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Efficiency and Technological Reliability of Contaminant Removal in Household WWTPs with Activated Sludge

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Abstract: The results of research on the efficiency and technological reliability of domestic wastewater purification in two household wastewater treatment plants (WWTPs) with activated sludge are presented in this paper. The studied facilities were located in the territory of the Roztocze National Park (Poland). The mean wastewater flow rate in the WWTPs was 1.0 and 1.6 m^3/day. In 2017–2019, 20 series of analyses were done, and 40 wastewater samples were taken. On the basis of the received results, the efficiency of basic pollutant removal was determined. The technological reliability of the tested facilities was specified using the Weibull method. The average removal efficiencies for the biochemical oxygen demand in 5 days (BOD_5) and chemical oxygen demand (COD) were 66–83% and 62–65%, respectively. Much lower effects were obtained for total suspended solids (TSS) and amounted to 17–48%, while the efficiency of total phosphorus (TP) and total nitrogen (TN) removal did not exceed 34%. The analyzed systems were characterized by the reliability of TSS, BOD_5, and COD removal at the level of 76–96%. However, the reliability of TN and TP elimination was less than 5%. Thus, in the case of biogenic compounds, the analyzed systems did not guarantee that the quality of treated wastewater would meet the requirements of the Polish law during any period of operation. This disqualifies the discussed technological solution in terms of its wide application in protected areas and near lakes, where the requirements for nitrogen and phosphorus removal are high.

Keywords: efficiency of contaminant removal; technological reliability; wastewater purification; activated sludge; national park

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1. Introduction

In national parks and protected areas, there are usually museums, forester's lodges, hostels, or tourist trails with resting places for visitors, which should be equipped with sanitary infrastructure that ensures their proper functioning. According to the Law on Nature Protection [1] in Poland and the Council Directive 92/43/EEC [2], in the area of national parks and nature reserves, it is forbidden to build or reconstruct any buildings or technical facilities with the exception of facilities and devices that serve to achieve the goals of the given national park or nature reserve. For this reason, it is essential in protected areas to use water supply systems and wastewater treatment plants (WWTPs) that do not interfere with the environment [3,4] and meet the criteria of sustainable development and nature protection [5–7].

Domestic wastewater generated by various tourist facilities in national parks or protected areas, just as in rural areas, is most often discharged to non-return tanks (septic tanks) and is then taken to collective WWTPs or disposed of in individual wastewater treatment systems, i.e., in so-called small household WWTPs [8,9]. A similar way of dealing with domestic sewage in protected and rural areas, where sewerage systems and collective treatment plants are lacking, is also in force in other countries around the world [10–19].

In recent years, household WWTPs have increasingly become one of the basic elements of technical infrastructure in protected areas where, due to natural and landscape values and large dispersion of tourist buildings, the installation of a sewerage network and a collective WWTP is not justified [9,13,14,17,19]. In accordance with Polish Standard PN-EN 12,566 [20], household WWTPs are defined as facilities for 50 inhabitants. However, on the basis to the Water Law [21], the maximum capacity of such systems in Poland should not exceed 5 m^3/day.

Various technological solutions are currently used to treat small amounts of wastewater, such as systems with drainage pipes, systems with a sand filter, WWTPs with activated sludge, systems with a biological bed, hybrid systems (activated sludge + biological bed), and constructed wetland systems (CWs) [7,22].

A review of the literature on the evolution of wastewater management and its development over the centuries was presented by Lofrano and Brown [23]. Currently, the activated sludge method is the most commonly used for wastewater purification in the world. Activated sludge is most often used for urban wastewater treatment [24–27], as well as for industrial wastewater [28,29]. The popularity of the activated sludge method used in large WWTPs around the world has led to the development of "miniature" facilities of this type, whereby for over 30 years, attempts have been made to replicate the technological processes [24,30–35]. However, it is important for household WWTPs with activated sludge, which are used to treat small sewage amounts, to meet the appropriate criteria.

The most important aspects that should be considered during the selection of a technological solution involving small WWTPs are the efficiency of pollutant removal and the reliability of operation [4]. These criteria should be taken into account especially for WWTPs installed in protected areas [36]. In the case of WWTPs, efficiency refers to the degree of removal of particular types of pollutants, which is determined by the amount of pollutants retained in the system in relation to the amount of pollutants entering the system. Reliability, on the other hand, is defined as the ability to treat wastewater to the degree required by the wastewater receiver over the assumed operating time, including changes in the quantity and the composition of the inflow [32,33]. The reliability level corresponds to the probability of reaching a value of the indicator in the outflow from the WWTPs that is lower than the acceptable value; thus, reliability can be understood as the percentage of time during which the expected concentrations of pollutants in the treated wastewater are in accordance with the accepted standards or purification objectives [37,38].

The reliability and operational efficiency of activated sludge WWTPs have been previously studied by different authors [32,33,35,37,39–41]. However, there is still a lack of research results on the technological reliability of household WWTPs with activated sludge, which are analyzed over a longer period of time, especially in facilities operating in protected areas. A comprehensive analysis of the efficiency of operation of different types of WWTPs based on statistical inference and taking into account elements of reliability theory makes it possible to identify technological solutions which are characterized by the highest efficiency and stability of operation under changing conditions during many years of operation. This is important from the administrative, legal, and ecological point of view. It allows estimating the chances of passing possible control procedures, as well as establishing a hierarchy of particular technological solutions in terms of their influence on the environment. The results regarding the efficiency and reliability of household WWTP technologies should be an important element in planning the development of technical infrastructure, enabling the selection of optimal solutions under given conditions [32].

The purpose of this paper is to present the results of research on the technological reliability and the efficiency of domestic wastewater purification in two household WWTPs with activated sludge located in the area of the Roztocze National Park (RNP) in Poland. The paper contributes new content to science, because, in the world, there remain few studies related to the technological reliability of household WWTPs operating on a real scale.

2. Materials and Methods

2.1. Presentation of the Studied Facilities

The RNP is located in southeastern Poland in a temperate, transitional climate zone. Groundwater, as well as surface water, in the RNP is of a very good quality; thus, it is crucial to protect it from degradation [42]. In order to protect the quality of surface water and groundwater, in recent years, within the area of the RNP, some steps have been taken to build household WWTPs to treat wastewater outflowing from foresters' lodges.

For the analysis, two household WWTPs located in the area of the RNP were selected. The studied facilities consist of a four-chamber preliminary settling tank and a special reactor with activated sludge. They are located in Obrocz for the office building (facility no. 1) and Rybakówka for the forester's lodge (facility no. 2). The exact location of these facilities in the RNP was presented by Micek et al. [9]. The mean wastewater flow rate in the studied WWTPs was 1.0 and 1.6 m^3/day, respectively. In Table 1, chosen technological parameters of the studied facilities are presented, and Figure 1 shows their technological scheme. The efficiency of pollutant removal in preliminary settling tanks, which are the first components of the selected household WWTPs in the RPN, was presented by Micek et al. [9].

Table 1. Technological parameters of the household WWTPs in the area of the RNP.

Technological Parameters	Facility No. 1—Obrocz	Facility No. 2—Rybakówka
Year of construction	2014	2014
Mean wastewater capacity Q (m^3/day)	1.0	1.6
Volume of a septic tank (m^3)	5.7	5.7
Volume of an activated sludge chamber (m^3)	1.42	1.83
Wastewater receiver	soil	soil

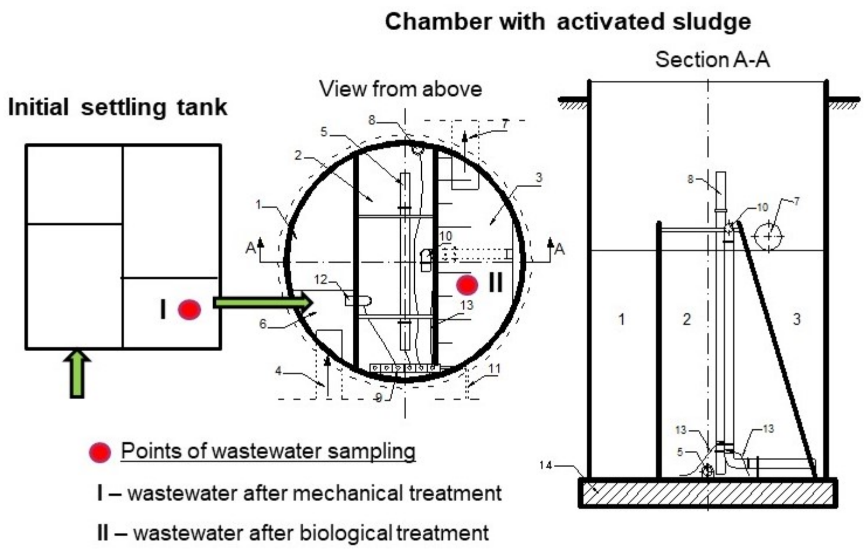

Figure 1. Technological scheme of the household wastewater treatment plants (WWTPs) in the area of the Roztocze National Park (RNP) (prepared on the basis of [43]). Scheme: 1—denitrification chamber; 2—nitrification chamber; 3—separation chamber; 4—wastewater inlet; 5—tube diffuser; 6—basket grate; 7—wastewater outlet; 8—sludge outlet; 9—air distributor; 10—sludge recirculation; 11—air supply; 12—sludge recirculation; 13—air for sludge recirculation; 14—concrete foundation.

2.2. Analytical and Statistical Methods

Studies on the technological reliability and the efficiency of pollutant removal in the two chosen facilities were performed in 2017–2019. Wastewater samples for analyses were taken in different seasons (spring, summer, autumn, and winter) from (I) the four-chamber of the preliminary settling tank—after mechanical treatment, and (II) the outflow from an activated sludge chamber—after biological treatment (Figure 1).

During the study, 20 series of analyses were done and 40 wastewater samples were taken, in which parameters such as total suspended solids (TSS), biochemical oxygen demand in 5 days (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), pH, dissolved oxygen (DO), nitrate nitrogen, nitrite nitrogen, and ammonium nitrogen were determined. Sampling, sample transportation, processing, and analyses were completed on the basis of Polish Standards of Wastewater Examination, which are compatible with the American Public Health Association—APHA [44,45]. The laboratory apparatus used to carry out the analyses was presented in another paper published by Micek et al. [9].

The obtained measurement data enabled calculating the mean, minimum, and maximum concentration of pollutant values and their standard deviation. The mean concentrations of the analyzed pollutant parameters in the influent and effluent from the WWTPs were used to determine the efficiency of pollutant removal (Figure 2).

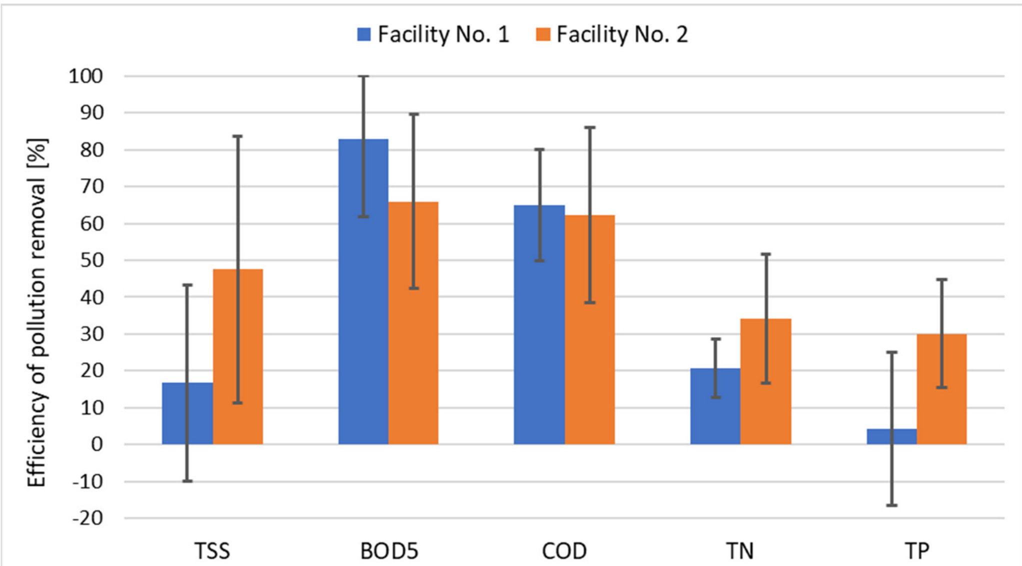

Figure 2. Average efficiency of pollutant removal in two studied household WWTPs.

The evaluation of the technological reliability of the WWTPs was carried out using elements of Weibull's reliability theory, which is a useful tool in assessing the risk of exceeding the normative values in wastewater discharged to the receiver [46].

The Weibull distribution is characterized by the following probability density function [46]:

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

where x is a variable describing the concentration of a pollution parameter in the treated effluent, b is a scale parameter, c is a shape parameter, θ is a position parameter, and e is a constant, assuming $\theta < x$, $b > 0$, $c > 0$, and e = 2.71828.

A variable specifying the values of basic pollution indicators (TSS, BOD_5, COD, TN, and TP) in treated wastewater (n = 20) was analyzed. The analysis consisted of the estimation of the Weibull distribution parameters using the maximum-likelihood method and the verification of the null hypothesis that the analyzed variable could be described by the Weibull distribution. The null hypothesis was verified with the Hollander–Proschan test at the significance level of 0.05 [36]. Reliability was determined from the cumulative distribution function plotted in the graphs, taking into account the normative values of the indicators specified in the Polish regulations [47] for wastewater discharged from treatment plants of up to 2000 PE (population equivalent): BOD_5—40 mg $O_2 \cdot dm^{-3}$, COD—150 mg $O_2 \cdot dm^{-3}$, TSS—50 mg$\cdot dm^{-3}$, TN—30 mg$\cdot dm^{-3}$, and TP—5 mg$\cdot dm^{-3}$. In the case of TN and TP, the values defined for wastewater discharged into lakes and their tributaries, as well as directly into artificial water reservoirs located in flowing waters, were adopted as standard values [47]. The analysis was carried out using Statistica 13.

3. Results and Discussion

3.1. The Efficiency of Pollutant Removal

The chosen statistical values of pollutants in wastewater from the studied household WWTPs are presented in Tables 2 and 3. The concentrations of pollutants in wastewater inflowing to the chambers with activated sludge (after mechanical treatment) were relevantly lower in comparison to raw wastewater flowing into the preliminary settling tanks (the first element of the system), as described in an earlier paper [9]. The values of pollutant concentrations in wastewater inflowing to the activated sludge chambers in the studied WWTPs were close to those described in the literature for wastewater treated mechanically in the preliminary settling tanks [34,35,46,48–50].

Table 2. Pollutant concentrations in the inflow and outflow of facility no. 1. TSS, total suspended solids; BOD_5, biochemical oxygen demand in 5 days; COD, chemical oxygen demand; TN, total nitrogen; TP, total phosphorus.

Parameters		Statistical Indicators							
		Mean		Min		Max		Standard Deviation	
		in	out	in	out	in	out	in	out
pH	-	-	-	7.90	6.29	8.22	7.72	-	-
Dissolved oxygen	mg O_2/dm^3	1.62	8.02	0.23	3.15	7.02	10.56	1.63	1.97
TSS	mg/dm^3	28.7	23.9	5.3	1.3	69.0	73.0	20.9	18.6
BOD_5	mgO_2/dm^3	53.0	9.0	12.3	1.0	80.0	53.0	22.1	12.9
COD	mgO_2/dm^3	180	63	111	20.7	236	130	34.3	27.43
Ammonium nitrogen	mg/dm^3	136.0	39.9	111.0	15.0	172.0	80.5	17.2	18.1
Nitrate nitrogen	mg/dm^3	1.97	61.17	0.09	25.5	5.70	87.7	1.89	17.88
Nitrite nitrogen	mg/dm^3	0.31	1.36	0.03	0.59	1.17	3.97	0.43	0.81
TN	mg/dm^3	160	127	121	94	207	159	24.4	15.3
TP	mg/dm^3	12.0	11.5	8.2	9.5	17.2	19.0	3.0	2.2

TSS is a measure of the floating solid content in wastewater, which indicates its clarity [51,52]. At the researched facilities no. 1 and 2, the removal efficiency of TSS was low and amounted to 17% and 48%, respectively (Figure 2). The low efficiency of TSS removal in the analyzed systems is due to the fact that a significant proportion (>60%) is removed in the preliminary settling tanks, which constitutes the first elements of the studied WWTPs [9]. Better results for TSS removal (58–94%) were found by Marzec and Jóźwiakowski [31] in three facilities with activated sludge but without preliminary settling tanks. Quite high TSS removal effects (90–96%) were also obtained by Jakubaszek and Stadnik [53] in household WWTPs operating with low activated sludge technology in a sequential batch reactor (SBR) system. A study conducted on two household hybrid CW WWTPs of VF/HF type (with vertical and horizontal flow) with common reed and willow, operating in the RNP, showed that they also provide quite high efficiency (80–87%) of TSS removal [36]. Furthermore, Marzec et al. [49], in a CW with common reed, manna grass, and Virginia mallow, obtained an efficiency of TSS removal of more than 86%.

Table 3. Pollutants concentrations in the inflow and outflow of the facility no. 2.

Parameters		Statistical Indicators							
		Mean		Min		Max		Standard Deviation	
		in	out	in	out	in	out	in	out
pH	-	-	-	7.04	6.14	11.9	7.86	-	-
Dissolved oxygen	mg O_2/dm^3	1.29	3.03	0.21	0.60	3.75	9.48	1.09	2.37
TSS	mg/dm^3	34.5	18.1	3.8	2.7	116	48.8	31.0	14.1
BOD_5	mgO_2/dm^3	85.6	29.1	16	1.6	250	63.4	58.2	24
COD	mgO_2/dm^3	251	95	109	18	400	179	88	52.3
Ammonium nitrogen	mg/dm^3	97.6	53.4	58	1.1	134	102	19.7	33.0
Nitrate nitrogen	mg/dm^3	0.62	11.5	0.18	0.5	1.2	54.2	0.32	17.70
Nitrite nitrogen	mg/dm^3	0.14	0.31	0.05	0.02	0.76	1.68	0.20	0.49
TN	mg/dm^3	117	77.0	60.0	35.0	182	104	25.1	18.7
TP	mg/dm^3	17.3	12.1	11.4	9.6	30.9	15.8	5.7	2.1

The conducted study shows that the average concentrations of TSS in outflow from the analyzed WWTPs were 23.9 mg/dm^3 for facility no. 1 and 18.1 mg/dm^3 for facility no. 2 (Tables 2 and 3). These values are lower than the permissible value (50 mg/dm^3) determined in Polish regulations [47]. However, Marzec and Jóźwiakowski [31] found significantly higher concentrations of TSS (55–122 mg/dm^3) in the outflow from three other facilities with activated sludge but without preliminary settling tanks.

BOD_5. The efficiency of BOD_5 removal in the studied facilities no. 1 and 2 was diverse and amounted to 83% and 66%, respectively (Figure 2). Similar effects of BOD_5 removal (61–95%) were found by Marzec and Jóźwiakowski [31] in three other facilities with activated sludge but without preliminary settling tanks. Quite high BOD_5 removal effects (92–97%) were also obtained by Jakubaszek and Stadnik [53] in household WWTPs operating with an SBR system. Very high (98–99%) BOD_5 removal efficiency was also obtained in two hybrid household CWs of VF/HF type operating in the RNP [36]. Moreover, Marzec et al. [49] in a household CW WWTP obtained an efficiency of BOD_5 removal greater than 95%.

The average BOD_5 in outflow from the studied facilities no. 1 and 2 was 9.0 and 29.1 mg/dm^3, respectively (Tables 2 and 3). These results are lower than the permissible value (40 mg/dm^3) specified in Polish regulations [47]. Significantly higher BOD_5 values (24.9 to 267 mg/dm^3) were found by Marzec and Jóźwiakowski [31] in three WWTPs with activated sludge operating without a classical mechanical stage.

COD. At the studied facilities no. 1 and 2, the COD removal efficiency was similar and amounted to 65% and 62%, respectively (Figure 2). Higher effects of COD removal (59–90%) were found by Marzec and Jóźwiakowski [31] in three other facilities with activated sludge without preliminary settling tanks. Similarly high COD removal effects (83–90%) were also obtained by Jakubaszek and Stadnik [53] in individual SBR systems. A study of two hybrid household CW WWTPs in the RNP showed that they also provide very high (96%) COD removal efficiency [36]. In a household hybrid CW, Marzec et al. [49] also obtained more than 95% COD removal efficiency.

The average COD values in the outflow from the analyzed facilities no. 1 and 2 were 63.0 and 95.0 mg/dm^3, respectively (Tables 2 and 3). These results are lower than the permissible value (150 mg/dm^3) specified in Polish regulations [47]. Marzec and Jóźwiakowski [31] studied some household WWTPs of similar construction to the analyzed facilities but lacking classical preliminary settling tanks, and they found higher COD values which amounted to 128–490 mg/dm^3.

Total Nitrogen. In the analyzed facilities no. 1 and 2, the efficiency of TN removal was low and amounted to 21% and 34%, respectively (Figure 2). Much lower effects of TN removal (<7%) were found by Marzec and Jóźwiakowski [31] in three other facilities with activated sludge without preliminary settling tanks. Significantly higher effects of TN removal (51–83%) were obtained by Jakubaszek and Stadnik [53] in household WWTPs operating with SBR systems. High TN removal effects (73–86%) were also obtained by Micek et al. [36] in hybrid household CW WWTPs of VF/HF type in the RNP. Furthermore, Marzec et al. [49], in a household hybrid CW, obtained more than 86% efficiency of TN removal.

The average values of TN concentration in the outflow from the analyzed facilities no. 1 and 2 were high and amounted to 127 and 77 mg/dm^3, respectively (Tables 2 and 3). These values are several times higher than the permissible limit (30 mg/dm^3) required in Poland for wastewater discharged into lakes and their tributaries [47]. Even higher concentrations of TN (124–320 mg/dm^3) were previously found by Marzec and Jóźwiakowski [31] in the outflow from three other facilities with activated sludge but without classical preliminary settling tanks.

The efficiency of TN removal in activated sludge systems depends primarily on the course of processes such as nitrification or denitrification, among others [54,55]. From the data presented in Tables 2 and 3, it can be seen that the nitrification process in the studied facilities proceeded properly, which is evidenced by a significant decrease in the concentration of ammonium nitrogen and an increase in the content of nitrate and nitrite nitrogen, as well as the concentration of oxygen in the treated wastewater. However, high concentrations of aerobic forms of nitrogen and TN in the outflow from the analyzed systems indicate that the household WWTPs with activated sludge are not able to create appropriate conditions for the denitrification process.

Total Phosphorus. In the studied facilities no. 1 and 2, the efficiency of TP removal was low and amounted to 4% and 30%, respectively (Figure 2). Marzec and Jóźwiakowski [31] found higher TP removal efficiencies (3–63%) in three other activated sludge facilities without preliminary settling tanks. Higher efficiencies of TP removal (46–74%) were obtained by Jakubaszek and Stadnik [53] in household WWTPs with SBR systems. A study of two household hybrid CWs of VF/HF type operating in the RNP showed that they provide significantly higher efficiency of TP removal (90–94%) than activated sludge systems [36]. Moreover, Marzec et al. [49] achieved high TP removal efficiency (over 95%) in a household hybrid CW.

The average values of TP in the outflow from the analyzed facilities no. 1 and 2 were very high and amounted to 11.5 and 12.1 mg/dm^3, respectively (Tables 2 and 3). These values are more than two times higher than the permissible value (5 mg/dm^3) required in Poland for wastewater discharged into lakes and their tributaries [47]. In the outflow from three other facilities with activated sludge but without preliminary settling tanks, Marzec and Jóźwiakowski [31] found even higher of TP concentrations in the outflow (23.2–50.6 mg/dm^3).

In the process occurring in activated sludge, phosphorus is mainly removed from wastewater via assimilation, sorption, and chemical precipitation [55]. During wastewater treatment, phosphorus is assimilated by the growing biomass and should be removed with the excess sludge. Effective biological phosphorus removal requires alternating aerobic and anaerobic conditions to allow the selection and growth of specific microorganisms that exhibit the ability to store phosphorus compounds within cells [56,57]. However, the conducted studies and observations show that the analyzed activated sludge WWTPs lack an anaerobic zone and the sludge from the secondary settling tank is not regularly removed, which probably has a negative impact on the effective removal of phosphorus from wastewater and causes its high concentrations in the outflow.

On the basis of the obtained research results and the literature review, it is concluded that household WWTPs with activated sludge provide significantly lower effects of pollutant removal than hybrid CWs, especially in terms of nutrient removal. Therefore, the authors of this paper do not recommend the widespread use of household WWTPs with activated sludge in protected areas.

3.2. Technological Reliability of the Studied Systems

The reliability of the analyzed WWTPs was determined using the Weibull method. In the first step, the distribution parameters were estimated, and the null hypothesis that empirical data can be described by a Weibull distribution was verified. The datasets were the values of the main pollutant indicators (BOD_5, COD, TSS, TN, and TP) in treated wastewater.

The determined values of the distribution parameters (θ, b, c) were consistent with the assumptions made. The null hypothesis was positively verified. The goodness of fit of the obtained distributions at the significance level of $\alpha = 0.05$ was high and was 68–98% for facility no. 1 and 51–99% for facility no. 2 (Table 4).

Table 4. Parameters of the Weibull distribution and the Hollander–Proschan goodness-of-fit test (n = 20).

Parameter	**Parameters of Weibull Distribution**			**Hollander–Proschan Goodness-of-Fit Test**	
	θ	c	b	**Stat**	p
			Facility no. 1—Obrocz		
TSS	−0.2000	1.2122	28.9624	0.0217	0.9826
BOD_5	0.9636	0.7691	10.0911	0.4015	0.6880
COD	14.6970	1.3850	80.1201	0.2532	0.8000
TN	58.8890	8.6765	132.4568	0.1400	0.8886
TP	9.4444	4.8527	12.5016	0.3000	0.7641
			Facility no. 2—Rybakówka		
TSS	2.2929	1.3035	21.5361	0.1127	0.9102
BOD_5	1.4000	1.0681	28.9343	−0.0998	0.9204
COD	−2.0000	1.8159	102.2153	−0.1191	0.9051
TN	−2.0000	3.1554	78.7167	−0,6526	0.5139
TP	−0.5000	5.5212	12.6970	−0.0081	0.9934

Symbols: stat—value of the test statistic, p—significance level of the test; when $p \leq 0.05$, the distribution of data does not obey a Weibull distribution.

The technological reliability of the studied WWTPs was determined on the basis of the distribution function (Figures 3–7), taking into account the limit values of the indicators, specified in the Regulation of the Minister of Maritime Economy and Inland Navigation [47] for WWTPs below 2000 PE.

Total suspended solids. The reliability of TSS removal in facility no. 1 was 86% (Figure 3A). On this basis, it can be concluded that, for a period of 51 days per year, the treatment plant malfunctioned. During this period, the concentration of TSS in treated wastewater exceeded the limit value (50 mg/dm^3). According to Andraka and Dzienis [58], for WWTPs below 2000 PE, the minimum reliability level should be 97.3%. This means that a treatment plant of this size can malfunction for 9 days per year without adversely affecting the rating of the facility. Taking these assumptions into account, it can be concluded that, in facility no. 1, the concentration of TSS in the outflow from the analyzed WWTP was excessive for 42 days per year.

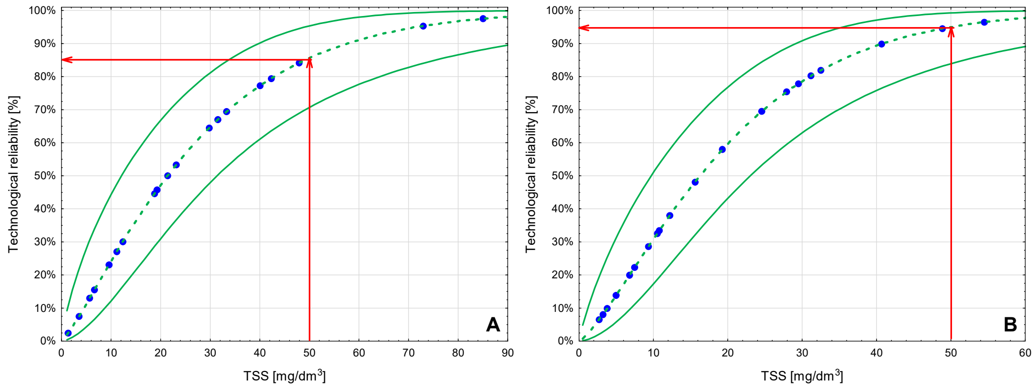

Figure 3. Weibull cumulative distribution functions and the technological reliabilities determined for TSS ((**A**)—facility no. 1; (**B**)—facility no. 2). Notation: dashed green line—reliability function, continuous green line—confidence intervals, red arrows—probability of achieving the indicators limit in the effluent.

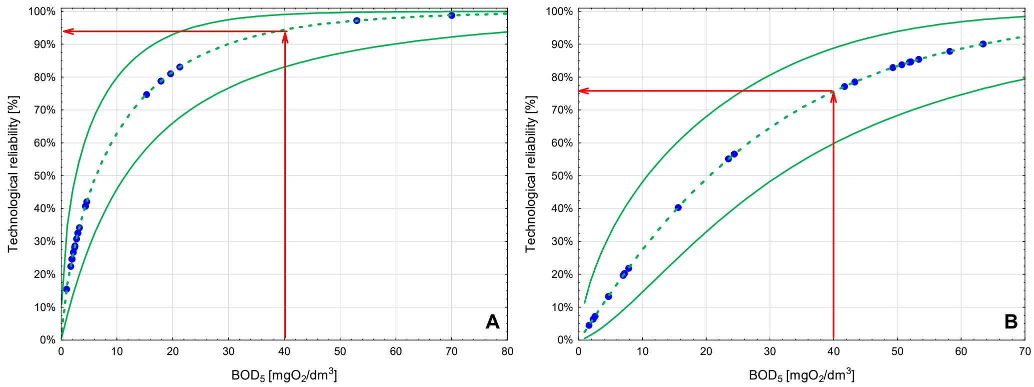

Figure 4. Weibull cumulative distribution functions and the technological reliabilities determined for BOD_5 ((**A**)—facility no. 1; (**B**)—facility no. 2). Notation:dashed green line—reliability function, continuous green line—confidence intervals, red arrows—probability of achieving the indicators limit in the effluent.

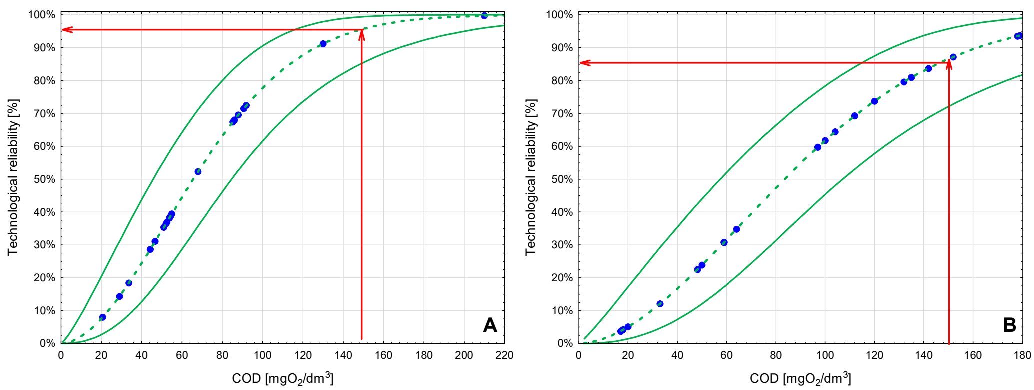

Figure 5. Weibull cumulative distribution functions and the technological reliabilities determined for COD ((**A**)—facility no. 1; (**B**)—facility no. 2). Notation:dashed green line—reliability function, continuous green line—confidence intervals, red arrows—probability of achieving the indicators limit in the effluent.

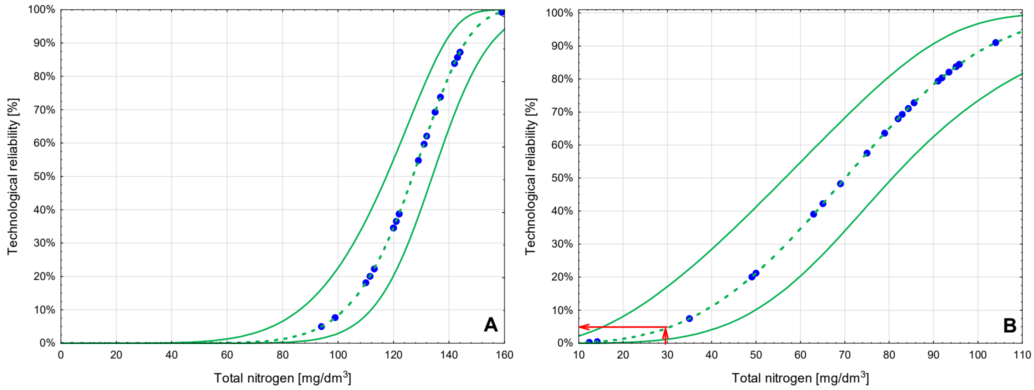

Figure 6. Weibull cumulative distribution functions and the technological reliabilities determined for TN ((**A**)—facility no. 1; (**B**)—facility no. 2). Notation:dashed green line—reliability function, continuous green line—confidence intervals, red arrows—probability of achieving the indicators limit in the effluent.

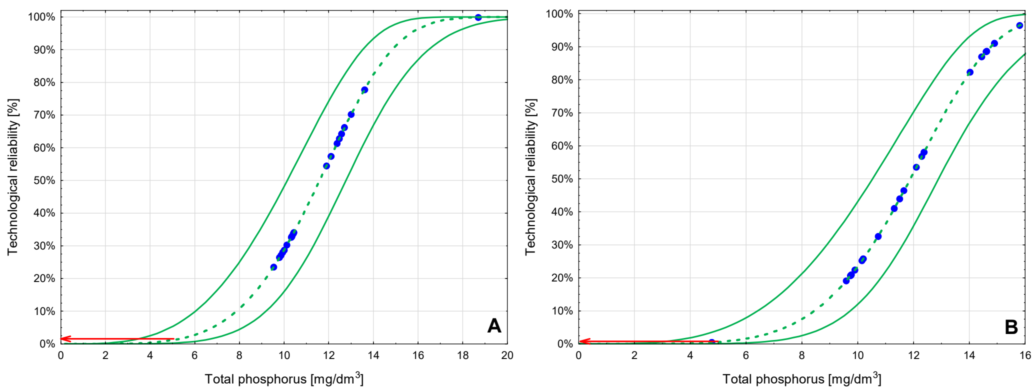

Figure 7. Weibull cumulative distribution functions and the technological reliabilities determined for TP ((**A**)—facility no. 1; (**B**)—facility no. 2). Notation: dashed green line—reliability function, continuous green line—confidence intervals, red arrows—probability of achieving the indicators limit in the effluent.

In facility no. 2, the reliability of TSS removal was 95% (Figure 3B), indicating faulty operation of the WWTP for 19 days per year. Taking into account the previously mentioned guidelines [58], it may be concluded that the level of TSS negatively influenced the facility assessment for 10 days per year. Lower reliability levels for the analyzed indicator (about 65%) were found in some studies concerning household WWTP with activated sludge conducted by Bugajski et al. [59] and Marzec [32]. However, 100% technological reliability of TSS removal in a small sequencing batch biofilm reactor (SBBR) with activated sludge was obtained by Jucherski et al. [35]. Research on two other household hybrid CW WWTPs of VF/HF type (with vertical and horizontal flow) operating in the RNP indicated that they also provide quite high (92–100%) reliability of TSS removal [36]. Additionally, Marzec et al. [33] obtained 100% reliability of TSS removal in a household CW. On the basis of the data obtained and the literature review, it appears that activated sludge systems have lower reliability of TSS removal than CW WWTPs.

BOD_5. The technological reliability of BOD_5 removal in facility no. 1 was 95% and that in facility no. 2 was 76% (Figure 4). In facility no. 1, the level of this indicator was higher than the permissible value for 10 days a year. Similarly, in facility no. 2, the level of BOD_5 was elevated for 78 days a year.

In comparison, in a WWTP of identical design but without a preliminary settling tank, the reliability of BOD_5 reduction was 70% [32]. On the other hand, Bugajski et al. [59] in a household system Biocompact BCT S-12 determined the reliability of reducing this indicator at the level of 88%. The BOD_5 removal reliability in a small SBBR was 77% [35]. On the other hand, maximum (100%) reliability of BOD_5 removal was reported in two other household hybrid CW WWTPs in the RNP [36]. Moreover, Marzec et al. [33] achieved 100% reliability of BOD_5 removal in a household hybrid CW.

COD. The reliability of COD removal was 96% in facility no. 1 and 87% in facility no. 2 (Figure 5). The obtained reliability levels are lower than the minimum required values given by Andraka and Dzienis [58]. In relation to the annual reference period, WWTP no. 1 provided the required level of organic pollutant removal expressed by COD for 359 days, while this value for WWTP no. 2 was 326 days.

The reliability indicators obtained in the analyzed activated sludge facilities in the RPN for COD are comparable to those obtained by Bugajski et al. [59] in a household WWTP working in activated sludge technology. At the same time, in the facilities in the RPN, the reliability of COD removal was higher than that found in a treatment plant based on an identical tank design but without a preliminary settling tank (60%) [32]. The reliability of COD removal in a small SBBR was 97.8% [35]. However, similarly to the case of BOD_5, maximum (100%) COD removal reliability was reported in two other household hybrid CWs WWTPs operating in the RNP [36]. Moreover, Marzec et al. [33] achieved 100% COD removal reliability in a household hybrid CW. The presented results indicate that the reliability of COD removal in household WWTPs with activated sludge is lower than that in CWs.

Total nitrogen. Both analyzed activated sludge WWTPs were characterized by extremely low reliability of TN removal. The probability that the concentration of TN in treated wastewater will not exceed the standard value (30 mg/dm^3) was 0% for facility no. 1 and 5% for facility no. 2 (Figure 6).

In the case of TN removal, facility no. 1 operated deficiently throughout the whole year and provided no assurance of passing inspection procedures. On the other hand, in WWTP no. 2, above-normative values of TN in treated wastewater occurred for a period of 338 days per year. Marzec [33], while analyzing a solution identical in terms of construction, but without a classical preliminary settling tank, obtained a reliability of TN removal at the level of 24%. The reliability of TN removal in a small SBBR was only 12.2% [35]. In contrast, TN removal reliability in two other household hybrid CW WWTPs operating in the RNP was much higher and amounted to 35% and 89% [36]. On the other hand, Marzec et al. [33] obtained 94% reliability of TN removal in a household hybrid CW. The analysis of the results of the conducted study through the prism of the results reported in the literature shows that the reliability of TN removal is lower in household WWTPs with activated sludge than in CWs.

Total phosphorus. The reliability of TP removal in the tested household WWTPs with activated sludge was even lower. The probability that the content of TP in the effluent from facility no. 1 will meet the permissible value at the operator risk of $\alpha = 0.05$ was 1%. For facility no. 2, this value was determined to be 0% (Figure 7).

During the research concerning the effluent from the analyzed facilities, no cases were observed when the values were below the permissible level 5 mg/dm^3 [47]. The obtained indicators allow concluding that household WWTPs with activated sludge are faulty in terms of TP removal throughout the year. The obtained results do not give a chance for a positive assessment of the facilities regarding the content of TP in treated sewage. In a similar facility, deprived of a classical mechanical treatment stage, a low technological reliability at the level of 5% was found [33]. On the other hand, the reliability of TN removal in a small SBBR was only 21.7% [35]. In contrast, a study conducted by Micek et al. [36] showed that TP removal reliability in two other household hybrid CW WWTPs operating in the RNP was much higher and amounted to 87% and 100%. Moreover, Marzec et al. [33] in a hybrid household CW achieved 100% reliability of TP removal. Similarly to other indicators, the reliability of TP removal in household WWTPs with activated sludge was lower than in CWs.

4. Conclusions

The analyzed household WWTPs with activated sludge demonstrated relatively high levels of technological reliability and efficiency regarding the removal of pollutants in terms of TSS, BOD_5, and COD. It is worth noting that the technological reliability of the analyzed systems was higher in comparison to corresponding systems with activated sludge but without a classical preliminary settling tank [32]. On this basis, it can be concluded that the modernization of the researched facilities, which included equipping them with preliminary settling tanks, brought positive effects. The use of an additional element in the form of a preliminary settling tank as the provision of a mechanical treatment stage and the extension of the retention time of wastewater in the system have improved the process of sedimentation of solids, as well as their initial biological decomposition. Unfortunately, no positive effects on the removal of biogenic compounds were observed in the studied facilities. The efficiency of nitrogen and phosphorus removal did not exceed 34%, while the levels of technological reliability oscillated below 5%. The obtained results indicate that, in the case of biogenic compounds, the researched facilities could not guarantee a quality of treated wastewater which would be consistent with the requirements specified in the Polish law during any period of their operation. This disqualifies the analyzed technological solution in terms of its wide application in protected areas and near lakes, where the requirements for nitrogen and phosphorus removal are high. On the other hand, previous research results presented in the literature indicate that hybrid constructed wetland systems are the most effective and reliable in terms of pollutant removal from domestic wastewater [36,49,50,60,61] and, therefore, should be recommended for use in protected areas.

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