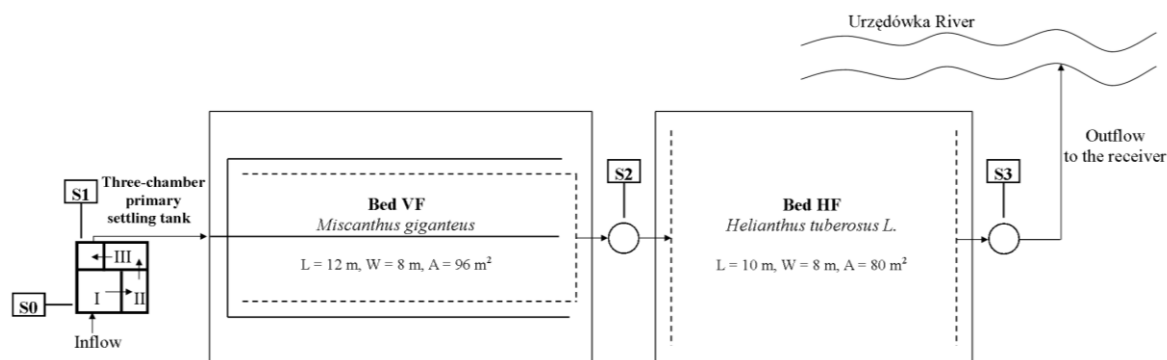
### 105 **2.1. Characteristics of the experimental facility**

106 The analysed plant is located in Skorczyce, Poland (51°00'36"N, 22°11'51"E). Its task is to  
107 treat domestic sewage from a multi-family building. The plant has been in operation since



2011 and its planned capacity is  $2.5 \text{ m}^3 \cdot \text{d}^{-1}$ . In the analyzed system, sewage from the building was drained into a three-chamber preliminary settling tank, where it was pre-treated in physical and biological processes.

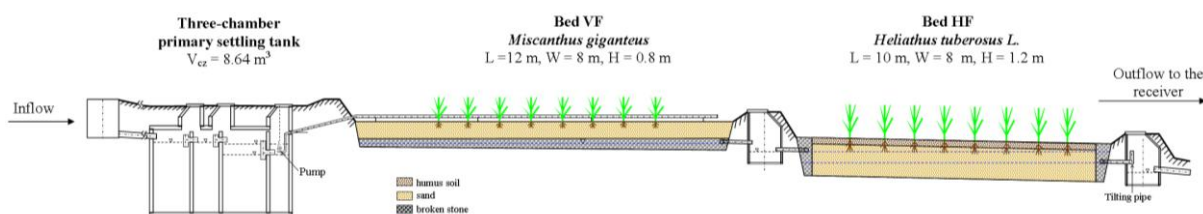
The tank is made of concrete, and its active capacity is  $8.64 \text{ m}^3$ . In the next stage, the sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). A first bed, with vertical sewage flow (VF), has an area of  $96 \text{ m}^2$  and a depth of  $0.8 \text{ m}$ , and the second bed, with horizontal sewage flow (HF), has an area of  $80 \text{ m}^2$  and a depth of  $1.2 \text{ m}$ . The beds have been isolated from the native soil by a PEHD waterproofing geomembrane of  $1 \text{ mm}$  thickness. The VF bed was filled with a layer of sand ( $1\text{-}2 \text{ mm}$ ) with a height of about  $0.8 \text{ m}$ . The filling of the HF bed to the height of  $1.0 \text{ m}$  consisted of sand ( $1\text{-}2 \text{ mm}$ ), on which there was laid the humus soil layer with a height of  $0.2 \text{ m}$  and it was obtained during the construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant miscanthus (*Miscanthus x giganteus* Greef et Deu.), the second with Jerusalem artichoke (*Helianthus tuberosus* L.) (Photo 1). Every year, after the winter season, the aboveground plant shoots and part of the tubers (Jerusalem artichoke) are removed from the fields. The recipient of the treated wastewater is the Urzędówka River (Figures 1, 2).



**Fig. 1.** Technological scheme of the tested VF-HF constructed wetland system

(Gizińska-Górna et al., 2012; 2017a)

Notation: S0, S1, S2, S3 – sampling points



**Fig. 2.** Longitudinal profile of the tested VF-HF constructed wetland system

(Gizińska-Górna et al., 2012)



132  
133 **Photo 1.** Hybrid constructed wetland, VF-HF type, with giant miscanthus (on the left) and  
134 Jerusalem artichoke (on the right) (Józwiakowski, 2016)  
135

136 During the study period, the amount of wastewater discharged to the treatment plant  
137 represented only about half of the design value, as the actual number of inhabitants served by  
138 the plant had decreased since its construction. The amount of sewage inflow to the treatment  
139 plant was determined on the basis of water meters readings in the building and average water  
140 consumption. In addition, the amount of sewage introduced into the VF-HF system was  
141 measured by using a flow meter installed on the discharge pipe between the preliminary  
142 settling tank and the VF bed. The average inflow of wastewater during the tests was  
143  $1.2 \text{ m}^3 \cdot \text{d}^{-1}$ , and the hydraulic load of the first bed was  $12.5 \text{ mm} \cdot \text{d}^{-1}$ . Mechanically treated  
144 wastewater was pumped into the first bed (VF) twice a day, about  $0.6 \text{ m}^3$  each time, and then  
145 it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow  
146 from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this  
147 field during summer. Theoretical wastewater retention time was determined on the basis of the  
148 parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the  
149 height of the layer filled with sewage) and average daily wastewater inflow (Conley et al.,  
150 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed,  
151 the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d  
152 in the winter period.  
153

## 154 **2.2. Analytical methods**

155 The efficiency and reliability of pollutant removal in the analysed treatment plant in south  
156 eastern Poland were assessed based on influent and effluent wastewater data collected in the  
157 years 2011–2016 (5 years). Sewage samples were taken seasonally: in February, May, August  
158 and November, at four points of the plant: S0 – raw sewage from the first chamber of the  
159 preliminary settling tank, S1 – mechanically treated wastewater, S2 – wastewater flowing out



160 of the VF bed with giant miscanthus, S3 – wastewater flowing out of the HF bed with  
161 Jerusalem artichoke (Figure 1). In total, 20 measurement series were made.

162 The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen,  
163 nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS),  
164 biochemical oxygen demand (BOD<sub>5</sub>) and chemical oxygen demand (COD). The concentration  
165 of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and  
166 nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen  
167 was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter  
168 instrument was also used to determine total nitrogen after oxidation of the samples in a  
169 thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010  
170 spectrophotometer after oxidation of the samples at 120°C. BOD<sub>5</sub> was measured by the  
171 dilution method using WTW Multi 340i, and COD was estimated by the same method with a  
172 WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were  
173 determined by filtration through paper filters. Sampling, transport and processing of the  
174 samples and their analysis were carried out in accordance with Polish standards (PN-74/C-  
175 04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO  
176 6878:2006P; PB-01/PS; PN-EN 872:2007), which are in accordance with APHA (2005).

177 In addition, the yield and chemical composition of plant biomass from beds were  
178 determined. Plant material for biomass research was collected annually (starting from 2013) at  
179 the end of winter, February or March. The samples of plants were collected by hand from  
180 plots with an area of 1 m<sup>2</sup>. In plant samples, there were determined such characteristics as dry  
181 matter content by gravimetric method, after drying at 105°C (PN-EN ISO 18134-3:2015-11)  
182 and the content of some selected chemical components, including nitrogen and phosphorus  
183 (PN-EN 15104:2011; PN-EN ISO 6491:2000).

184

### 185 **2.3. Statistical analysis**

186 On the basis of the obtained results, characteristic values of pollution parameters in sewage  
187 from the three different treatment stages were determined, including average, minimum and  
188 maximum values, medians, standard deviations, and coefficients of variation. Additionally,  
189 the relative frequency of occurrence of the characteristic concentration levels of the tested  
190 parameters in the sewage flowing into the treatment plant was determined. The classes for  
191 each pollution parameter have been chosen to obtain a frequency distribution that would be  
192 as detailed as possible without affecting the clarity of the structure of the statistical collection.



193 On the basis of the average values of the pollution parameters in the incoming ( $C_{in}$ ) and  
194 outgoing ( $C_{out}$ ) wastewater, the average pollutant removal efficiency was calculated according  
195 to equation 1:

$$196 \quad \eta = 100 \left( 1 - \frac{C_{out}}{C_{in}} \right) [\%] \quad (1)$$

197 Additionally, the effectiveness of the tested hybrid system was analysed on the basis of  
198 mass removal rates ( $MRR$ ) of the main pollutants contained in wastewater.  $MRR$  values were  
199 determined from equation 2 (Gajewska and Obarska-Pempkowiak, 2011):

$$200 \quad MRR = \frac{C_{in} Q_{in} - C_{out} Q_{out}}{A} [\text{g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}] \quad (2)$$

201 where:  $A$  – surface area of the constructed wetland system [ $\text{m}^2$ ],  $Q_{in}$  and  $Q_{out}$  – average inflow  
202 and outflow of wastewater [ $\text{m}^3 \cdot \text{d}^{-1}$ ],  $C_{in}$  and  $C_{out}$  – average concentrations of pollutants in the  
203 wastewater flowing into and out of the system [ $\text{g} \cdot \text{m}^{-3}$ ].

204 The calculated indicators are theoretical, because they are based on the assumption that the  
205 outflow of sewage from particular elements of the treatment plant is equal to the inflow.

206 The technological reliability of the wastewater treatment plant in Skorczyce was assessed  
207 for the basic pollution parameters ( $\text{BOD}_5$ ,  $\text{COD}$ , total suspended solids, total nitrogen, and  
208 total phosphorus) using elements of Weibull's reliability theory. The Weibull distribution is an  
209 overall probability distribution used in reliability testing and assessment of the risk of  
210 exceeding the limit values for pollutant concentrations in treated wastewater (Bugajski, 2014;  
211 Jucherski et al., 2017; Jóźwiakowski et al., 2017; Bugajski et al., 2012; Jóźwiakowski et al.,  
212 2018). The Weibull distribution is characterised by the following probability density function:

$$213 \quad f(x) = \frac{c}{b} \cdot \frac{x-\theta}{b}^{(c-1)} \cdot e^{-\left(\frac{x-\theta}{b}\right)^c} \quad (3)$$

214 where:  $x$  – a variable describing the concentration of a pollution parameter in the treated  
215 effluent,  $b$  – scale parameter,  $c$  – shape parameter,  $\theta$  – position parameter.

216 Assuming:  $\theta < x$ ,  $b > 0$ ,  $c > 0$ .

217 The reliability analysis was based on the estimation of Weibull distribution parameters  
218 using the method of highest reliability. The null hypothesis that the analyzed variable could be  
219 described by the Weibull distribution was verified with the Hollander-Proschan test at the  
220 significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters  
221 in treated wastewater discharged to the receiver were analysed. Reliability was determined  
222 from the distribution figures, taking into account the normative values of the parameters  
223 specified in the Regulation of the Minister of the Environment (2014) for wastewater  
224 discharged from treatment plants of less than 2000 p.e.:  $\text{BOD}_5$  –  $40 \text{ mgO}_2 \cdot \text{dm}^{-3}$ ,  $\text{COD}$  –

225  $150 \text{ mgO}_2 \cdot \text{dm}^{-3}$ , total suspended solids –  $50 \text{ mg} \cdot \text{dm}^{-3}$ , total nitrogen –  $30 \text{ mg} \cdot \text{dm}^{-3}$ , and total  
226 phosphorus –  $5 \text{ mg} \cdot \text{dm}^{-3}$ . In the case of nitrogen and total phosphorus, the values defined for  
227 wastewater discharged into lakes and their tributaries and directly into artificial water  
228 reservoirs situated in flowing waters were adopted as standard values (Regulation of the  
229 Minister of the Environment, 2014). The analysis was carried out using Statistica 13 software.  
230

### 231 **3. Results and discussion**

#### 232 **3.1. Pollutant concentrations in treated wastewater**

233 The efficiency and reliability of pollution removal in the tested treatment plant in  
234 south-eastern Poland were determined on the basis of results of tests of mechanically treated  
235 sewage (S1) flowing into the VF-HF constructed wetland system and sewage treated in beds  
236 with vertical (S2) and horizontal (S3) flow. Characteristic values of the pollution parameters  
237 are presented in Table 1.

238 In addition, the quality of raw sewage flowing from the building to the primary settling  
239 tank (S0) was taken into account, but it was not the subject of the main analysis.  
240

#### 241 **Pollutant concentrations in sewage flowing into the treatment plant**

242 The average values of pollution indicators in raw sewage outflowing from the building to  
243 the preliminary settling tank were respectively:  $704 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for BOD<sub>5</sub>,  $1486 \text{ mgO}_2 \cdot \text{dm}^{-3}$   
244 for COD,  $710 \text{ mg} \cdot \text{dm}^{-3}$  for total suspended solids,  $172 \text{ mg} \cdot \text{dm}^{-3}$  for total nitrogen and  $23.5$   
245  $\text{mg} \cdot \text{dm}^{-3}$  for total phosphorus (Table 1). These values were clearly higher than those reported  
246 in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may  
247 have resulted from the fact that the majority of the building's inhabitants were unemployed  
248 people in a difficult financial situation. Due to the low standard of water and wastewater  
249 facilities and the need for economical water management, its unit consumption in the building  
250 was at a low level, which could result in an increase in the concentration of pollutants in the  
251 sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of  
252 physical processes, TSS content decreased by nearly 60%. At the same time, there was  
253 observed a decrease in the concentration of organic pollutants, expressed as BOD<sub>5</sub> (by 23%)  
254 and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%).  
255 Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank  
256 to the system of VF-HF beds was high. The average values of these parameters at this stage of  
257 treatment were:  $537 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for BOD<sub>5</sub>,  $1309 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for COD,  $297 \text{ mg} \cdot \text{dm}^{-3}$  for total  
258 suspended solids,  $157 \text{ mg} \cdot \text{dm}^{-3}$  for total nitrogen, and  $21.0 \text{ mg} \cdot \text{dm}^{-3}$  for total phosphorus





259 (Table 1). The pH value ranged from 6.67 to 7.94, and the concentration of dissolved oxygen  
 260 was in the range of 0.09 to 2.60, with the average concentration of 0.50 mg·dm<sup>-3</sup>. The average  
 261 contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated  
 262 wastewater were 136 mg·dm<sup>-3</sup>, 2.87 mg·dm<sup>-3</sup>, and 0.23 mg·dm<sup>-3</sup>, respectively. The recorded  
 263 values were significantly higher than those reported in the literature for mechanically treated  
 264 wastewater from single-family buildings (Jucherski et al., 2017; Józwiakowski et al., 2017;  
 265 Józwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water  
 266 consumption, leading to the formation of highly concentrated wastewater.

267

268 **Table 1.** Basic statistics for the indicator values in the treated wastewater (n = 20)

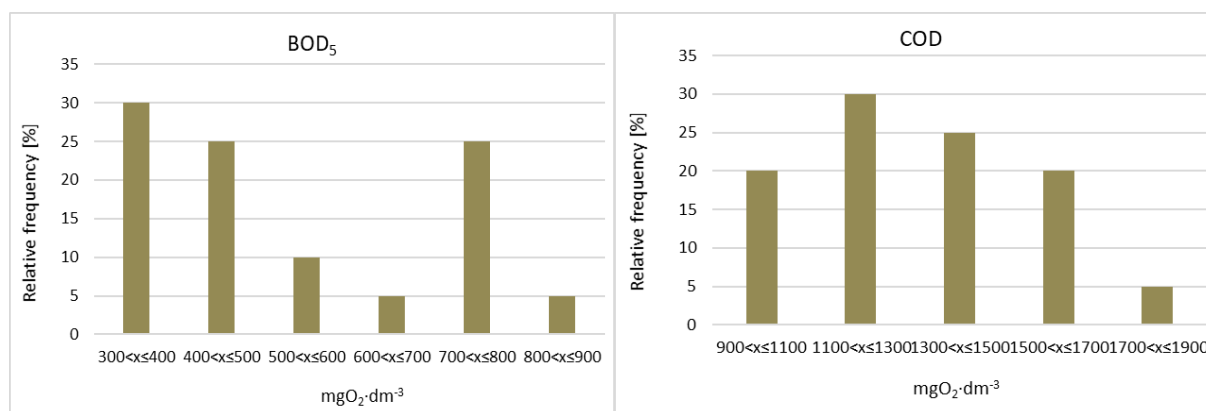
Parameters		Statistic					
		Average	Median	Min	Max	SD	Cv
Dissolved oxygen [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>0.35</b>	0.22	0.08	1.19	0.31	89.51
	S1	<b>0.50</b>	0.37	0.09	2.60	0.55	109.11
	S2	<b>2.92</b>	3.03	0.37	5.17	1.34	45.89
	S3	<b>5.58</b>	5.55	1.27	11.42	2.69	48.24
pH	S0	<b>7.26</b>	7.29	6.50	7.89	0.44	6.04
	S1	<b>7.17</b>	7.13	6.67	7.94	0.29	4.06
	S2	<b>7.10</b>	7.08	6.68	7.55	0.24	3.37
	S3	<b>7.47</b>	7.42	6.93	8.70	0.49	6.51
BOD <sub>5</sub> [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>704.0</b>	690.5	376.0	1262.0	202.9	28.82
	S1	<b>537.0</b>	471.0	310.0	862.0	172.4	32.10
	S2	<b>18.2</b>	16.3	1.8	58.0	15.1	82.60
	S3	<b>6.6</b>	3.1	0.1	36.9	9.1	137.40
COD [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>1486.9</b>	1485.0	990.0	1920.0	249.8	16.80
	S1	<b>1309.0</b>	1295.0	910.0	1740.0	237.4	18.08
	S2	<b>68.4</b>	52.0	11.0	170.0	43.4	63.52
	S3	<b>31.8</b>	29.0	8.0	81.0	20.3	63.83
TSS [mg·dm <sup>-3</sup> ]	S0	<b>710.9</b>	523.2	136.0	2052.0	520.4	73.20
	S1	<b>297.0</b>	235.0	60.0	1390.0	284.7	95.67
	S2	<b>39.0</b>	28.5	1.9	114.0	31.1	79.77
	S3	<b>18.0</b>	10.2	1.8	65.1	20.2	112.45
Total nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>172.3</b>	171.0	114.0	238.0	32.2	18.70
	S1	<b>157.0</b>	150.5	120.0	216.0	22.7	14.45
	S2	<b>82.4</b>	83.0	34.0	134.0	25.1	30.42
	S3	<b>56.4</b>	39.0	10.0	150.0	43.7	77.46
Ammonium nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>147.2</b>	139.5	47.0	230.0	42.7	29.02
	S1	<b>136.0</b>	134.5	43.0	204.0	31.3	23.06
	S2	<b>21.3</b>	18.2	1.6	65.2	18.7	87.77
	S3	<b>12.9</b>	3.8	0.1	47.1	16.4	127.44
Nitrate nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>2.11</b>	0.99	0.03	17.11	3.64	172.89
	S1	<b>2.87</b>	0.86	0.28	29.67	6.47	225.24
	S2	<b>24.48</b>	24.96	2.71	57.70	16.07	65.65
	S3	<b>20.25</b>	13.48	0.86	58.20	19.89	98.22

Nitrite nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>0.28</b>	0.270	0.08	0.471	0.15	55.07
	S1	<b>0.23</b>	0.19	0.08	0.43	0.13	56.71
	S2	<b>1.03</b>	0.73	0.06	4.04	1.02	98.99
	S3	<b>0.50</b>	0.13	0.03	3.62	1.00	198.99
Total phosphorus [mg·dm <sup>-3</sup> ]	S0	<b>23.5</b>	23.1	15.3	30.2	4.6	19.69
	S1	<b>21.0</b>	21.1	17.2	23.9	1.9	8.89
	S2	<b>12.0</b>	11.6	8.5	21.0	3.0	24.83
	S3	<b>6.7</b>	6.8	1.3	11.0	2.6	39.47

269 Notation: S0 – raw wastewater ;S1 - inflow to bed VF; S2 - outflow from bed VF; S3 - outflow from  
270 bed HF; SD - standard deviation; Cv - coefficient of variation, n - number of samples

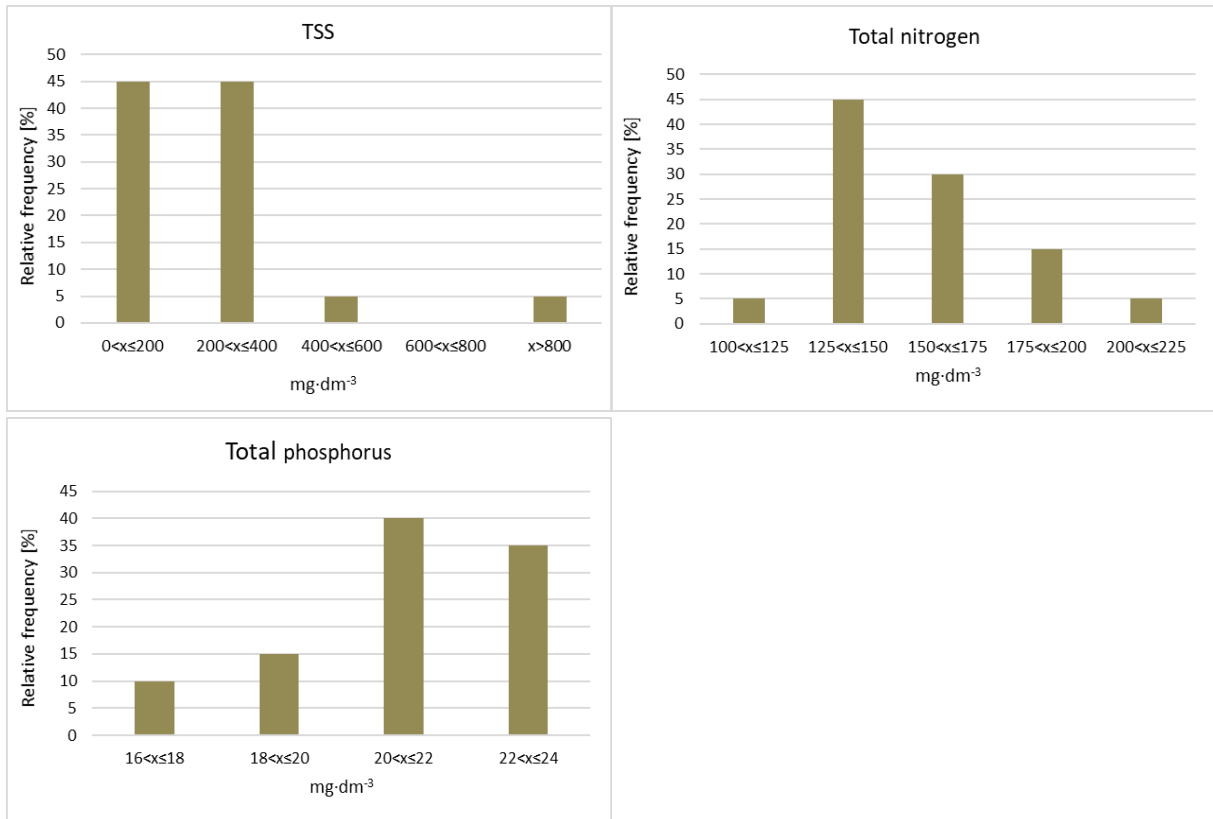
271  
272 Figure 3 shows nomograms of the frequency of occurrence of pollution parameter  
273 concentrations, grouped in different ranges. BOD<sub>5</sub> in the wastewater flowing into the hybrid  
274 VF-HF system did not fall below 300 mgO<sub>2</sub>·dm<sup>-3</sup> across measurements. The most common  
275 values were in the range of 300–400 mgO<sub>2</sub>·dm<sup>-3</sup> (30% of cases), 400–500 and 700–800  
276 mgO<sub>2</sub>·dm<sup>-3</sup> (25% each), and 500–600 mgO<sub>2</sub>·dm<sup>-3</sup> (10%). The COD values were very high and  
277 showed little volatility. In 30% of cases, the parameter was within the range of 1100–1300  
278 mgO<sub>2</sub>·dm<sup>-3</sup>, in 25% – 1300–1500 mgO<sub>2</sub>·dm<sup>-3</sup>, and in 20% – 900–1100 and 1500–1700  
279 mgO<sub>2</sub>·dm<sup>-3</sup> (Figure 3). Differentiation of COD values in mechanically treated sewage could be  
280 the result of variability in the composition of raw sewage and also the operation of the settling  
281 tank. Lower COD values were recorded during the tank's working phase, when the  
282 sedimentation process played a major role. A similar effect could occur after each removing of  
283 scum and some part of sludge from the tank, which was one of the operating works. In other  
284 periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation  
285 effect and increased the concentration of pollutants in sewage flowing out from the settling  
286 tank.

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**Fig. 3.** Frequency histogram of influent parameter values

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(BOD<sub>5</sub>, COD, TSS, total nitrogen, total phosphorus)

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As a rule, total suspended solids did not exceed 400 mg·dm<sup>-3</sup> (90%). However, this cannot be considered a satisfactory result, given that it concerns wastewater treated mechanically in a three-chamber pre-settling tank. All recorded concentrations of total nitrogen were above 100 mg·dm<sup>-3</sup>, of which 50% were between 125 and 150 mg·dm<sup>-3</sup>. Total phosphorus concentrations exceeded 16 mg·dm<sup>-3</sup> and showed a slight variability. 75% of the results were in the range of 20–24 mg·dm<sup>-3</sup>; the remaining values (25% of cases) were grouped in the range of 16–20 mg·dm<sup>-3</sup> (Figure 3).

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In addition to the concentrations of pollutants in the treated wastewater, the ratios between the various individual parameters also have a significant impact on the clean-up process. The most important ratios are: COD/BOD<sub>5</sub>, BOD<sub>5</sub>/TN, and BOD<sub>5</sub>/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD<sub>5</sub> (2.4) and BOD<sub>5</sub>/TN (3.0) ratios; the BOD<sub>5</sub>/TP ratio was 25.6 (Table 2).

**Table 2.** Relationships between average values of selected indicators of pollution

Relationship	Recommended value (Heidrich et al., 2008)	Test value
COD/BOD <sub>5</sub>	≤2.2	2.4
BOD <sub>5</sub> /TN	≥4.0	3.4

BOD <sub>5</sub> /TP	≥25	25.6
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308

### 309 **Pollutant concentrations in the effluent from the VF bed**

310 After treatment of the wastewater in the VF bed, the average BOD<sub>5</sub> and COD values were  
 311 18 mgO<sub>2</sub>·dm<sup>-3</sup> and 68.4 mgO<sub>2</sub>·dm<sup>-3</sup>, respectively. The average concentration of total  
 312 suspended solids was 39.0 mg·dm<sup>-3</sup>, total phosphorus 12.0 mg·dm<sup>-3</sup>, total nitrogen  
 313 82.4 mg·dm<sup>-3</sup>. The average values of BOD<sub>5</sub>, COD, and total suspended solids in wastewater  
 314 treated in the VF bed met the requirements specified in the Regulation of the Minister of  
 315 Environment (2014) for wastewater discharged to waters or to the ground from treatment  
 316 plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable  
 317 conditions for the oxidation of organic pollutants and nitrification. The average oxygen  
 318 content in the wastewater flowing out from the first bed increased to about 3 mg·dm<sup>-3</sup>  
 319 compared to the mechanically treated wastewater, while the average concentration of  
 320 ammonia nitrogen slightly exceeded 20 mg·dm<sup>-3</sup>. The total nitrogen balance in the VF bed  
 321 indicates the existence of processes leading to the permanent removal of this component from  
 322 the wastewater, including, mainly, the process of denitrification and uptake by vegetation.  
 323 Despite this, the content of total nitrogen at the outflow from the VF bed remained high, on  
 324 average 82.4 mg·dm<sup>-3</sup>, with values well above 100 mg·dm<sup>-3</sup>. High concentration of total  
 325 nitrogen suggests that a significant part of ammonia nitrogen after transformation to the  
 326 nitrate form did not undergo any further transformation. Therefore, the average concentration  
 327 of nitrate nitrogen in the wastewater discharged from the VF bed was 24.5 mg·dm<sup>-3</sup> (Table 1).  
 328 The wastewater discharged from the first bed also contained high concentrations of total  
 329 phosphorus (an average of 11.0 mg·dm<sup>-3</sup>). For both biogenic parameters, the average values  
 330 were more than twice as high as the level stipulated by the law as acceptable for treatment  
 331 plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of  
 332 the Environment, 2014).

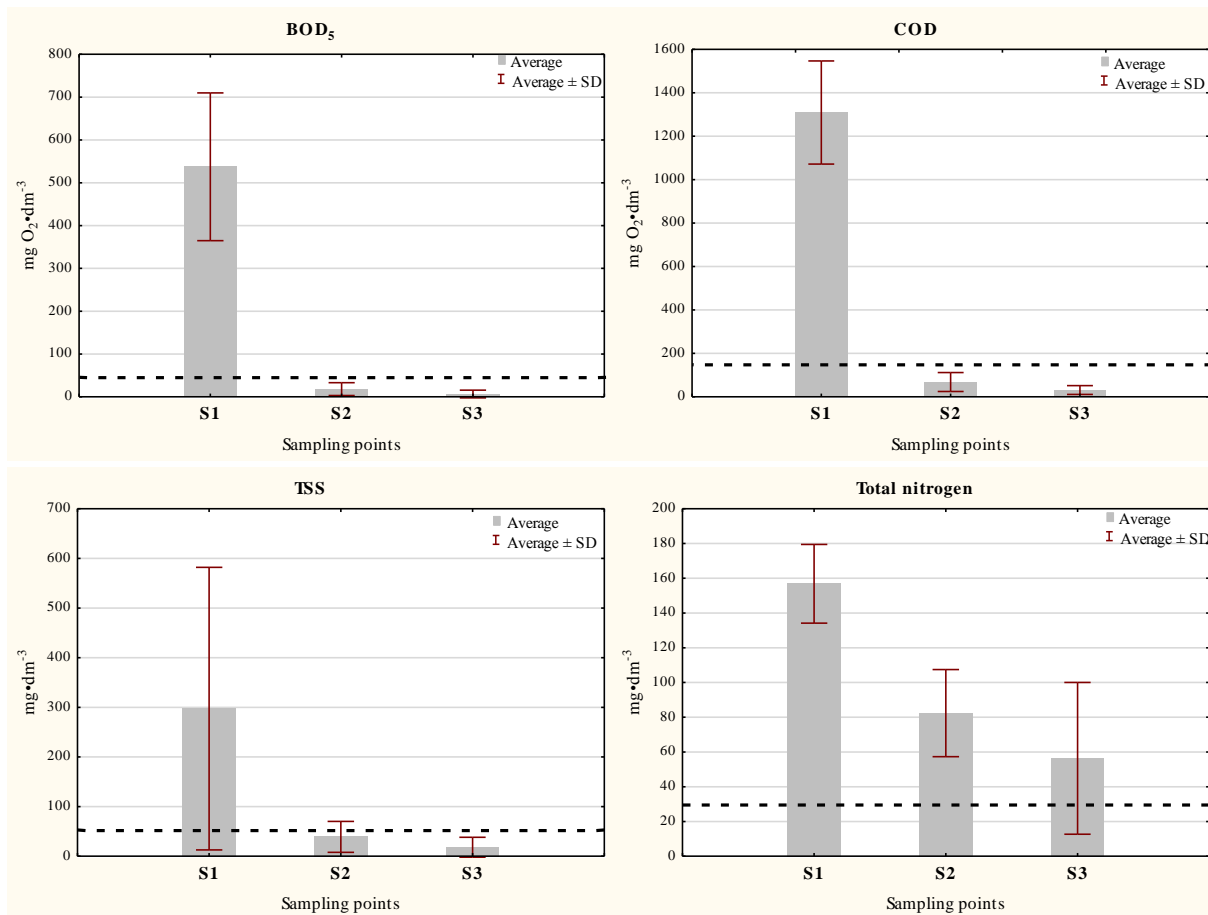
333

### 334 **Pollutant concentrations in the effluent from the HF bed**

335 An HF bed in a hybrid system is designed to optimise total nitrogen and organic  
 336 compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun,  
 337 2012). The average concentrations of BOD<sub>5</sub>, COD, and total suspended solids in wastewater  
 338 discharged from the HF bed into the receiver were 6.6 mg·dm<sup>-3</sup>, 31.8 mg·dm<sup>-3</sup>, and  
 339 18.0 mg·dm<sup>-3</sup>, respectively (Table 1). The respective median values were 3.1, 29.0, and  
 340 10.2 mg·dm<sup>-3</sup>. These values were significantly lower than the limit values stipulated in the

341 Regulation of the Minister of the Environment (2014). The average concentrations of total  
 342 nitrogen and total phosphorus in treated wastewater ( $56.4 \text{ mg}\cdot\text{dm}^{-3}$  and  $6.7 \text{ mg}\cdot\text{dm}^{-3}$ ,  
 343 respectively) did not meet the above requirements (Figure 4). The average value of total  
 344 nitrogen in treated wastewater was most strongly affected by the results collected during the  
 345 initial period of operation of the plant (about 18 months), when the vegetation was not yet  
 346 fully developed. The analysis of basic statistics highlights two tendencies: clear discrepancies  
 347 between the extreme values, and high coefficients of variation for the individual pollution  
 348 parameters of wastewater outflowing from the VF-HF system. Because the concentrations of  
 349 contaminants in the effluent were low, the results may have been much more strongly  
 350 influenced by environmental factors, precipitation and temperature, or random changes in  
 351 operating conditions compared with the results for S1 and S2.

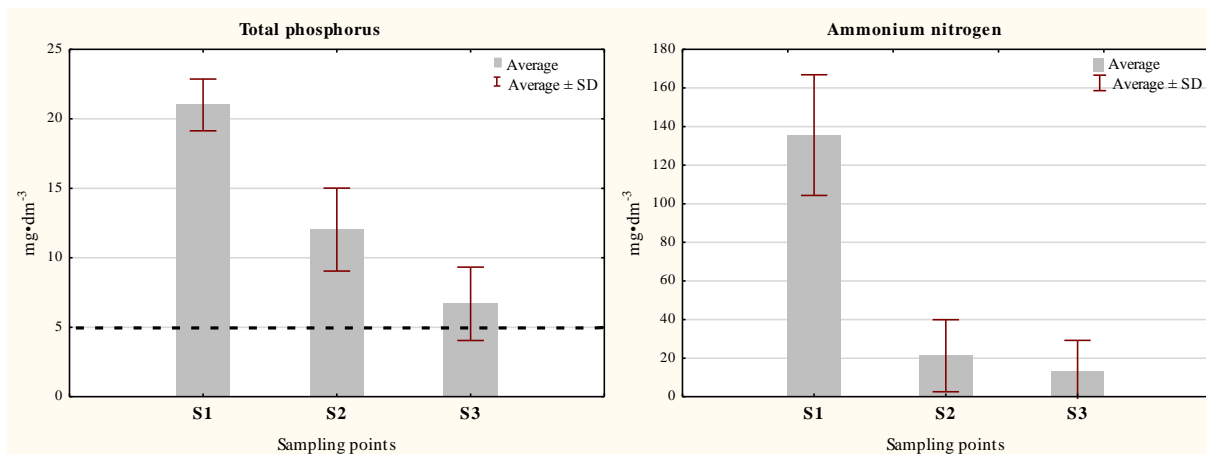
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 357 **Fig. 4.** Dynamics of reduction of pollutant concentrations in the successive stages of treatment  
 358 Notation: dashed black line – Polish legal requirements for wastewater discharged into water and soil  
 359 from treatment plants below 2000 p.e.  
 360 (Regulation of the Minister of the Environment, 2014)  
 361

### 362 **3.2. Pollutant removal efficiency**

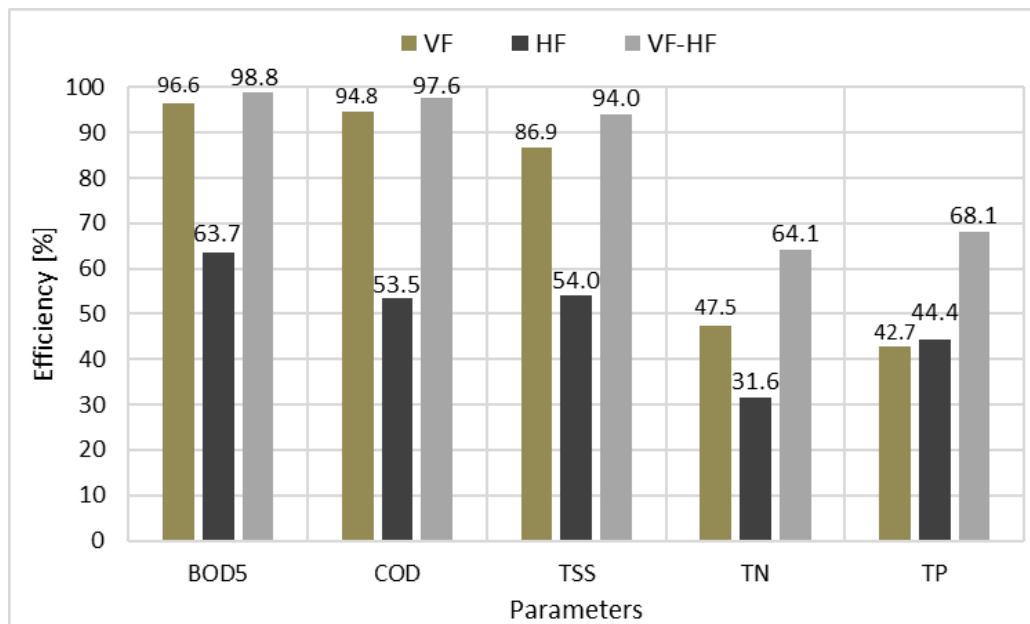
363 The results indicate that the investigated CW had a high efficiency of removal of organic  
 364 pollutants and total suspended solids, and a lower efficiency of elimination of biogenic  
 365 compounds (total nitrogen and total phosphorus). The differences between the various stages  
 366 of treatment were clear-cut. The largest proportion of the investigated pollutants were  
 367 eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of  
 368 organic pollutants and moderately good conditions for the removal of biogenic pollutants.  
 369 Several factors may have been of significance here, including the way the bed was fed with  
 370 sewage and the associated availability of oxygen, the hydraulic and pollution loads on the  
 371 bed, the vegetation, and air and wastewater temperature. The low hydraulic load of the VF  
 372 bed (an average of 12.5 mm·d<sup>-1</sup>) ensured optimal time of contact of sewage with the  
 373 microorganisms forming the biological membrane on the filling material (Saeed and Sun,  
 374 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet  
 375 periods, may have, in accordance with generally accepted opinions, increased the diffusion of  
 376 atmospheric oxygen and improved the conditions for the oxidation of organic pollutants and  
 377 the course of the nitrification process (Jia et al., 2010; Gervin and Brix, 2001).

378 The average efficiency of the entire VF-HF system in removing organic pollutants from  
 379 wastewater in the 5-year research period was 98.8% for BOD<sub>5</sub> and 97.6% for COD (Figure 5).  
 380 The effects of BOD<sub>5</sub> and COD removal were similar to or higher than those recorded by other  
 381 authors in hybrid constructed wetland systems operating under similar climatic conditions



382 (Krzanowski et al., 2005; Gajewska and Obarska-Pempkowiak, 2009; Vymazal and  
383 Kröpfelová, 2009).

384 The largest part of the pollution load was eliminated in the first stage of treatment in the  
385 VF bed. Although the amount of sewage flowing into the treatment plant constituted about  
386 50% of the designed value, the load of organic pollutants in the first bed, was quite high and  
387 amounted to  $6.7 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  ( $\text{BOD}_5$ ) and  $16.4 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  (COD), respectively. Moreover, the  
388 wastewater flowing into the VF bed was characterised by an unfavourable  $\text{BOD}_5/\text{COD}$  ratio  
389 (2.4), which testified to the lower susceptibility of the tested wastewater to biological  
390 decomposition. Despite this, nearly 97% of  $\text{BOD}_5$  and 95% COD were removed from the VF  
391 bed, which is a very good result. The system under investigation was rather insensitive to the  
392 high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia  
393 (2006) observed a similar relationship in their studies. Research carried out under similar  
394 climatic conditions has shown that the removal efficiency of VF reservoirs with regard to  
395  $\text{BOD}_5$  is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011;  
396 Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to  
397 various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010;  
398 Masi and Martinuzzi, 2007).



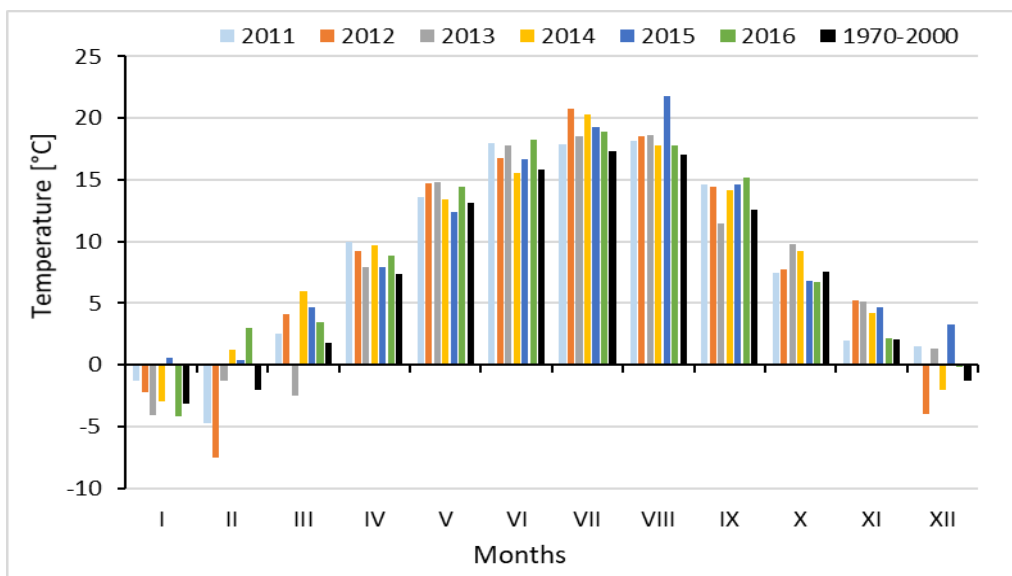
399  
400 **Fig. 5.** Average pollutant removal efficiency of the investigated system

401  
402 In the HF bed, the elimination of organic pollutants ( $\text{BOD}_5$  and COD) was 63.7% and  
403 53.5%, respectively. Research carried out by Obarska-Pempkowiak et al. (2010) indicates that  
404 HF type systems can provide a higher degree of COD reduction, but at higher contaminant  
405 loads.

406 The average efficiency of removal of total suspended solids in the analysed system was  
407 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed  
408 54% of the solids. The efficiency of the tested system in removing total suspended solids was  
409 higher than demonstrated by other authors. For comparison, a HF-VF system investigated by  
410 Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result  
411 that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by  
412 Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids  
413 removal efficiency of 89%.

414 The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%,  
415 with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to  
416 Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid  
417 constructed wetland systems may range from 23 to 80%, depending on the configuration and  
418 operating conditions of the beds. In the light of these reports, the effectiveness of the facility  
419 tested in this present study was moderately high, but not high enough to obtain stable results  
420 at the outflow that would meet the requirements set out in the Polish regulations (Regulation  
421 of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have  
422 been caused by a lack of appropriate conditions for effective denitrification in the HF bed,  
423 especially the deficit of organic compounds and the unfavourable BOD<sub>5</sub>/TN ratio inhibiting  
424 the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of  
425 meteorological conditions in the area of the conducted research (meteorological station in  
426 Radawiec near Lublin) showed that the significance of this last factor could have been  
427 smaller. Against the background of some long-term data, there can be observed a tendency of  
428 increasing the average air temperature (Figure 6). Throughout the entire research period  
429 (2011-2016) average annual temperatures were higher than the long-term average  
430 (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April  
431 to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from  
432 October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can  
433 be concluded that, apart from periods that are considered to be unfavorable in a moderate  
434 climate (December-February) temperature should not be a limiting factor for microbial  
435 removal processes.





**Fig. 6.** The average monthly temperatures for Radawiec near Lublin in the years 2011-2016 (IMWM, 2011-2016; CSO, 2017)

436  
437  
438  
439

440 The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The  
441 two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare,  
442 the average total phosphorus removal efficiencies for hybrid CW systems studied by other  
443 authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the  
444 highest phosphorus removal rates were found in the initial period of the plant's operation,  
445 which confirms the observation that the kind of filling of beds plays an important role in the  
446 process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant  
447 removal in different facilities or in different units of the same system is the mass removal rate  
448 (MRR), which provides a measure of the amount of a component removed per unit area of  
449 a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass  
450 removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage  
451 treatment plant in south-eastern Poland. The indicators were determined on the basis of the  
452 assumption that the average annual sewage outflow from individual purification stages is  
453 equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to  
454 evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration  
455 efficiency in CW is subject to great fluctuations, depending on seasonal conditions, it can  
456 range from 0 to 50 mm·d<sup>-1</sup> (Chazarenc et al. 2010). According to Herbst and Kappen (1999) in  
457 natural bog systems with common reed in northern Germany, in the full vegetation period, it  
458 may exceed 10 mm·d<sup>-1</sup>, but in other periods (from November to April) it approaches zero.  
459 These researchers also found that under certain conditions (cloudy and rainy weather) the

460 efficiency of evapotranspiration during the year may be similar or even lower than the total  
 461 precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the  
 462 multi-stage constructed wetland confirmed the possibility of maintaining balance of beds  
 463 evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant,  
 464 factors limiting the efficiency of evapotranspiration could be the proximity of high plants at  
 465 the south-western side, which cause periodic shading of beds and reduce air movement.  
 466 Moreover, the research of Toscano et al. (2015) indicate that the efficiency of  
 467 evapotranspiration on the beds planted with giant miscanthus, even under warm climate  
 468 conditions, is clearly lower than on the beds with common reed.

469 Despite the lower than planned hydraulic load, the pollution load in the investigated system  
 470 was comparable to those found in other constructed wetlands tested in Poland (Gajewska and  
 471 Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were  
 472 relatively high, similar to those recorded in two- and three-stage constructed wetland systems,  
 473 described by Gajewska and Obarska-Pempkowiak (2011).

474 Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the  
 475 values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al.,  
 476 2003).

477 The VF bed played a decisive role in the removal of organic pollutants. The mass removal  
 478 rates determined for this field were many times higher than in the case of the HF bed  
 479 (Table 3).

480

481 **Table 3.** Mass removal rates of BOD<sub>5</sub>, COD, total nitrogen (TN) and total phosphorus (TP)

Parameters		VF	HF	VF-HF
BOD <sub>5</sub>	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	6.71	0.27	3.66
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	6.49	0.17	3.62
COD	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	16.36	1.02	8.93
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	15.51	0.54	8.70
TN	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	1.96	1.23	1.07
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.93	0.39	0.68
TP	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.26	0.18	0.14
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.11	0.08	0.10

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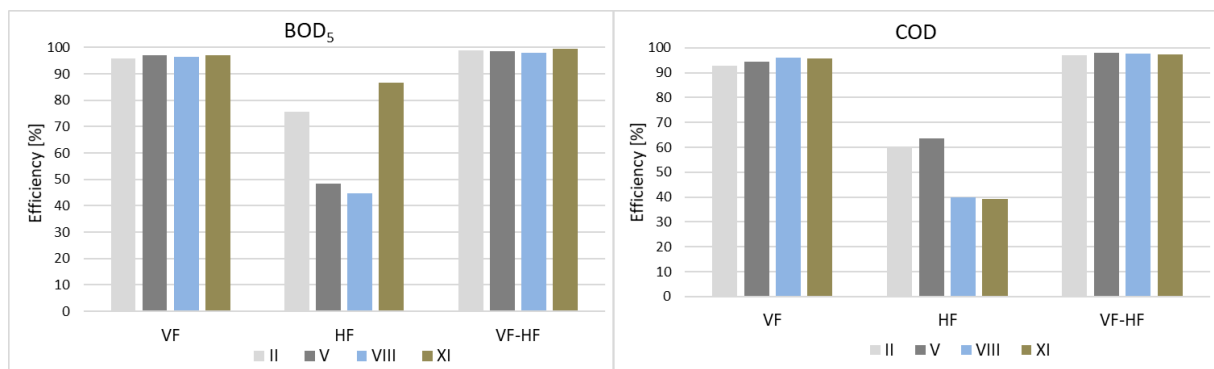
483 The investigated wastewater treatment plant in south-eastern Poland, with giant miscanthus  
 484 and Jerusalem artichoke, provided efficiency in the area of organic and biogenic compounds  
 485 removal similar to other systems using classic plant species that function under similar  
 486 operating conditions. In such systems, plants perform an auxiliary role, creating favorable



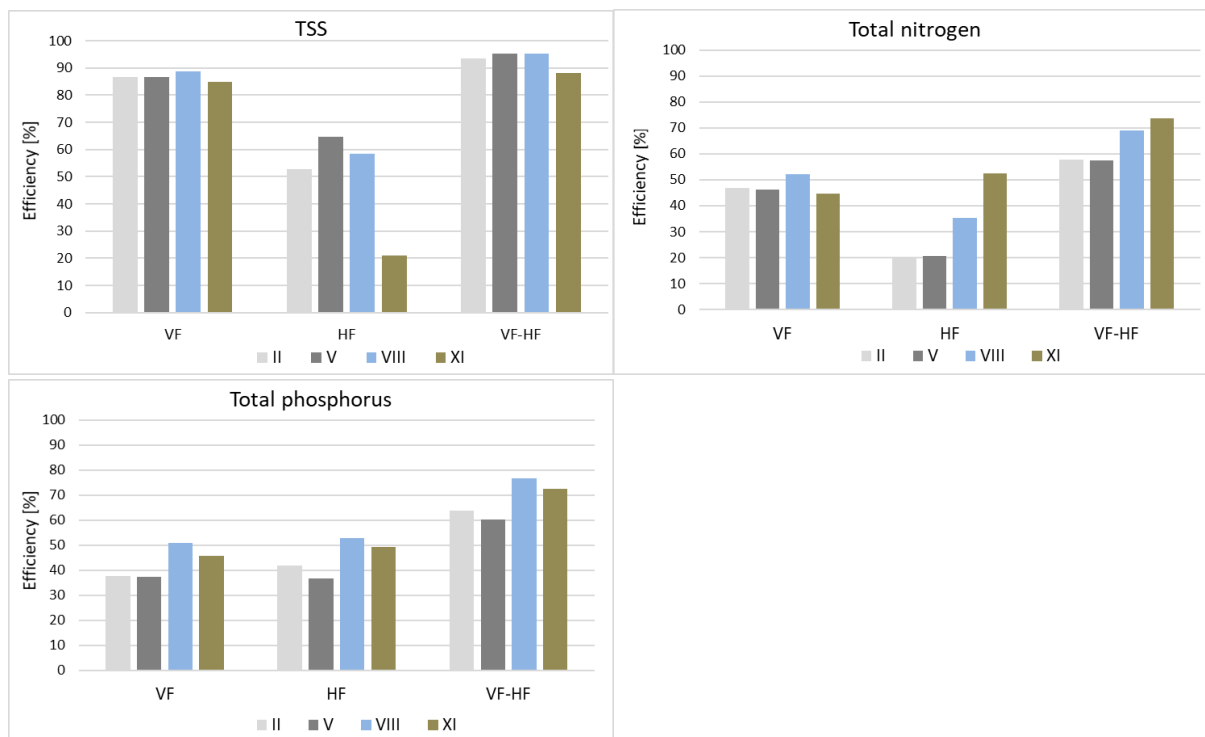
487 conditions for the activity of microorganisms and the course of biochemical processes in the  
 488 bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out  
 489 on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment  
 490 effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the  
 491 average removal effects were constant during the whole year (Figure 7). Higher variability  
 492 was found on the HF field, however, it is difficult to relate this to seasonal conditions, because  
 493 the average efficiency of BOD<sub>5</sub> decreasing was the highest in autumn and winter. Most  
 494 researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although  
 495 some studies did not show differences between the removal of these compounds in the  
 496 summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on  
 497 microbial removal processes can be associated with the dominance of physical processes. In  
 498 addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of  
 499 kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen  
 500 conditions.

501 The average efficiency of nitrogen and phosphorus removal from wastewater was slightly  
 502 higher in August and November. However, the share of plants in the uptake of pollutants from  
 503 sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The  
 504 yield of giant miscanthus on the VF field in the first year of operation was at a low level –  
 505 0.42 kg DM·m<sup>-2</sup> (Gizińska-Górna et al., 2017b). In the following years, it fluctuated within  
 506 the limits of 3.55–4.43 kg DM·m<sup>-2</sup> and was clearly higher than the yields recorded in field  
 507 crops of this plant (Szulczewski et al., 2018). The average nitrogen content in aboveground  
 508 parts of giant miscanthus was 5.8 g·kg DM<sup>-1</sup>, which means that with the highest yield (2016),  
 509 approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of  
 510 phosphorus – 0.26 g·kg DM<sup>-1</sup> its mass accumulated in aboveground parts of giant miscanthus  
 511 amounted to a maximum level of 0.11 kg.

512



513



**Fig. 7.** Average removal efficiency of pollutants in different months of the research.  
 Notation: II – February; V – May; VIII – August; XI – November

The yield of Jerusalem artichoke on the HF bed ranged from 0.83 kg DM·m<sup>-2</sup> in 2013 to 1.43 kg DM·m<sup>-2</sup> in 2015. The average nitrogen content in aboveground parts of plants was 3.4 g·kg DM<sup>-1</sup>, and phosphorus – 0.34 g·kg DM<sup>-1</sup>. In 2015, the nitrogen and phosphorus masses contained in the aboveground biomass were respectively 0.47 kg and 0.047 kg.

In the years which were most favorable in terms of yield of giant miscanthus and Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of both plants in relation to the mass of nitrogen removed in these years in the VF-HF system ranged from 5% to 6.3%. For phosphorus, it was about 2.6%. Baring in mind the fact that the plant activity associated with biomass production is limited to the growing season (in south-eastern Poland it usually lasts from April to September), it can be concluded that real contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the case of nitrogen and 5% in the case of phosphorus.

In this case, it can be concluded that the physicochemical processes, such as oxidation or adsorption by the substrate elements, could have a big influence on nitrogen removal (Bulc, 2006; Saeed and Sun, 2012). Physicochemical processes, especially substrate sorption, could also be very important in the elimination of phosphorus from wastewater (Jóźwiakowski et al., 2018; Xu et al., 2006).

536

### 537 **3.3. Pollutant removal reliability**

538 The reliability of the tested wastewater treatment plant, defined as its ability to dispose of  
539 the expected amount of wastewater to the extent required by the wastewater receiver, was  
540 determined using the Weibull method. The method allows a more in-depth analysis of  
541 qualitative data than is possible with average values, through the prism of legal requirements  
542 for sewage discharged to the environment. The first step was to estimate the parameters of  
543 distribution and verify the null hypothesis that empirical data could be described by Weibull's  
544 distribution. The data sets were the values of the basic pollution parameters (BOD<sub>5</sub>, COD,  
545 TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF  
546 constructed wetland system to the receiver.

547 The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit  
548 test along with the estimated parameters, are presented in Table 4.

549

550 **Table 4.** Parameters of the Weibull distribution and results of the Hollander-Proschan

551

goodness-of-fit test

Parameter	Parameters of Weibull distribution			Hollander-Proschan goodness-of-fit test	
	$\theta$	$c$	$b$	stat	p
BOD <sub>5</sub>	0.0000	0.8410	5.9731	0.1732	0.8625
COD	5.4646	1.7097	35.8400	0.1496	0.8810
TSS	1.6182	0.9676	17.6798	0.3140	0.7535
Total Nitrogen	9.0606	1.3572	61.8000	0.1807	0.8565
Total Phosphorus	-0.2000	2.8367	7.4737	-0.3043	0.7608

552

553 Symbols: stat – value of the test statistic, p – significance level of the test; when  $p \leq 0.05$  the  
554 distribution of data is not a Weibull distribution

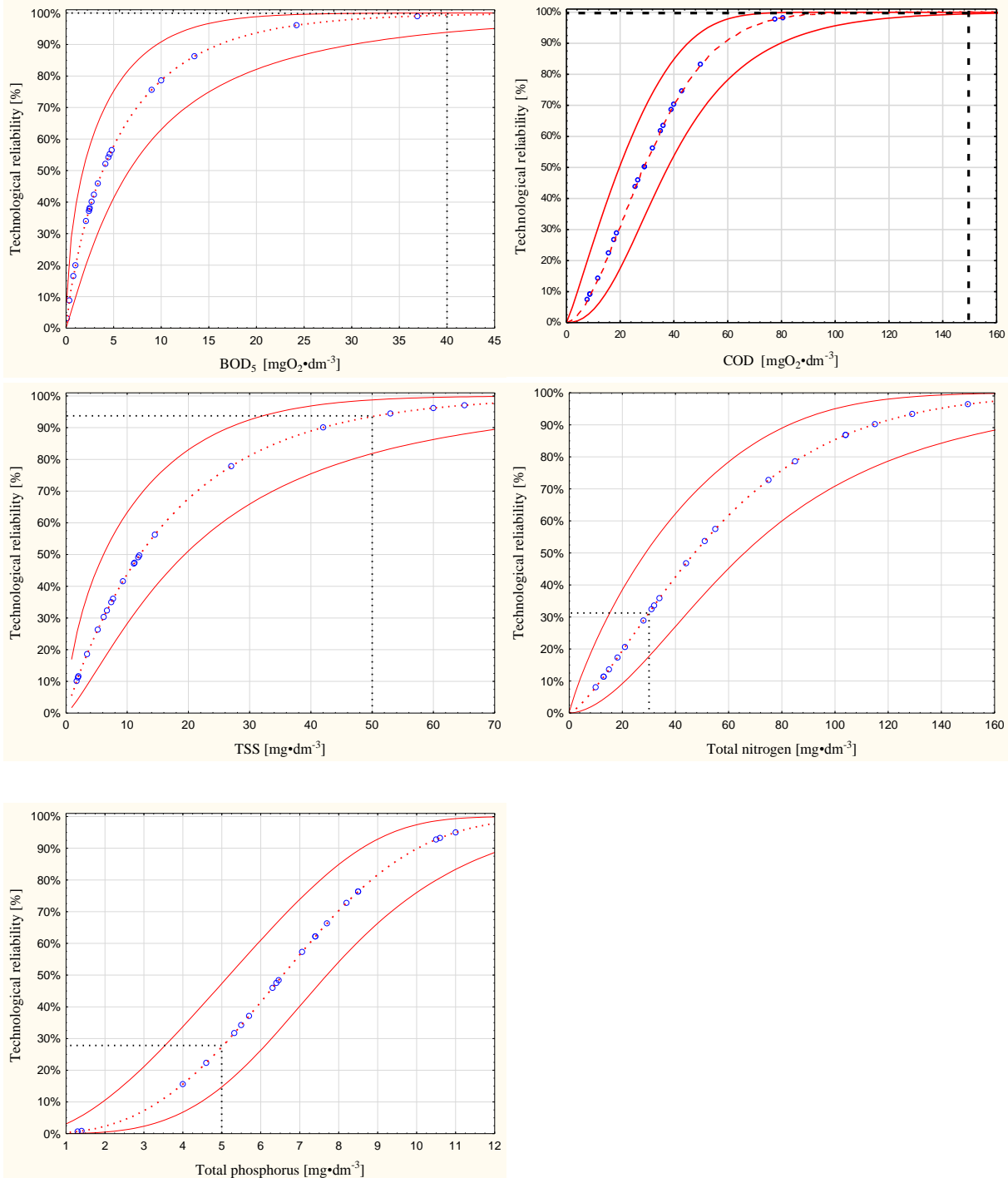
555

556 The goodness-of-fit of the obtained distributions was high at 75–88%, at a significance  
557 level  $\alpha = 0.05$ . The technological reliability of the treatment plant was determined on the basis  
558 of the distribution functions, taking into account the limit values for the parameters, as  
559 specified in the Regulation of the Minister of Environment for WWTPs of less than 2000 p.e.  
560 (Regulation of the Minister of the Environment, 2014) (Figure 8).

561 The organic pollutant removal reliability expressed by BOD<sub>5</sub> and COD was 100%  
562 (Figure 8). This means that the plant operated without any problems throughout the testing  
563 period, and the values of the tested parameters in the treated wastewater did not exceed the  
564 acceptable levels stipulated in the Polish law (40 and 150 mgO<sub>2</sub>·dm<sup>-3</sup>, respectively). This

565 leads to the conclusion that, with an operator risk of  $\alpha = 0.05$ , the plant should successfully  
566 pass inspection with regard to the parameters concerned throughout the year.

567 The reliability of removal of total suspended solids from sewage in the tested system was  
568 93%. On this basis, it can be concluded that the plant operated smoothly on average 339 days  
569 a year. The period of failure-free operation is equivalent to the period when the concentration  
570 of total suspension particles in the wastewater discharged to the receiver was below the  
571 required limit ( $50 \text{ mg}\cdot\text{dm}^{-3}$ ).



572

573

574

575



576 | **Fig. 86.** Weibull cumulative distribution functions and the technological reliabilities  
577 | determined for each pollution parameter

578 | Notation: dashed red line – reliability function, continuous red line – confidence intervals,  
579 | dashed black line – probability of reaching the effluent parameter limit

580 |  
581 | According to the guidelines proposed by Andraka and Dzienis (2003), the minimum  
582 | reliability level for treatment plants below 2000 p.e. should be 97.27%, which means that  
583 | these plants, even when operating poorly for 9 days a year, still have a 95% chance of  
584 | successfully going through inspection procedures. Given these guidelines, it can be assumed  
585 | that the limit concentrations of total suspended solids in the CW investigated in this present  
586 | study can be exceeded without affecting the plant's operation on 17 days a year.

587 | The reliability of removal of nutrients was significantly lower than in the case of organic  
588 | pollutants. The probability that the total nitrogen concentration in treated effluents would  
589 | reach the limit value ( $30 \text{ mg}\cdot\text{dm}^{-3}$ ) established for effluents discharged from a treatment plant  
590 | of less than 2000 p.e. to standing waters was 32%. This means that the total nitrogen  
591 | concentration in treated wastewater exceeded the limit value, and the plant operated  
592 | incorrectly on 249 days a year.

593 | An even lower level of reliability was found for total phosphorus removal. The probability  
594 | that the concentration of this parameter in treated wastewater would reach a value below  
595 |  $5 \text{ mg}\cdot\text{dm}^{-3}$  was 28%. This means that the plant operated correctly for only 102 days a year,  
596 | and excessive concentrations of total phosphorus in treated wastewater were recorded on  
597 | 254 days a year.

598 | The reliability levels obtained indicate that the hybrid constructed wetland with giant  
599 | miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant  
600 | removal. The facility guaranteed stable low BOD<sub>5</sub> and COD results for the treated wastewater,  
601 | which meant it was highly likely to be positively evaluated in the case of an inspection. These  
602 | conclusions are consistent with the reports of other authors, which indicate that hybrid  
603 | systems are very reliable with respect to BOD<sub>5</sub> and COD reduction (Jucherski et al., 2017;  
604 | Józwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher  
605 | than that of single-stage constructed wetland systems (Józwiakowski, 2012; Józwiakowski et  
606 | al., 2017) or other small sewage treatment plants using other technological solutions. For  
607 | comparison, the organic pollutant removal reliabilities (expressed as BOD<sub>5</sub> and COD) of  
608 | plants operating on the basis of conventional treatment methods (activated sludge, biological



609 bed, hybrid reactor), were 60–88% and 89–92%, respectively, and in extreme cases as low as  
610 30% (Marzec, 2017; Bugajski et al., 2012; Wałęga et al., 2008).

611 The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the  
612 tested facility were 32 and 28%, respectively, which indicates that treated wastewater was  
613 highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the  
614 performance of the system was not satisfactory in this respect. Tests carried out in other  
615 facilities show that similar or higher levels of nutrient removal reliability are reached in  
616 single-stage constructed wetland systems (Józwiakowski, 2012; Józwiakowski et al., 2018).  
617 Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the  
618 hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen  
619 and 95.2% for total phosphorus. It should be noted, however, that the normative values for  
620 nitrogen and total phosphorus used in reliability assessment refer only to specific cases when  
621 treated wastewater is discharged to lakes and their tributaries and directly to artificial water  
622 reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014).  
623 Moreover, according to the Polish law, there is no obligation to control the operation of  
624 domestic sewage treatment plants or to perform quality tests of sewage discharged to the  
625 environment. In this light, the assessment of nutrient removal reliability of domestic treatment  
626 plants is a theoretical issue, which does not mean that it should not become a common part of  
627 wastewater management practice in the future. In combination with an analysis of the  
628 effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of  
629 wastewater treatment plants allows to determine what technological solutions should be  
630 promoted when building sewage systems in rural areas to support water protection against  
631 pollution and eutrophication. The use of highly efficient and reliable wastewater treatment  
632 systems can reduce the use of the cheapest solutions, which instead of protecting the  
633 environment pose a potential threat to it. According to the emerging suggestions, it also seems  
634 necessary to create administrative and legal instruments in Poland which would enable control  
635 of all sewage treatment plants, regardless of their size and type of receiver (Józwiakowski et  
636 al., 2015; Marzec, 2017; Józwiakowski et al., 2018).

637

#### 638 **4. Conclusions**

639 In the five-year research period, the hydraulic load of the analysed VF-HF system with  
640 giant miscanthus and Jerusalem artichoke in south-eastern Poland was about 50% of the  
641 design value; however, the load of contaminants did not differ significantly from that found in  
642 similar constructed wetlands.



643 The average effectiveness of organic pollutant removal expressed as BOD<sub>5</sub> and COD was  
644 98.8 and 97.6%, respectively; the corresponding value for total suspended solids was 93%.  
645 Under the conditions typical for moderate climate, the hybrid VF-HF system provided high  
646 and stable effects of organic pollutants removal throughout the whole year. In the VF bed, the  
647 concentration of organic pollutants (BOD<sub>5</sub> and COD) in the inflowing sewage was removed  
648 on average by over 94%.

649 Technological reliability of the constructed wetland wastewater treatment plant with giant  
650 miscanthus and Jerusalem artichoke concerning BOD<sub>5</sub> and COD amounted to 100%. Under  
651 given operating conditions, the facility ensures failure-free operation and the fulfillment of  
652 Polish legal requirements throughout the whole year. The reliability of removal of total  
653 suspended solids was 93%.

654 The efficiencies of total nitrogen and total phosphorus removal were 64.1 % and 68.1%,  
655 respectively, and the average values of these components in the outflow from the treatment  
656 plant exceeded the standard levels. The lower efficiency of total nitrogen removal was  
657 probably caused by unfavourable denitrification conditions in the HF bed, including the  
658 deficit of organic compounds.

659 The CW had low total nitrogen and total phosphorus removal reliabilities (32% and 28%,  
660 respectively).

661 Giant miscanthus and Jerusalem artichoke showed favorable features when it comes to  
662 their use in constructed wetlands, also under moderate climate conditions. They were  
663 characterized by high resistance to unfavorable environmental conditions, and even at low  
664 hydraulic load, high yield potential. Despite the high yield, their share in the uptake of  
665 biogenic pollutants from wastewater was relatively small.

666 Giant miscanthus is characterized by a clearly higher biomass production than Jerusalem  
667 artichoke, has a well-developed root system, and the operation of miscanthus beds is simpler.  
668 Jerusalem artichoke generates large amounts of tubers, which allow the plant to compact the  
669 entire surface of the bed, and after some time their accumulation can affect the balance of  
670 pollutants in the bed. To avoid this, there is often a need to remove them during the operation  
671 of the facility.

672 The investigated hybrid constructed wetland system with giant miscanthus and Jerusalem  
673 artichoke had organic and biogenic pollutant removal efficiencies that were similar to those  
674 obtained in systems using classic plant species such as reed and willow. Giant miscanthus and  
675 Jerusalem artichoke can be successfully used to support wastewater treatment processes in



676 constructed wetland systems, and, owing to their high biomass production potential, they can  
677 also be exploited as energy yielding materials.

678

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680

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690

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1 **The efficiency and reliability of pollutant removal in a hybrid constructed**  
2 **wetland with giant miscanthus and Jerusalem artichoke in Poland**

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12  
13 **ABSTRACT**

14 In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and  
15 horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and  
16 Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated  
17 domestic sewage at an average flow rate of  $1.2 \text{ m}^3 \cdot \text{d}^{-1}$ . The tests were carried out during  
18 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage  
19 samples were collected from three stages of wastewater treatment in four seasons (winter –  
20 February, spring – May, summer – August, and autumn – November). The following  
21 parameters were measured: BOD<sub>5</sub>, COD, total suspended solids, total nitrogen, and total  
22 phosphorus. The average effectiveness of organic pollutant removal expressed by BOD<sub>5</sub> and  
23 COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids  
24 was 93%. The average values of BOD<sub>5</sub>, COD, and total suspended solids in wastewater  
25 discharged to the receiver were significantly lower than the limit values required in Poland.  
26 The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%,  
27 respectively, and the average values of these components in the outflow from the treatment  
28 plant exceeded the standard levels. A reliability analysis performed using the Weibull  
29 probability model showed that the reliability of pollutant removal in the tested CW system  
30 was very high for BOD<sub>5</sub> and COD (100%). It was also demonstrated that the tested CW did  
31 not provide effective elimination of biogenic elements (nitrogen and phosphorus), as  
32 evidenced by the low reliability values – 32 and 28%, respectively. The investigated hybrid  
33 CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic  
34 pollutants with a similar efficiency as systems using classic plant species such as reed and  
35 willow.

36  
37 **Key words:** wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal  
38 flow, pollutant removal, efficiency and reliability

39

## 40 **1. Introduction**

41 Domestic wastewater treatment plants are an optimal solution for the disposal of small  
42 amounts of wastewater in areas of dispersed development, where the construction of a sewage  
43 system is economically unjustified (García et al., 2013; Mikosz and Mucha, 2014;  
44 Józwiakowski et al., 2015). Issues related to the operational reliability of low capacity  
45 treatment plants below  $5 \text{ m}^3 \cdot \text{d}^{-1}$  are still rarely brought up due to the lack of precise  
46 requirements regarding the application of various technological solutions for home sewage  
47 treatment plants and their control during operation. Such a situation is not conducive to the  
48 creation and implementation of new, effective technologies. On the contrary, it favours the  
49 cheapest solutions, mainly systems with a leach drain, which are used for discharging  
50 untreated wastewater into the ground, and therefore, their application for waste water  
51 treatment raises serious questions (Józwiakowski et al., 2015, Zhang et al., 2015). Moreover,  
52 many solutions applied in small sewage treatment plants, including those based on  
53 conventional methods, in conditions of high variability of hydraulic load, pollution load and  
54 operating conditions do not guarantee high efficiency of removal of pollutants from sewage  
55 (Marzec, 2017). With a constant increase in the number of ineffective technological solutions  
56 applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawelek  
57 and Bugajski, 2017).

58 Therefore, the reliability of small sewage treatment plants should be an important criterion  
59 in planning the development of technical infrastructure in rural areas, which will enable the  
60 selection of optimal and environmentally safe solutions (Józwiakowski et al., 2015; Jucherski  
61 et al., 2017). There are more and more suggestions that all treatment plants, regardless of their  
62 size and type of receiver, should be placed under the control of competent authorities. At the  
63 same time, the popularity of constructed wetland systems, which can be used in various  
64 conditions, including protected areas and areas of high landscape value, is increasing due to  
65 their high pollutant removal efficiency (Vymazal, 2011; 2013; Józwiakowski, 2012; Paruch et  
66 al., 2011; Józwiakowski et al., 2017; Gajewska et al., 2015).

67 Constructed wetlands, and in particular hybrid treatment plants consisting of at least two  
68 beds with different sewage flows (vertical and horizontal), ensure effective removal of organic  
69 matter ( $\text{BOD}_5$  and COD) (Vymazal, 2011) and slightly less effective removal of nutrients  
70 (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in  
71 constructed wetland systems is related to the functioning of the biological membrane formed  
72 during the flow of wastewater through the material filling the beds. The plants growing in the  
73 wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and



74 Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated  
75 microenvironment, while other layers of the bed provide anaerobic or anoxic conditions.  
76 Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its  
77 structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different  
78 plant species have been used in constructed wetland systems, mainly common reed and  
79 willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite  
80 intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the  
81 possibility of using constructed wetland systems not only for wastewater treatment, but also  
82 for biomass production for energy purposes (Cerbin et al., 2012; Posadas et al., 2014; Lu and  
83 Zhang, 2013). In this respect, research on the use of other plants, e.g. giant miscanthus or  
84 Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al.,  
85 2016). The high energy potential of these plants is a result of high yield and biomass calorific  
86 value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy  
87 et al., 2009; Long et al., 2010). In European conditions, the yield of giant miscanthus in field  
88 cultivation ranges from 10 to 30 Mg DM·ha<sup>-1</sup> (Szulczewski et al., 2018), and Jerusalem  
89 artichoke from 9 to 25 Mg DM·ha<sup>-1</sup> (Baldini et al., 2004; Gunnarsson et al., 2014). The  
90 calorific value of dried biomass of giant miscanthus varies from 14 to 17 MJ·kg DM<sup>-1</sup>, and for  
91 Jerusalem artichoke varies from 15 to 19 MJ·kg DM<sup>-1</sup> (Szulczewski et al., 2018;  
92 Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less  
93 recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used  
94 in constructed wetland systems yet, while research on the use giant miscanthus has been  
95 carried out on a pilot scale and under warm climate conditions. Their results indicate that the  
96 efficiency of pollutants removal in the beds planted with giant miscanthus may be similar to  
97 those found in the case of classical plant species, including common reed (Toscano et al.,  
98 2015; Barbagallo et al., 2014).

99 The aim of the present study is to analyse the reliability and effectiveness of pollutant  
100 removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus  
101 (*Miscanthus giganteus* x Greif et Deu) and Jerusalem artichoke (*Helianthus tuberosus* L.)  
102 during five years of its operation.

103

## 104 **2. Materials and methods**

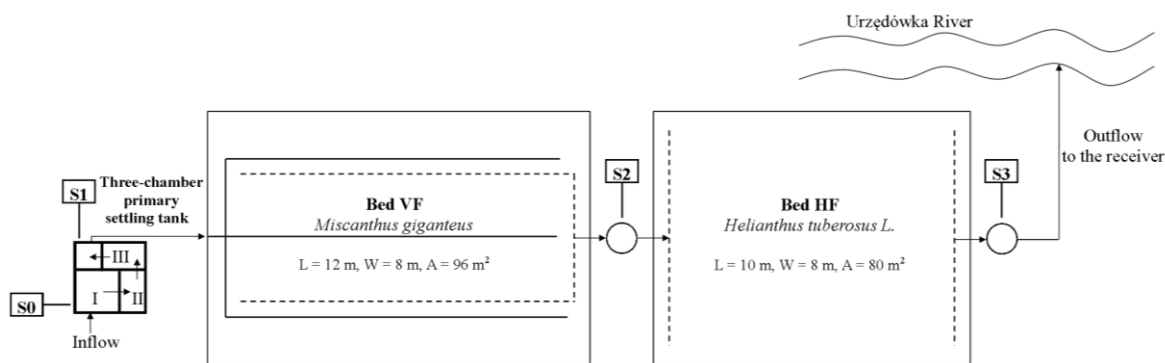
### 105 **2.1. Characteristics of the experimental facility**

106 The analysed plant is located in Skorczyce, Poland (51°00'36"N, 22°11'51"E). Its task is to  
107 treat domestic sewage from a multi-family building. The plant has been in operation since



2011 and its planned capacity is  $2.5 \text{ m}^3 \cdot \text{d}^{-1}$ . In the analyzed system, sewage from the building was drained into a three-chamber preliminary settling tank, where it was pre-treated in physical and biological processes.

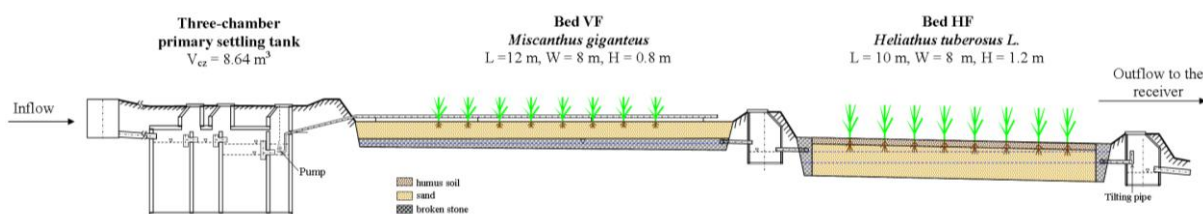
The tank is made of concrete, and its active capacity is  $8.64 \text{ m}^3$ . In the next stage, the sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). A first bed, with vertical sewage flow (VF), has an area of  $96 \text{ m}^2$  and a depth of  $0.8 \text{ m}$ , and the second bed, with horizontal sewage flow (HF), has an area of  $80 \text{ m}^2$  and a depth of  $1.2 \text{ m}$ . The beds have been isolated from the native soil by a PEHD waterproofing geomembrane of  $1 \text{ mm}$  thickness. The VF bed was filled with a layer of sand ( $1\text{-}2 \text{ mm}$ ) with a height of about  $0.8 \text{ m}$ . The filling of the HF bed to the height of  $1.0 \text{ m}$  consisted of sand ( $1\text{-}2 \text{ mm}$ ), on which there was laid the humus soil layer with a height of  $0.2 \text{ m}$  and it was obtained during the construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant miscanthus (*Miscanthus x giganteus* Greef et Deu.), the second with Jerusalem artichoke (*Helianthus tuberosus* L.) (Photo 1). Every year, after the winter season, the aboveground plant shoots and part of the tubers (Jerusalem artichoke) are removed from the fields. The recipient of the treated wastewater is the Urzędówka River (Figures 1, 2).



**Fig. 1.** Technological scheme of the tested VF-HF constructed wetland system

(Gizińska-Górna et al., 2012; 2017a)

Notation: S0, S1, S2, S3 – sampling points



**Fig. 2.** Longitudinal profile of the tested VF-HF constructed wetland system

(Gizińska-Górna et al., 2012)





132  
133 **Photo 1.** Hybrid constructed wetland, VF-HF type, with giant miscanthus (on the left) and  
134 Jerusalem artichoke (on the right) (Józwiakowski, 2016)  
135

136 During the study period, the amount of wastewater discharged to the treatment plant  
137 represented only about half of the design value, as the actual number of inhabitants served by  
138 the plant had decreased since its construction. The amount of sewage inflow to the treatment  
139 plant was determined on the basis of water meters readings in the building and average water  
140 consumption. In addition, the amount of sewage introduced into the VF-HF system was  
141 measured by using a flow meter installed on the discharge pipe between the preliminary  
142 settling tank and the VF bed. The average inflow of wastewater during the tests was  
143  $1.2 \text{ m}^3 \cdot \text{d}^{-1}$ , and the hydraulic load of the first bed was  $12.5 \text{ mm} \cdot \text{d}^{-1}$ . Mechanically treated  
144 wastewater was pumped into the first bed (VF) twice a day, about  $0.6 \text{ m}^3$  each time, and then  
145 it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow  
146 from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this  
147 field during summer. Theoretical wastewater retention time was determined on the basis of the  
148 parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the  
149 height of the layer filled with sewage) and average daily wastewater inflow (Conley et al.,  
150 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed,  
151 the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d  
152 in the winter period.  
153

## 154 **2.2. Analytical methods**

155 The efficiency and reliability of pollutant removal in the analysed treatment plant in south  
156 eastern Poland were assessed based on influent and effluent wastewater data collected in the  
157 years 2011–2016 (5 years). Sewage samples were taken seasonally: in February, May, August  
158 and November, at four points of the plant: S0 – raw sewage from the first chamber of the  
159 preliminary settling tank, S1 – mechanically treated wastewater, S2 – wastewater flowing out

160 of the VF bed with giant miscanthus, S3 – wastewater flowing out of the HF bed with  
161 Jerusalem artichoke (Figure 1). In total, 20 measurement series were made.

162 The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen,  
163 nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS),  
164 biochemical oxygen demand (BOD<sub>5</sub>) and chemical oxygen demand (COD). The concentration  
165 of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and  
166 nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen  
167 was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter  
168 instrument was also used to determine total nitrogen after oxidation of the samples in a  
169 thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010  
170 spectrophotometer after oxidation of the samples at 120°C. BOD<sub>5</sub> was measured by the  
171 dilution method using WTW Multi 340i, and COD was estimated by the same method with a  
172 WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were  
173 determined by filtration through paper filters. Sampling, transport and processing of the  
174 samples and their analysis were carried out in accordance with Polish standards (PN-74/C-  
175 04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO  
176 6878:2006P; PB-01/PS; PN-EN 872:2007), which are in accordance with APHA (2005).

177 In addition, the yield and chemical composition of plant biomass from beds were  
178 determined. Plant material for biomass research was collected annually (starting from 2013) at  
179 the end of winter, February or March. The samples of plants were collected by hand from  
180 plots with an area of 1 m<sup>2</sup>. In plant samples, there were determined such characteristics as dry  
181 matter content by gravimetric method, after drying at 105°C (PN-EN ISO 18134-3:2015-11)  
182 and the content of some selected chemical components, including nitrogen and phosphorus  
183 (PN-EN 15104:2011; PN-EN ISO 6491:2000).

184

### 185 **2.3. Statistical analysis**

186 On the basis of the obtained results, characteristic values of pollution parameters in sewage  
187 from the three different treatment stages were determined, including average, minimum and  
188 maximum values, medians, standard deviations, and coefficients of variation. Additionally,  
189 the relative frequency of occurrence of the characteristic concentration levels of the tested  
190 parameters in the sewage flowing into the treatment plant was determined. The classes for  
191 each pollution parameter have been chosen to obtain a frequency distribution that would be  
192 as detailed as possible without affecting the clarity of the structure of the statistical collection.



193 On the basis of the average values of the pollution parameters in the incoming ( $C_{in}$ ) and  
194 outgoing ( $C_{out}$ ) wastewater, the average pollutant removal efficiency was calculated according  
195 to equation 1:

$$196 \quad \eta = 100 \left( 1 - \frac{C_{out}}{C_{in}} \right) [\%] \quad (1)$$

197 Additionally, the effectiveness of the tested hybrid system was analysed on the basis of  
198 mass removal rates ( $MRR$ ) of the main pollutants contained in wastewater.  $MRR$  values were  
199 determined from equation 2 (Gajewska and Obarska-Pempkowiak, 2011):

$$200 \quad MRR = \frac{C_{in} Q_{in} - C_{out} Q_{out}}{A} [\text{g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}] \quad (2)$$

201 where:  $A$  – surface area of the constructed wetland system [ $\text{m}^2$ ],  $Q_{in}$  and  $Q_{out}$  – average inflow  
202 and outflow of wastewater [ $\text{m}^3 \cdot \text{d}^{-1}$ ],  $C_{in}$  and  $C_{out}$  – average concentrations of pollutants in the  
203 wastewater flowing into and out of the system [ $\text{g} \cdot \text{m}^{-3}$ ].

204 The calculated indicators are theoretical, because they are based on the assumption that the  
205 outflow of sewage from particular elements of the treatment plant is equal to the inflow.

206 The technological reliability of the wastewater treatment plant in Skorczyce was assessed  
207 for the basic pollution parameters ( $\text{BOD}_5$ ,  $\text{COD}$ , total suspended solids, total nitrogen, and  
208 total phosphorus) using elements of Weibull's reliability theory. The Weibull distribution is an  
209 overall probability distribution used in reliability testing and assessment of the risk of  
210 exceeding the limit values for pollutant concentrations in treated wastewater (Bugajski, 2014;  
211 Jucherski et al., 2017; Jóźwiakowski et al., 2017; Bugajski et al., 2012; Jóźwiakowski et al.,  
212 2018). The Weibull distribution is characterised by the following probability density function:

$$213 \quad f(x) = \frac{c}{b} \cdot \frac{x-\theta}{b}^{(c-1)} \cdot e^{-\left(\frac{x-\theta}{b}\right)^c} \quad (3)$$

214 where:  $x$  – a variable describing the concentration of a pollution parameter in the treated  
215 effluent,  $b$  – scale parameter,  $c$  – shape parameter,  $\theta$  – position parameter.

216 Assuming:  $\theta < x$ ,  $b > 0$ ,  $c > 0$ .

217 The reliability analysis was based on the estimation of Weibull distribution parameters  
218 using the method of highest reliability. The null hypothesis that the analyzed variable could be  
219 described by the Weibull distribution was verified with the Hollander-Proschan test at the  
220 significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters  
221 in treated wastewater discharged to the receiver were analysed. Reliability was determined  
222 from the distribution figures, taking into account the normative values of the parameters  
223 specified in the Regulation of the Minister of the Environment (2014) for wastewater  
224 discharged from treatment plants of less than 2000 p.e.:  $\text{BOD}_5$  –  $40 \text{ mgO}_2 \cdot \text{dm}^{-3}$ ,  $\text{COD}$  –



225  $150 \text{ mgO}_2 \cdot \text{dm}^{-3}$ , total suspended solids –  $50 \text{ mg} \cdot \text{dm}^{-3}$ , total nitrogen –  $30 \text{ mg} \cdot \text{dm}^{-3}$ , and total  
226 phosphorus –  $5 \text{ mg} \cdot \text{dm}^{-3}$ . In the case of nitrogen and total phosphorus, the values defined for  
227 wastewater discharged into lakes and their tributaries and directly into artificial water  
228 reservoirs situated in flowing waters were adopted as standard values (Regulation of the  
229 Minister of the Environment, 2014). The analysis was carried out using Statistica 13 software.  
230

### 231 **3. Results and discussion**

#### 232 **3.1. Pollutant concentrations in treated wastewater**

233 The efficiency and reliability of pollution removal in the tested treatment plant in  
234 south-eastern Poland were determined on the basis of results of tests of mechanically treated  
235 sewage (S1) flowing into the VF-HF constructed wetland system and sewage treated in beds  
236 with vertical (S2) and horizontal (S3) flow. Characteristic values of the pollution parameters  
237 are presented in Table 1.

238 In addition, the quality of raw sewage flowing from the building to the primary settling  
239 tank (S0) was taken into account, but it was not the subject of the main analysis.  
240

#### 241 **Pollutant concentrations in sewage flowing into the treatment plant**

242 The average values of pollution indicators in raw sewage outflowing from the building to  
243 the preliminary settling tank were respectively:  $704 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for BOD<sub>5</sub>,  $1486 \text{ mgO}_2 \cdot \text{dm}^{-3}$   
244 for COD,  $710 \text{ mg} \cdot \text{dm}^{-3}$  for total suspended solids,  $172 \text{ mg} \cdot \text{dm}^{-3}$  for total nitrogen and  $23.5$   
245  $\text{mg} \cdot \text{dm}^{-3}$  for total phosphorus (Table 1). These values were clearly higher than those reported  
246 in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may  
247 have resulted from the fact that the majority of the building's inhabitants were unemployed  
248 people in a difficult financial situation. Due to the low standard of water and wastewater  
249 facilities and the need for economical water management, its unit consumption in the building  
250 was at a low level, which could result in an increase in the concentration of pollutants in the  
251 sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of  
252 physical processes, TSS content decreased by nearly 60%. At the same time, there was  
253 observed a decrease in the concentration of organic pollutants, expressed as BOD<sub>5</sub> (by 23%)  
254 and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%).  
255 Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank  
256 to the system of VF-HF beds was high. The average values of these parameters at this stage of  
257 treatment were:  $537 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for BOD<sub>5</sub>,  $1309 \text{ mgO}_2 \cdot \text{dm}^{-3}$  for COD,  $297 \text{ mg} \cdot \text{dm}^{-3}$  for total  
258 suspended solids,  $157 \text{ mg} \cdot \text{dm}^{-3}$  for total nitrogen, and  $21.0 \text{ mg} \cdot \text{dm}^{-3}$  for total phosphorus



259 (Table 1). The pH value ranged from 6.67 to 7.94, and the concentration of dissolved oxygen  
 260 was in the range of 0.09 to 2.60, with the average concentration of 0.50 mg·dm<sup>-3</sup>. The average  
 261 contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated  
 262 wastewater were 136 mg·dm<sup>-3</sup>, 2.87 mg·dm<sup>-3</sup>, and 0.23 mg·dm<sup>-3</sup>, respectively. The recorded  
 263 values were significantly higher than those reported in the literature for mechanically treated  
 264 wastewater from single-family buildings (Jucherski et al., 2017; Józwiakowski et al., 2017;  
 265 Józwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water  
 266 consumption, leading to the formation of highly concentrated wastewater.

267

268 **Table 1.** Basic statistics for the indicator values in the treated wastewater (n = 20)

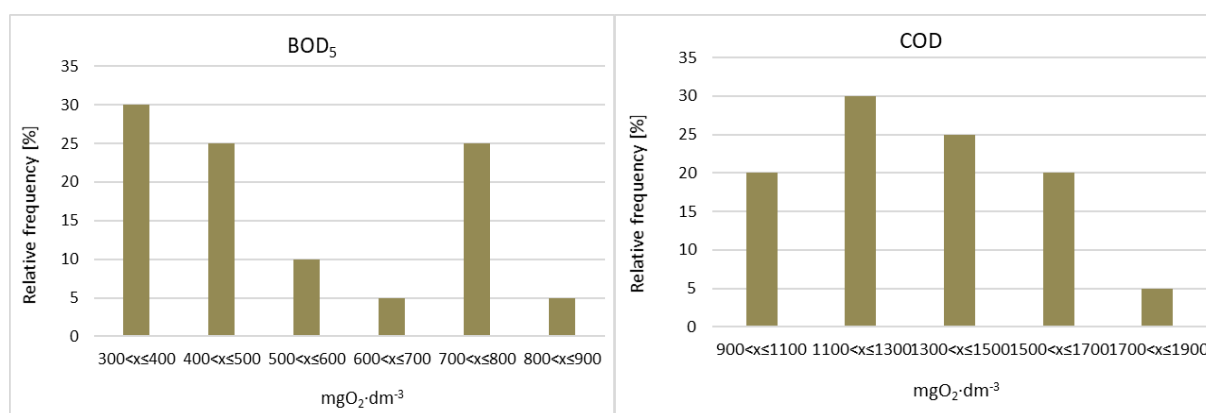
Parameters		Statistic					
		Average	Median	Min	Max	SD	Cv
Dissolved oxygen [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>0.35</b>	0.22	0.08	1.19	0.31	89.51
	S1	<b>0.50</b>	0.37	0.09	2.60	0.55	109.11
	S2	<b>2.92</b>	3.03	0.37	5.17	1.34	45.89
	S3	<b>5.58</b>	5.55	1.27	11.42	2.69	48.24
pH	S0	<b>7.26</b>	7.29	6.50	7.89	0.44	6.04
	S1	<b>7.17</b>	7.13	6.67	7.94	0.29	4.06
	S2	<b>7.10</b>	7.08	6.68	7.55	0.24	3.37
	S3	<b>7.47</b>	7.42	6.93	8.70	0.49	6.51
BOD <sub>5</sub> [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>704.0</b>	690.5	376.0	1262.0	202.9	28.82
	S1	<b>537.0</b>	471.0	310.0	862.0	172.4	32.10
	S2	<b>18.2</b>	16.3	1.8	58.0	15.1	82.60
	S3	<b>6.6</b>	3.1	0.1	36.9	9.1	137.40
COD [mgO <sub>2</sub> ·dm <sup>-3</sup> ]	S0	<b>1486.9</b>	1485.0	990.0	1920.0	249.8	16.80
	S1	<b>1309.0</b>	1295.0	910.0	1740.0	237.4	18.08
	S2	<b>68.4</b>	52.0	11.0	170.0	43.4	63.52
	S3	<b>31.8</b>	29.0	8.0	81.0	20.3	63.83
TSS [mg·dm <sup>-3</sup> ]	S0	<b>710.9</b>	523.2	136.0	2052.0	520.4	73.20
	S1	<b>297.0</b>	235.0	60.0	1390.0	284.7	95.67
	S2	<b>39.0</b>	28.5	1.9	114.0	31.1	79.77
	S3	<b>18.0</b>	10.2	1.8	65.1	20.2	112.45
Total nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>172.3</b>	171.0	114.0	238.0	32.2	18.70
	S1	<b>157.0</b>	150.5	120.0	216.0	22.7	14.45
	S2	<b>82.4</b>	83.0	34.0	134.0	25.1	30.42
	S3	<b>56.4</b>	39.0	10.0	150.0	43.7	77.46
Ammonium nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>147.2</b>	139.5	47.0	230.0	42.7	29.02
	S1	<b>136.0</b>	134.5	43.0	204.0	31.3	23.06
	S2	<b>21.3</b>	18.2	1.6	65.2	18.7	87.77
	S3	<b>12.9</b>	3.8	0.1	47.1	16.4	127.44
Nitrate nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>2.11</b>	0.99	0.03	17.11	3.64	172.89
	S1	<b>2.87</b>	0.86	0.28	29.67	6.47	225.24
	S2	<b>24.48</b>	24.96	2.71	57.70	16.07	65.65
	S3	<b>20.25</b>	13.48	0.86	58.20	19.89	98.22

Nitrite nitrogen [mg·dm <sup>-3</sup> ]	S0	<b>0.28</b>	0.270	0.08	0.471	0.15	55.07
	S1	<b>0.23</b>	0.19	0.08	0.43	0.13	56.71
	S2	<b>1.03</b>	0.73	0.06	4.04	1.02	98.99
	S3	<b>0.50</b>	0.13	0.03	3.62	1.00	198.99
Total phosphorus [mg·dm <sup>-3</sup> ]	S0	<b>23.5</b>	23.1	15.3	30.2	4.6	19.69
	S1	<b>21.0</b>	21.1	17.2	23.9	1.9	8.89
	S2	<b>12.0</b>	11.6	8.5	21.0	3.0	24.83
	S3	<b>6.7</b>	6.8	1.3	11.0	2.6	39.47

269 Notation: S0 – raw wastewater ;S1 - inflow to bed VF; S2 - outflow from bed VF; S3 - outflow from  
270 bed HF; SD - standard deviation; Cv - coefficient of variation, n - number of samples

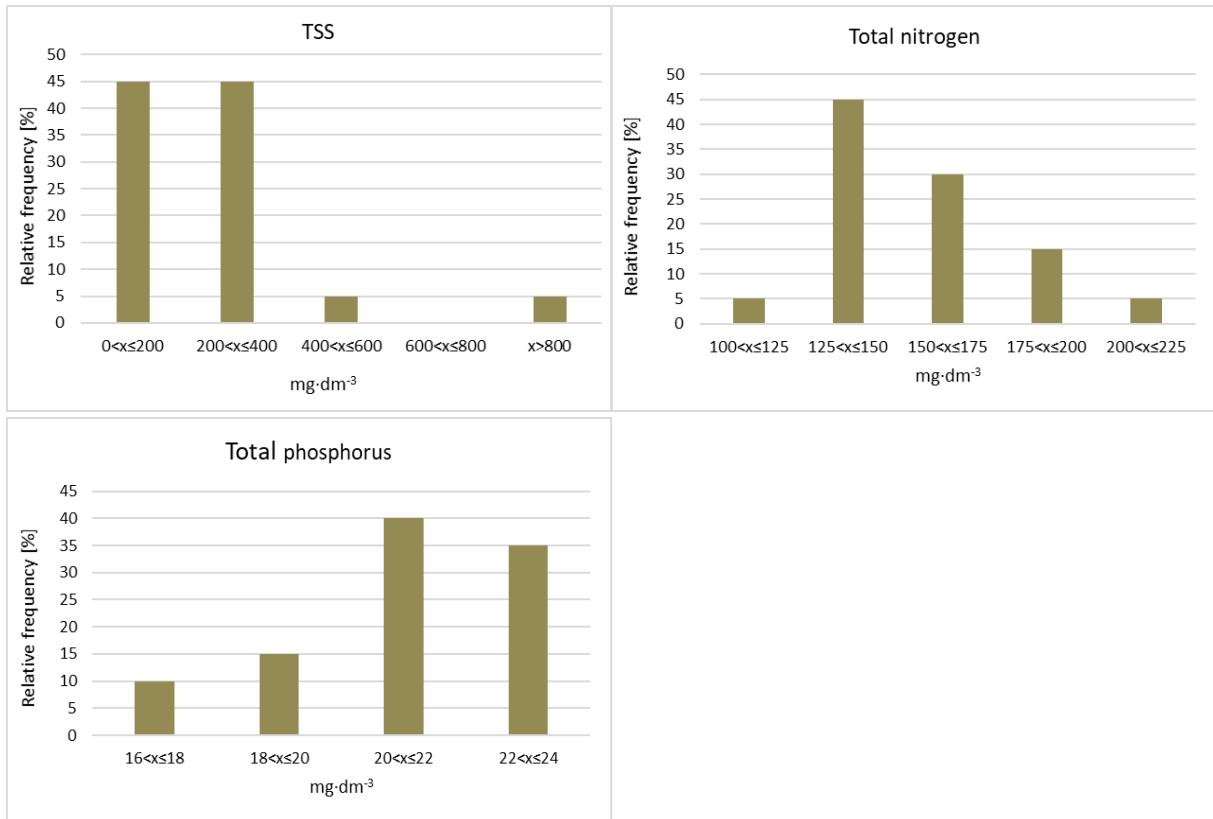
271  
272 Figure 3 shows nomograms of the frequency of occurrence of pollution parameter  
273 concentrations, grouped in different ranges. BOD<sub>5</sub> in the wastewater flowing into the hybrid  
274 VF-HF system did not fall below 300 mgO<sub>2</sub>·dm<sup>-3</sup> across measurements. The most common  
275 values were in the range of 300–400 mgO<sub>2</sub>·dm<sup>-3</sup> (30% of cases), 400–500 and 700–800  
276 mgO<sub>2</sub>·dm<sup>-3</sup> (25% each), and 500–600 mgO<sub>2</sub>·dm<sup>-3</sup> (10%). The COD values were very high and  
277 showed little volatility. In 30% of cases, the parameter was within the range of 1100–1300  
278 mgO<sub>2</sub>·dm<sup>-3</sup>, in 25% – 1300–1500 mgO<sub>2</sub>·dm<sup>-3</sup>, and in 20% – 900–1100 and 1500–1700  
279 mgO<sub>2</sub>·dm<sup>-3</sup> (Figure 3). Differentiation of COD values in mechanically treated sewage could be  
280 the result of variability in the composition of raw sewage and also the operation of the settling  
281 tank. Lower COD values were recorded during the tank's working phase, when the  
282 sedimentation process played a major role. A similar effect could occur after each removing of  
283 scum and some part of sludge from the tank, which was one of the operating works. In other  
284 periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation  
285 effect and increased the concentration of pollutants in sewage flowing out from the settling  
286 tank.

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**Fig. 3.** Frequency histogram of influent parameter values  
(BOD<sub>5</sub>, COD, TSS, total nitrogen, total phosphorus)

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As a rule, total suspended solids did not exceed 400 mg·dm<sup>-3</sup> (90%). However, this cannot be considered a satisfactory result, given that it concerns wastewater treated mechanically in a three-chamber pre-settling tank. All recorded concentrations of total nitrogen were above 100 mg·dm<sup>-3</sup>, of which 50% were between 125 and 150 mg·dm<sup>-3</sup>. Total phosphorus concentrations exceeded 16 mg·dm<sup>-3</sup> and showed a slight variability. 75% of the results were in the range of 20–24 mg·dm<sup>-3</sup>; the remaining values (25% of cases) were grouped in the range of 16–20 mg·dm<sup>-3</sup> (Figure 3).

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In addition to the concentrations of pollutants in the treated wastewater, the ratios between the various individual parameters also have a significant impact on the clean-up process. The most important ratios are: COD/BOD<sub>5</sub>, BOD<sub>5</sub>/TN, and BOD<sub>5</sub>/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD<sub>5</sub> (2.4) and BOD<sub>5</sub>/TN (3.0) ratios; the BOD<sub>5</sub>/TP ratio was 25.6 (Table 2).

**Table 2.** Relationships between average values of selected indicators of pollution

Relationship	Recommended value (Heidrich et al., 2008)	Test value
COD/BOD <sub>5</sub>	≤2.2	2.4
BOD <sub>5</sub> /TN	≥4.0	3.4

BOD <sub>5</sub> /TP	≥25	25.6
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### 309 **Pollutant concentrations in the effluent from the VF bed**

310 After treatment of the wastewater in the VF bed, the average BOD<sub>5</sub> and COD values were  
 311 18 mgO<sub>2</sub>·dm<sup>-3</sup> and 68.4 mgO<sub>2</sub>·dm<sup>-3</sup>, respectively. The average concentration of total  
 312 suspended solids was 39.0 mg·dm<sup>-3</sup>, total phosphorus 12.0 mg·dm<sup>-3</sup>, total nitrogen  
 313 82.4 mg·dm<sup>-3</sup>. The average values of BOD<sub>5</sub>, COD, and total suspended solids in wastewater  
 314 treated in the VF bed met the requirements specified in the Regulation of the Minister of  
 315 Environment (2014) for wastewater discharged to waters or to the ground from treatment  
 316 plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable  
 317 conditions for the oxidation of organic pollutants and nitrification. The average oxygen  
 318 content in the wastewater flowing out from the first bed increased to about 3 mg·dm<sup>-3</sup>  
 319 compared to the mechanically treated wastewater, while the average concentration of  
 320 ammonia nitrogen slightly exceeded 20 mg·dm<sup>-3</sup>. The total nitrogen balance in the VF bed  
 321 indicates the existence of processes leading to the permanent removal of this component from  
 322 the wastewater, including, mainly, the process of denitrification and uptake by vegetation.  
 323 Despite this, the content of total nitrogen at the outflow from the VF bed remained high, on  
 324 average 82.4 mg·dm<sup>-3</sup>, with values well above 100 mg·dm<sup>-3</sup>. High concentration of total  
 325 nitrogen suggests that a significant part of ammonia nitrogen after transformation to the  
 326 nitrate form did not undergo any further transformation. Therefore, the average concentration  
 327 of nitrate nitrogen in the wastewater discharged from the VF bed was 24.5 mg·dm<sup>-3</sup> (Table 1).  
 328 The wastewater discharged from the first bed also contained high concentrations of total  
 329 phosphorus (an average of 11.0 mg·dm<sup>-3</sup>). For both biogenic parameters, the average values  
 330 were more than twice as high as the level stipulated by the law as acceptable for treatment  
 331 plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of  
 332 the Environment, 2014).

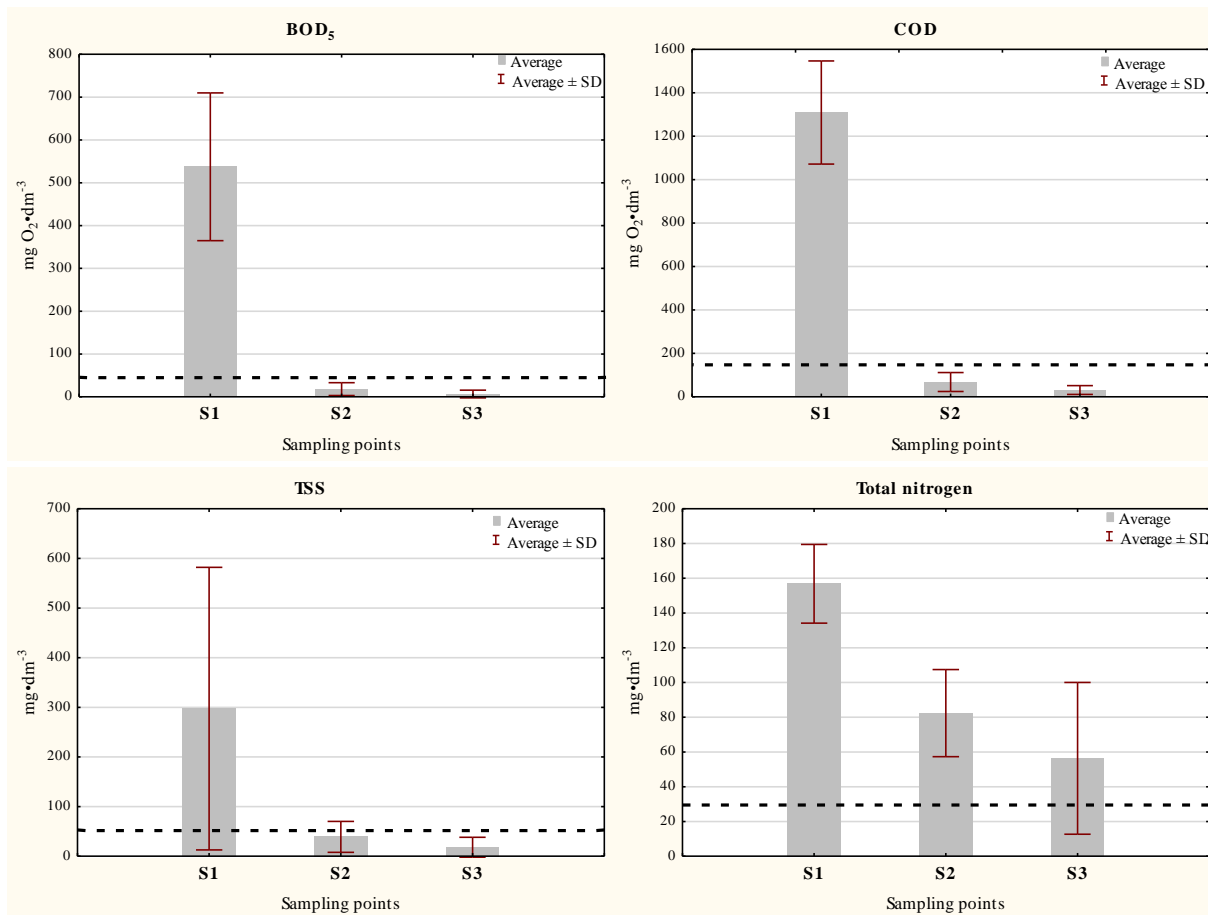
333

### 334 **Pollutant concentrations in the effluent from the HF bed**

335 An HF bed in a hybrid system is designed to optimise total nitrogen and organic  
 336 compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun,  
 337 2012). The average concentrations of BOD<sub>5</sub>, COD, and total suspended solids in wastewater  
 338 discharged from the HF bed into the receiver were 6.6 mg·dm<sup>-3</sup>, 31.8 mg·dm<sup>-3</sup>, and  
 339 18.0 mg·dm<sup>-3</sup>, respectively (Table 1). The respective median values were 3.1, 29.0, and  
 340 10.2 mg·dm<sup>-3</sup>. These values were significantly lower than the limit values stipulated in the

341 Regulation of the Minister of the Environment (2014). The average concentrations of total  
 342 nitrogen and total phosphorus in treated wastewater ( $56.4 \text{ mg}\cdot\text{dm}^{-3}$  and  $6.7 \text{ mg}\cdot\text{dm}^{-3}$ ,  
 343 respectively) did not meet the above requirements (Figure 4). The average value of total  
 344 nitrogen in treated wastewater was most strongly affected by the results collected during the  
 345 initial period of operation of the plant (about 18 months), when the vegetation was not yet  
 346 fully developed. The analysis of basic statistics highlights two tendencies: clear discrepancies  
 347 between the extreme values, and high coefficients of variation for the individual pollution  
 348 parameters of wastewater outflowing from the VF-HF system. Because the concentrations of  
 349 contaminants in the effluent were low, the results may have been much more strongly  
 350 influenced by environmental factors, precipitation and temperature, or random changes in  
 351 operating conditions compared with the results for S1 and S2.

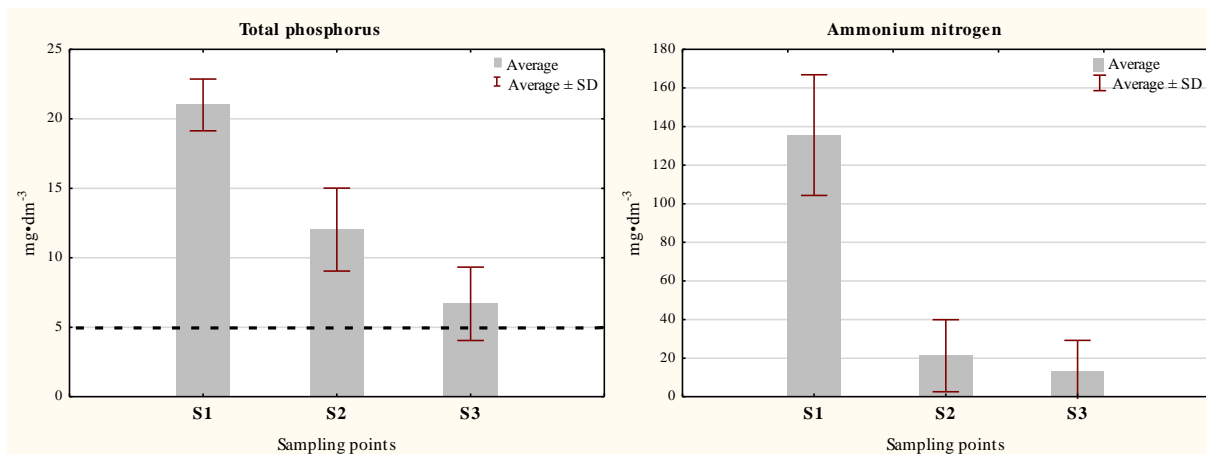
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 357 **Fig. 4.** Dynamics of reduction of pollutant concentrations in the successive stages of treatment  
 358 Notation: dashed black line – Polish legal requirements for wastewater discharged into water and soil  
 359 from treatment plants below 2000 p.e.  
 360 (Regulation of the Minister of the Environment, 2014)  
 361

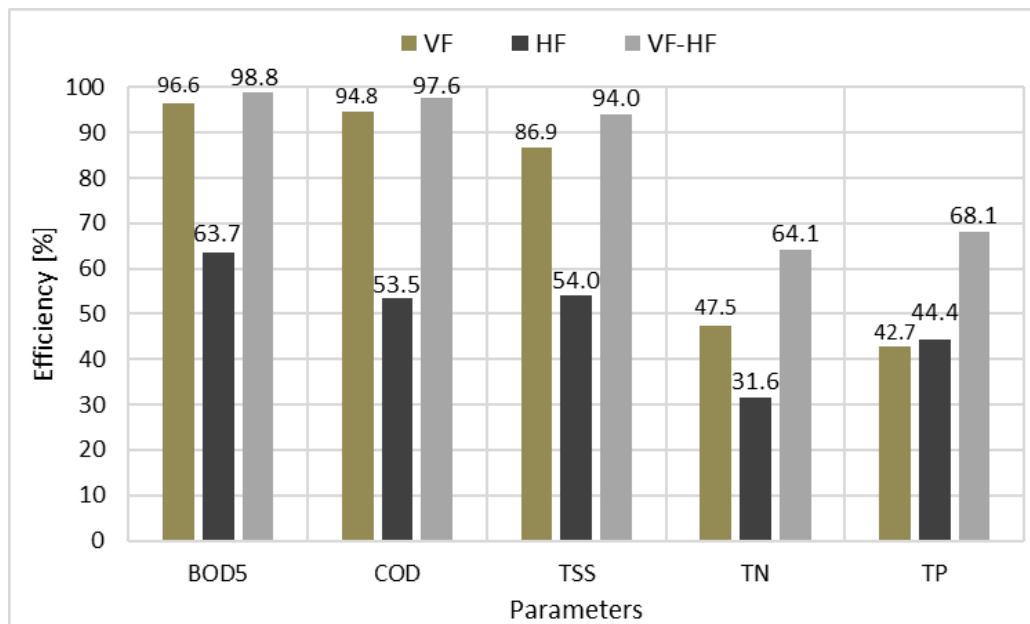
### 362 **3.2. Pollutant removal efficiency**

363 The results indicate that the investigated CW had a high efficiency of removal of organic  
 364 pollutants and total suspended solids, and a lower efficiency of elimination of biogenic  
 365 compounds (total nitrogen and total phosphorus). The differences between the various stages  
 366 of treatment were clear-cut. The largest proportion of the investigated pollutants were  
 367 eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of  
 368 organic pollutants and moderately good conditions for the removal of biogenic pollutants.  
 369 Several factors may have been of significance here, including the way the bed was fed with  
 370 sewage and the associated availability of oxygen, the hydraulic and pollution loads on the  
 371 bed, the vegetation, and air and wastewater temperature. The low hydraulic load of the VF  
 372 bed (an average of 12.5 mm·d<sup>-1</sup>) ensured optimal time of contact of sewage with the  
 373 microorganisms forming the biological membrane on the filling material (Saeed and Sun,  
 374 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet  
 375 periods, may have, in accordance with generally accepted opinions, increased the diffusion of  
 376 atmospheric oxygen and improved the conditions for the oxidation of organic pollutants and  
 377 the course of the nitrification process (Jia et al., 2010; Gervin and Brix, 2001).

378 The average efficiency of the entire VF-HF system in removing organic pollutants from  
 379 wastewater in the 5-year research period was 98.8% for BOD<sub>5</sub> and 97.6% for COD (Figure 5).  
 380 The effects of BOD<sub>5</sub> and COD removal were similar to or higher than those recorded by other  
 381 authors in hybrid constructed wetland systems operating under similar climatic conditions

382 (Krzanowski et al., 2005; Gajewska and Obarska-Pempkowiak, 2009; Vymazal and  
383 Kröpfelová, 2009).

384 The largest part of the pollution load was eliminated in the first stage of treatment in the  
385 VF bed. Although the amount of sewage flowing into the treatment plant constituted about  
386 50% of the designed value, the load of organic pollutants in the first bed, was quite high and  
387 amounted to  $6.7 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  ( $\text{BOD}_5$ ) and  $16.4 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  (COD), respectively. Moreover, the  
388 wastewater flowing into the VF bed was characterised by an unfavourable  $\text{BOD}_5/\text{COD}$  ratio  
389 (2.4), which testified to the lower susceptibility of the tested wastewater to biological  
390 decomposition. Despite this, nearly 97% of  $\text{BOD}_5$  and 95% COD were removed from the VF  
391 bed, which is a very good result. The system under investigation was rather insensitive to the  
392 high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia  
393 (2006) observed a similar relationship in their studies. Research carried out under similar  
394 climatic conditions has shown that the removal efficiency of VF reservoirs with regard to  
395  $\text{BOD}_5$  is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011;  
396 Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to  
397 various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010;  
398 Masi and Martinuzzi, 2007).



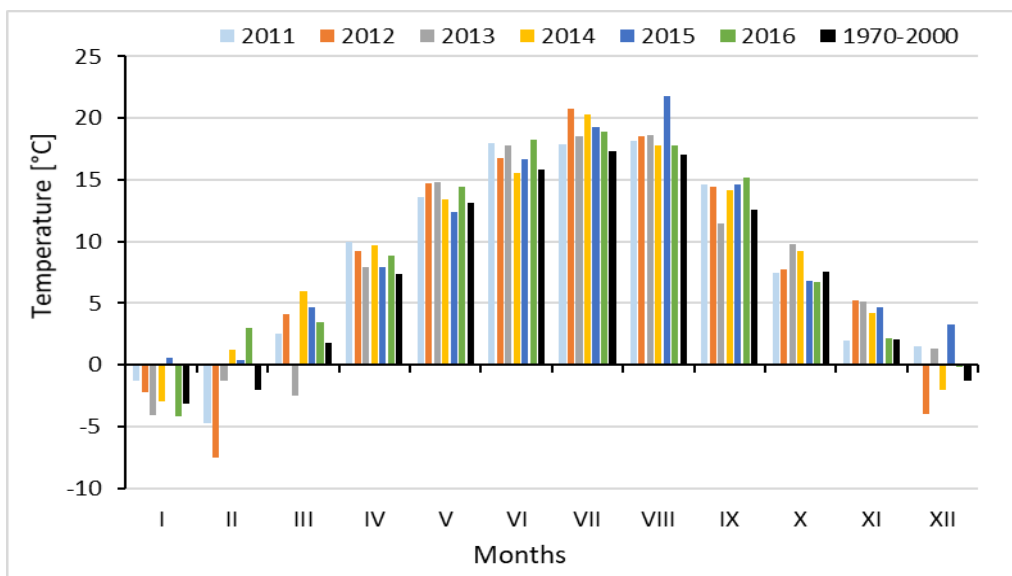
399  
400 **Fig. 5.** Average pollutant removal efficiency of the investigated system

401  
402 In the HF bed, the elimination of organic pollutants ( $\text{BOD}_5$  and COD) was 63.7% and  
403 53.5%, respectively. Research carried out by Obarska-Pempkowiak et al. (2010) indicates that  
404 HF type systems can provide a higher degree of COD reduction, but at higher contaminant  
405 loads.

406 The average efficiency of removal of total suspended solids in the analysed system was  
407 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed  
408 54% of the solids. The efficiency of the tested system in removing total suspended solids was  
409 higher than demonstrated by other authors. For comparison, a HF-VF system investigated by  
410 Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result  
411 that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by  
412 Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids  
413 removal efficiency of 89%.

414 The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%,  
415 with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to  
416 Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid  
417 constructed wetland systems may range from 23 to 80%, depending on the configuration and  
418 operating conditions of the beds. In the light of these reports, the effectiveness of the facility  
419 tested in this present study was moderately high, but not high enough to obtain stable results  
420 at the outflow that would meet the requirements set out in the Polish regulations (Regulation  
421 of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have  
422 been caused by a lack of appropriate conditions for effective denitrification in the HF bed,  
423 especially the deficit of organic compounds and the unfavourable BOD<sub>5</sub>/TN ratio inhibiting  
424 the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of  
425 meteorological conditions in the area of the conducted research (meteorological station in  
426 Radawiec near Lublin) showed that the significance of this last factor could have been  
427 smaller. Against the background of some long-term data, there can be observed a tendency of  
428 increasing the average air temperature (Figure 6). Throughout the entire research period  
429 (2011-2016) average annual temperatures were higher than the long-term average  
430 (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April  
431 to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from  
432 October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can  
433 be concluded that, apart from periods that are considered to be unfavorable in a moderate  
434 climate (December-February) temperature should not be a limiting factor for microbial  
435 removal processes.





**Fig. 6.** The average monthly temperatures for Radawiec near Lublin in the years 2011-2016 (IMWM, 2011-2016; CSO, 2017)

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440 The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The  
441 two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare,  
442 the average total phosphorus removal efficiencies for hybrid CW systems studied by other  
443 authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the  
444 highest phosphorus removal rates were found in the initial period of the plant's operation,  
445 which confirms the observation that the kind of filling of beds plays an important role in the  
446 process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant  
447 removal in different facilities or in different units of the same system is the mass removal rate  
448 (MRR), which provides a measure of the amount of a component removed per unit area of  
449 a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass  
450 removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage  
451 treatment plant in south-eastern Poland. The indicators were determined on the basis of the  
452 assumption that the average annual sewage outflow from individual purification stages is  
453 equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to  
454 evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration  
455 efficiency in CW is subject to great fluctuations, depending on seasonal conditions, it can  
456 range from 0 to 50 mm·d<sup>-1</sup> (Chazarenc et al. 2010). According to Herbst and Kappen (1999) in  
457 natural bog systems with common reed in northern Germany, in the full vegetation period, it  
458 may exceed 10 mm·d<sup>-1</sup>, but in other periods (from November to April) it approaches zero.  
459 These researchers also found that under certain conditions (cloudy and rainy weather) the

460 efficiency of evapotranspiration during the year may be similar or even lower than the total  
 461 precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the  
 462 multi-stage constructed wetland confirmed the possibility of maintaining balance of beds  
 463 evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant,  
 464 factors limiting the efficiency of evapotranspiration could be the proximity of high plants at  
 465 the south-western side, which cause periodic shading of beds and reduce air movement.  
 466 Moreover, the research of Toscano et al. (2015) indicate that the efficiency of  
 467 evapotranspiration on the beds planted with giant miscanthus, even under warm climate  
 468 conditions, is clearly lower than on the beds with common reed.

469 Despite the lower than planned hydraulic load, the pollution load in the investigated system  
 470 was comparable to those found in other constructed wetlands tested in Poland (Gajewska and  
 471 Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were  
 472 relatively high, similar to those recorded in two- and three-stage constructed wetland systems,  
 473 described by Gajewska and Obarska-Pempkowiak (2011).

474 Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the  
 475 values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al.,  
 476 2003).

477 The VF bed played a decisive role in the removal of organic pollutants. The mass removal  
 478 rates determined for this field were many times higher than in the case of the HF bed  
 479 (Table 3).

480

481 **Table 3.** Mass removal rates of BOD<sub>5</sub>, COD, total nitrogen (TN) and total phosphorus (TP)

Parameters		VF	HF	VF-HF
BOD <sub>5</sub>	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	6.71	0.27	3.66
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	6.49	0.17	3.62
COD	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	16.36	1.02	8.93
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	15.51	0.54	8.70
TN	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	1.96	1.23	1.07
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.93	0.39	0.68
TP	Load [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.26	0.18	0.14
	Mass Removal Rate [g·m <sup>-2</sup> ·d <sup>-1</sup> ]	0.11	0.08	0.10

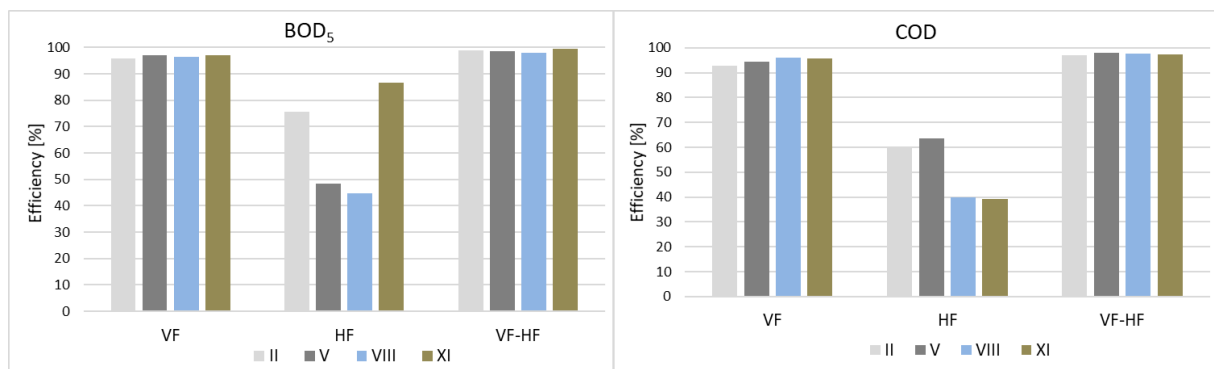
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483 The investigated wastewater treatment plant in south-eastern Poland, with giant miscanthus  
 484 and Jerusalem artichoke, provided efficiency in the area of organic and biogenic compounds  
 485 removal similar to other systems using classic plant species that function under similar  
 486 operating conditions. In such systems, plants perform an auxiliary role, creating favorable

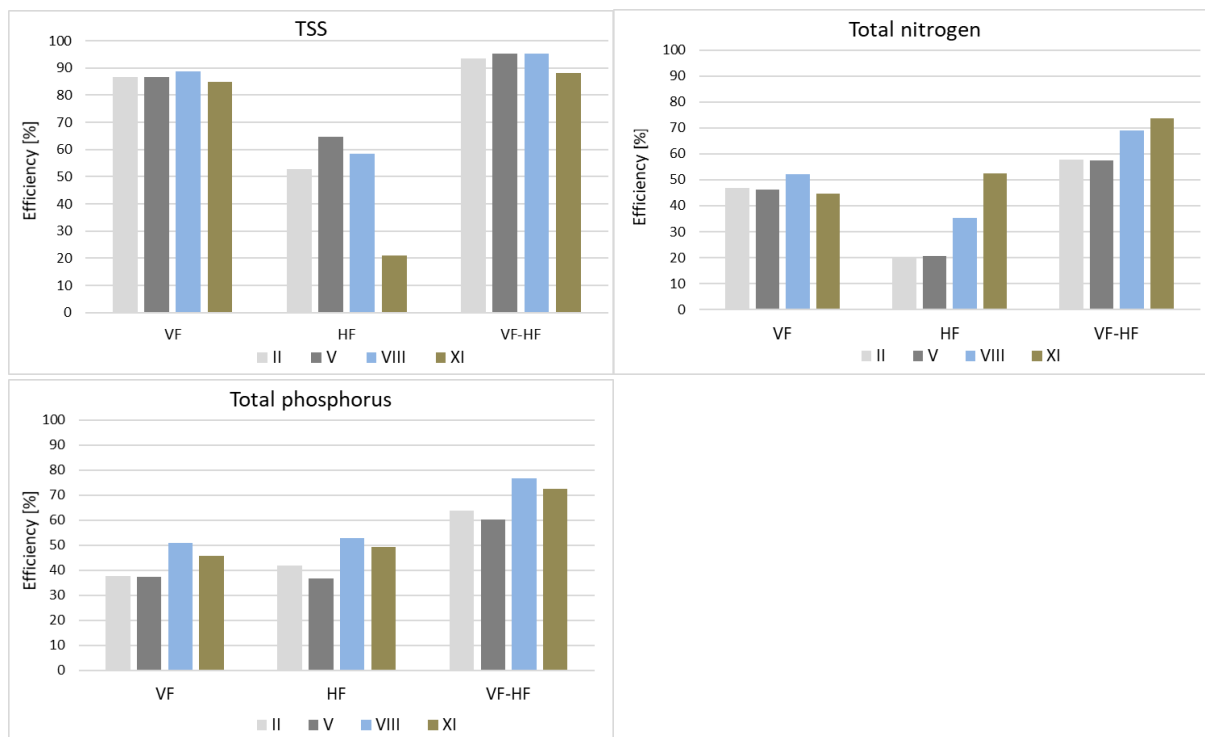
487 conditions for the activity of microorganisms and the course of biochemical processes in the  
 488 bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out  
 489 on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment  
 490 effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the  
 491 average removal effects were constant during the whole year (Figure 7). Higher variability  
 492 was found on the HF field, however, it is difficult to relate this to seasonal conditions, because  
 493 the average efficiency of BOD<sub>5</sub> decreasing was the highest in autumn and winter. Most  
 494 researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although  
 495 some studies did not show differences between the removal of these compounds in the  
 496 summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on  
 497 microbial removal processes can be associated with the dominance of physical processes. In  
 498 addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of  
 499 kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen  
 500 conditions.

501 The average efficiency of nitrogen and phosphorus removal from wastewater was slightly  
 502 higher in August and November. However, the share of plants in the uptake of pollutants from  
 503 sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The  
 504 yield of giant miscanthus on the VF field in the first year of operation was at a low level –  
 505 0.42 kg DM·m<sup>-2</sup> (Gizińska-Górna et al., 2017b). In the following years, it fluctuated within  
 506 the limits of 3.55–4.43 kg DM·m<sup>-2</sup> and was clearly higher than the yields recorded in field  
 507 crops of this plant (Szulczewski et al., 2018). The average nitrogen content in aboveground  
 508 parts of giant miscanthus was 5.8 g·kg DM<sup>-1</sup>, which means that with the highest yield (2016),  
 509 approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of  
 510 phosphorus – 0.26 g·kg DM<sup>-1</sup> its mass accumulated in aboveground parts of giant miscanthus  
 511 amounted to a maximum level of 0.11 kg.

512



513



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517

**Fig. 7.** Average removal efficiency of pollutants in different months of the research.  
Notation: II – February; V – May; VIII – August; XI – November

518

519 The yield of Jerusalem artichoke on the HF bed ranged from 0.83 kg DM·m<sup>-2</sup> in 2013 to  
520 1.43 kg DM·m<sup>-2</sup> in 2015. The average nitrogen content in aboveground parts of plants was  
521 3.4 g·kg DM<sup>-1</sup>, and phosphorus – 0.34 g·kg DM<sup>-1</sup>. In 2015, the nitrogen and phosphorus  
522 masses contained in the aboveground biomass were respectively 0.47 kg and 0.047 kg.

523 In the years which were most favorable in terms of yield of giant miscanthus and  
524 Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of  
525 both plants in relation to the mass of nitrogen removed in these years in the VF-HF system  
526 ranged from 5% to 6.3%. For phosphorus, it was about 2.6%. Baring in mind the fact that the  
527 plant activity associated with biomass production is limited to the growing season (in south-  
528 eastern Poland it usually lasts from April to September), it can be concluded that real  
529 contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the  
530 case of nitrogen and 5% in the case of phosphorus.

531 In this case, it can be concluded that the physicochemical processes, such as oxidation or  
532 adsorption by the substrate elements, could have a big influence on nitrogen removal (Bulc,  
533 2006; Saeed and Sun, 2012). Physicochemical processes, especially substrate sorption, could  
534 also be very important in the elimination of phosphorus from wastewater (Józwiakowski et  
535 al., 2018; Xu et al., 2006).



536

### 537 **3.3. Pollutant removal reliability**

538 The reliability of the tested wastewater treatment plant, defined as its ability to dispose of  
539 the expected amount of wastewater to the extent required by the wastewater receiver, was  
540 determined using the Weibull method. The method allows a more in-depth analysis of  
541 qualitative data than is possible with average values, through the prism of legal requirements  
542 for sewage discharged to the environment. The first step was to estimate the parameters of  
543 distribution and verify the null hypothesis that empirical data could be described by Weibull's  
544 distribution. The data sets were the values of the basic pollution parameters (BOD<sub>5</sub>, COD,  
545 TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF  
546 constructed wetland system to the receiver.

547 The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit  
548 test along with the estimated parameters, are presented in Table 4.

549

550 **Table 4.** Parameters of the Weibull distribution and results of the Hollander-Proschan

551

goodness-of-fit test

Parameter	Parameters of Weibull distribution			Hollander-Proschan goodness-of-fit test	
	$\theta$	$c$	$b$	stat	p
BOD <sub>5</sub>	0.0000	0.8410	5.9731	0.1732	0.8625
COD	5.4646	1.7097	35.8400	0.1496	0.8810
TSS	1.6182	0.9676	17.6798	0.3140	0.7535
Total Nitrogen	9.0606	1.3572	61.8000	0.1807	0.8565
Total Phosphorus	-0.2000	2.8367	7.4737	-0.3043	0.7608

552

553 Symbols: stat – value of the test statistic, p – significance level of the test; when  $p \leq 0.05$  the  
554 distribution of data is not a Weibull distribution

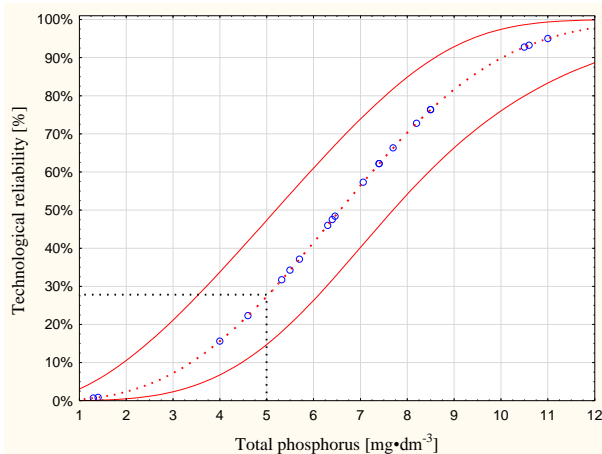
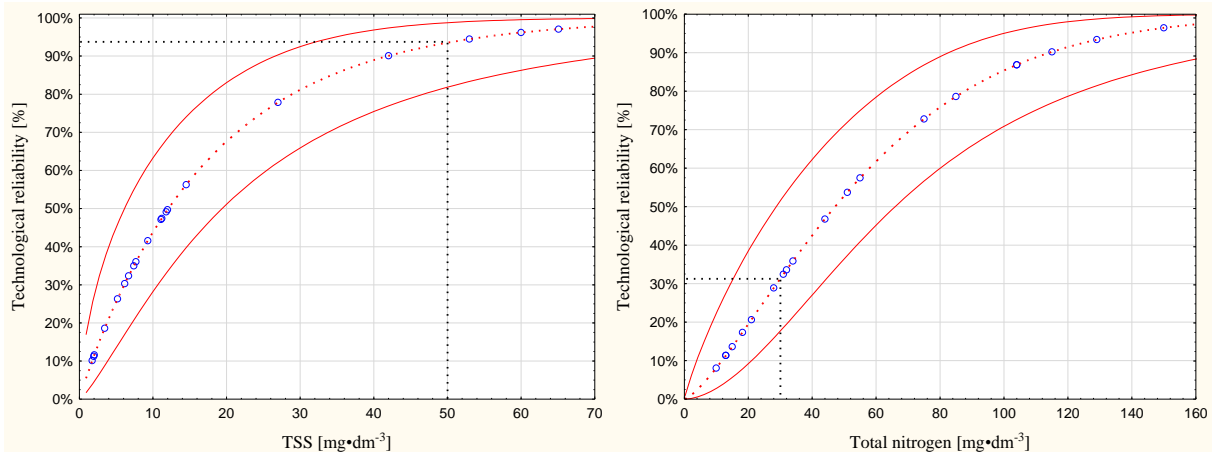
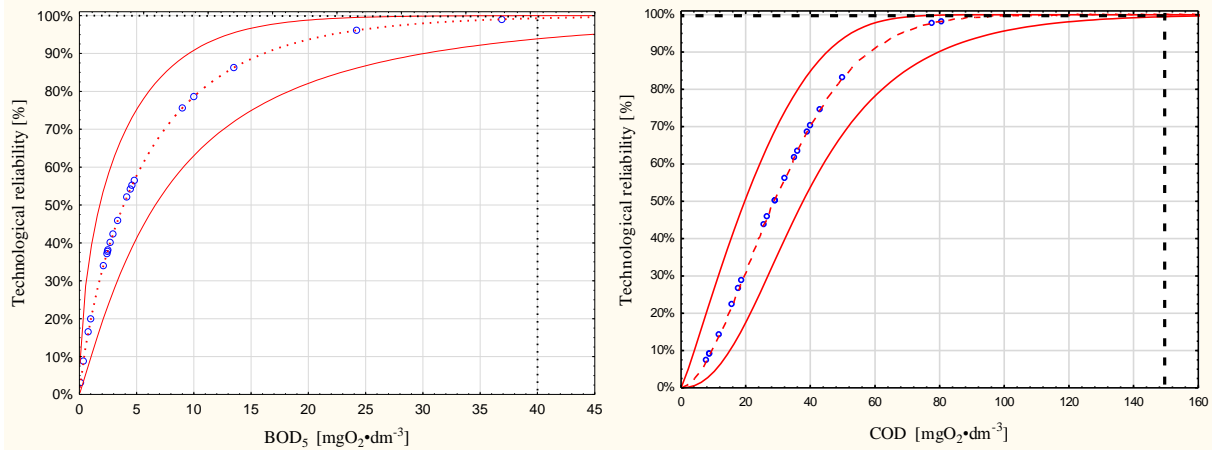
555

556 The goodness-of-fit of the obtained distributions was high at 75–88%, at a significance  
557 level  $\alpha = 0.05$ . The technological reliability of the treatment plant was determined on the basis  
558 of the distribution functions, taking into account the limit values for the parameters, as  
559 specified in the Regulation of the Minister of Environment for WWTPs of less than 2000 p.e.  
560 (Regulation of the Minister of the Environment, 2014) (Figure 8).

561 The organic pollutant removal reliability expressed by BOD<sub>5</sub> and COD was 100%  
562 (Figure 8). This means that the plant operated without any problems throughout the testing  
563 period, and the values of the tested parameters in the treated wastewater did not exceed the  
564 acceptable levels stipulated in the Polish law (40 and 150 mgO<sub>2</sub>·dm<sup>-3</sup>, respectively). This

565 leads to the conclusion that, with an operator risk of  $\alpha = 0.05$ , the plant should successfully  
566 pass inspection with regard to the parameters concerned throughout the year.

567 The reliability of removal of total suspended solids from sewage in the tested system was  
568 93%. On this basis, it can be concluded that the plant operated smoothly on average 339 days  
569 a year. The period of failure-free operation is equivalent to the period when the concentration  
570 of total suspension particles in the wastewater discharged to the receiver was below the  
571 required limit ( $50 \text{ mg}\cdot\text{dm}^{-3}$ ).



576 **Fig. 8.** Weibull cumulative distribution functions and the technological reliabilities  
577 determined for each pollution parameter

578 Notation: dashed red line – reliability function, continuous red line – confidence intervals,  
579 dashed black line – probability of reaching the effluent parameter limit

580  
581 According to the guidelines proposed by Andraka and Dzienis (2003), the minimum  
582 reliability level for treatment plants below 2000 p.e. should be 97.27%, which means that  
583 these plants, even when operating poorly for 9 days a year, still have a 95% chance of  
584 successfully going through inspection procedures. Given these guidelines, it can be assumed  
585 that the limit concentrations of total suspended solids in the CW investigated in this present  
586 study can be exceeded without affecting the plant's operation on 17 days a year.

587 The reliability of removal of nutrients was significantly lower than in the case of organic  
588 pollutants. The probability that the total nitrogen concentration in treated effluents would  
589 reach the limit value ( $30 \text{ mg}\cdot\text{dm}^{-3}$ ) established for effluents discharged from a treatment plant  
590 of less than 2000 p.e. to standing waters was 32%. This means that the total nitrogen  
591 concentration in treated wastewater exceeded the limit value, and the plant operated  
592 incorrectly on 249 days a year.

593 An even lower level of reliability was found for total phosphorus removal. The probability  
594 that the concentration of this parameter in treated wastewater would reach a value below  
595  $5 \text{ mg}\cdot\text{dm}^{-3}$  was 28%. This means that the plant operated correctly for only 102 days a year,  
596 and excessive concentrations of total phosphorus in treated wastewater were recorded on  
597 254 days a year.

598 The reliability levels obtained indicate that the hybrid constructed wetland with giant  
599 miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant  
600 removal. The facility guaranteed stable low BOD<sub>5</sub> and COD results for the treated wastewater,  
601 which meant it was highly likely to be positively evaluated in the case of an inspection. These  
602 conclusions are consistent with the reports of other authors, which indicate that hybrid  
603 systems are very reliable with respect to BOD<sub>5</sub> and COD reduction (Jucherski et al., 2017;  
604 Józwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher  
605 than that of single-stage constructed wetland systems (Józwiakowski, 2012; Józwiakowski et  
606 al., 2017) or other small sewage treatment plants using other technological solutions. For  
607 comparison, the organic pollutant removal reliabilities (expressed as BOD<sub>5</sub> and COD) of  
608 plants operating on the basis of conventional treatment methods (activated sludge, biological



609 bed, hybrid reactor), were 60–88% and 89–92%, respectively, and in extreme cases as low as  
610 30% (Marzec, 2017; Bugajski et al., 2012; Wałęga et al., 2008).

611 The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the  
612 tested facility were 32 and 28%, respectively, which indicates that treated wastewater was  
613 highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the  
614 performance of the system was not satisfactory in this respect. Tests carried out in other  
615 facilities show that similar or higher levels of nutrient removal reliability are reached in  
616 single-stage constructed wetland systems (Józwiakowski, 2012; Józwiakowski et al., 2018).  
617 Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the  
618 hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen  
619 and 95.2% for total phosphorus. It should be noted, however, that the normative values for  
620 nitrogen and total phosphorus used in reliability assessment refer only to specific cases when  
621 treated wastewater is discharged to lakes and their tributaries and directly to artificial water  
622 reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014).  
623 Moreover, according to the Polish law, there is no obligation to control the operation of  
624 domestic sewage treatment plants or to perform quality tests of sewage discharged to the  
625 environment. In this light, the assessment of nutrient removal reliability of domestic treatment  
626 plants is a theoretical issue, which does not mean that it should not become a common part of  
627 wastewater management practice in the future. In combination with an analysis of the  
628 effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of  
629 wastewater treatment plants allows to determine what technological solutions should be  
630 promoted when building sewage systems in rural areas to support water protection against  
631 pollution and eutrophication. The use of highly efficient and reliable wastewater treatment  
632 systems can reduce the use of the cheapest solutions, which instead of protecting the  
633 environment pose a potential threat to it. According to the emerging suggestions, it also seems  
634 necessary to create administrative and legal instruments in Poland which would enable control  
635 of all sewage treatment plants, regardless of their size and type of receiver (Józwiakowski et  
636 al., 2015; Marzec, 2017; Józwiakowski et al., 2018).

637

#### 638 **4. Conclusions**

639 In the five-year research period, the hydraulic load of the analysed VF-HF system with  
640 giant miscanthus and Jerusalem artichoke in south-eastern Poland was about 50% of the  
641 design value; however, the load of contaminants did not differ significantly from that found in  
642 similar constructed wetlands.

643 The average effectiveness of organic pollutant removal expressed as BOD<sub>5</sub> and COD was  
644 98.8 and 97.6%, respectively; the corresponding value for total suspended solids was 93%.  
645 Under the conditions typical for moderate climate, the hybrid VF-HF system provided high  
646 and stable effects of organic pollutants removal throughout the whole year. In the VF bed, the  
647 concentration of organic pollutants (BOD<sub>5</sub> and COD) in the inflowing sewage was removed  
648 on average by over 94%.

649 Technological reliability of the constructed wetland wastewater treatment plant with giant  
650 miscanthus and Jerusalem artichoke concerning BOD<sub>5</sub> and COD amounted to 100%. Under  
651 given operating conditions, the facility ensures failure-free operation and the fulfillment of  
652 Polish legal requirements throughout the whole year. The reliability of removal of total  
653 suspended solids was 93%.

654 The efficiencies of total nitrogen and total phosphorus removal were 64.1 % and 68.1%,  
655 respectively, and the average values of these components in the outflow from the treatment  
656 plant exceeded the standard levels. The lower efficiency of total nitrogen removal was  
657 probably caused by unfavourable denitrification conditions in the HF bed, including the  
658 deficit of organic compounds.

659 The CW had low total nitrogen and total phosphorus removal reliabilities (32% and 28%,  
660 respectively).

661 Giant miscanthus and Jerusalem artichoke showed favorable features when it comes to  
662 their use in constructed wetlands, also under moderate climate conditions. They were  
663 characterized by high resistance to unfavorable environmental conditions, and even at low  
664 hydraulic load, high yield potential. Despite the high yield, their share in the uptake of  
665 biogenic pollutants from wastewater was relatively small.

666 Giant miscanthus is characterized by a clearly higher biomass production than Jerusalem  
667 artichoke, has a well-developed root system, and the operation of miscanthus beds is simpler.  
668 Jerusalem artichoke generates large amounts of tubers, which allow the plant to compact the  
669 entire surface of the bed, and after some time their accumulation can affect the balance of  
670 pollutants in the bed. To avoid this, there is often a need to remove them during the operation  
671 of the facility.

672 The investigated hybrid constructed wetland system with giant miscanthus and Jerusalem  
673 artichoke had organic and biogenic pollutant removal efficiencies that were similar to those  
674 obtained in systems using classic plant species such as reed and willow. Giant miscanthus and  
675 Jerusalem artichoke can be successfully used to support wastewater treatment processes in



676 constructed wetland systems, and, owing to their high biomass production potential, they can  
677 also be exploited as energy yielding materials.

678

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680

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690

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