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Evaluating the Efficiency of Wastewater Treatment Plants in the Northern Hungarian Plains Using Physicochemical and Microbiological Parameters

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Abstract: The discharge of nutrients and organic pollutants is increasing at an alarming rate, driven by the rapid development of human activities. This growing pollution is contributing to significant environmental issues, including eutrophication, making the treatment of wastewater essential before its release into the environment. Prior to being released into water bodies, treated wastewater must undergo rigorous laboratory analysis. For this reason, analysis using standard methods was carried out at the Laboratory Waterworks in Debrecen on multiple samples taken from various wastewater treatment plants in Hungary. The primary objective of this research was to assess the quality of effluents from (14) wastewater treatment plants and investigate their efficiency by measuring various physicochemical and microbiological parameters as indicators. The microbiological indicator monitored was the heterotrophic count (HPC) by estimating its total number. The results revealed that substantial removal efficiencies were demonstrated by parameters including total nitrogen (TN), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5), with reductions averaging 91%, 92%, and 87%, respectively. However, the reduction in nitrogenous compounds (nitrite NO_2^- and nitrate NO_3^-) was limited, indicating areas for process improvement. Recommendations for enhancing treatment efficiency are proposed to optimize the overall performance of the wastewater treatment plants.

Keywords: WWTPs; microbiological parameters; physicochemical parameters; efficiency

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1. Introduction

The direct discharge of wastewater into the environment from communities and industries is not recommended. Without proper treatment, this can lead to severe environmental and public health issues. Therefore, wastewater should be directed to treatment facilities, which are responsible for releasing clean water that complies with regulations while effectively removing pollutants present in wastewater. This is achieved through a combination of physicochemical and biological processes [1,2].

Hungary aims to build sewage treatment systems and facilities. This involves expanding and modernizing existing wastewater collection and treatment processes, as well as enhancing the recycling process and treatment of sludge [3–5]. Conservation and protection of water bodies require the treatment of wastewater from various sources and the improvement of the purification efficiency of treatment technologies and processes. The development of wastewater treatment is a key issue, since organisms always react to changed environmental conditions. Therefore, it is essential to assess how interventions can improve purification processes [5,6]. Furthermore, the Hungarian government is focused on ensuring the effective transportation of sufficient liquid waste (via on-road routes), its treatment, and the promotion of its use in settlements or areas devoid of a sewer system, especially in vulnerable regions where professional, individual wastewater disposal is not sustainable. In addition to improving and expanding sludge treatment and utilization, Hungary aims to decrease the overall amount of municipal liquid waste generated. Following the EU agreement, smaller-scale treatment facilities are required to produce treated water with a higher quality of discharge. These changes can largely be attributed to practical employment or fluctuating economic considerations [7].

The direct discharge of wastewater into the natural environment disturbs the aquatic equilibrium by transforming the acceptor medium into sewers. This pollution can even result in the disappearance of all life. Therefore, it is necessary to purify and eliminate as much waste from wastewater as possible before discharging it into the environment, minimizing its impact on water quality and the aquatic environment [8,9]. Purification involves eliminating the largest organic or mineral debris, different densities of water such as sand grains and mineral particles, as well as residual pollutants that could pose downstream problems (i.e., pathogens, nitrogen, phosphorus, etc.). This is implemented in wastewater treatment plants that are equipped with treatment facilities and devices for treating the sludge produced [10–12]. There are many processes and approaches for evaluating the efficiency of specific wastewater treatment plants. In Europe, many municipal wastewater treatment plants do not function properly. For example, a study in Spain revealed that, out of eight small wastewater treatment plants examined, 50% were defective, 25% were functioning adequately and the remaining 25% were operating correctly [13]. Similarly, in Greece, out of the 71 small municipal wastewater treatment plants examined, only 55% were operational, 21% functioned well, 51% performed adequately and 28% were not functioning correctly [14]. Changes in the ecological status can be recognized using individual biological and physicochemical parameters or indicators. An indicator is defined as "a feature of the environment that, when measured, quantifies the magnitude of the stress, the habitat characteristics, the degree of exposure to the stressor, or the degree of ecological response to the stress" [15,16].

The European Union directive on urban wastewater treatment (Directive 91/271/EEC), established on 21 May 1991, reports clear obligatory standards for community wastewater management. In order to protect against adverse effects of sewage discharge, it is essential to monitor treatment plants, receiving waters, and sludge disposal. Additionally, discharge from certain sectors that involve biodegradable industrial wastewater, which does not undergo treatment in urban wastewater treatment plants prior to its discharge to receiving waters, should be subject to suitable requirements.

The growing population and development needs in the world highlight the need for more reuse of treated wastewater. For instance, the international discharge standards outlined in Table 1 provide thresholds for critical parameters such as pH, BOD_5, COD, and other pollutants, essential for ensuring the safety and sustainability of water ecosystems.

However, it is important to note that treated wastewater contains a large number of pathogens, making proper treatment essential before any potential reuse. Standard plate counts (SPC) were used to estimate the total microbial concentration in different wastewater treatment plant effluents, counting total coliforms (TC), fecal coliforms (FC) and coliphages (CPg), considering their importance in wastewater treatment compared to traditional pollution indicators [17–19].

Traditionally, colony-forming unit (CFU) measurements have been used to estimate microbial concentrations and activity in microbiological evaluations of wastewater treatment plant (WWTP) efficiency. However, this approach does not capture the complete complexity of microbial dynamics and treatment processes, despite its continuous widespread use. More modern and reliable methods, such as respiration rate, dehydrogenase activity, and nitrification activity measurements, can provide a better understanding of the role of microorganisms and the overall functionality of WWTPs system [20,21]. Recent reviews have highlighted an increasing trend toward more accurate and sensitive assays that provide clear benefits in assessing microbial toxicity and efficiency in WWTPs [22].

Table 1. International discharge standards.

Parameters	Units	Thresholds
pH	-	6.5–8.5
BOD_5	mg L^{-1}	<30
COD	mg L^{-1}	<90
TSS	mg L^{-1}	<20
NH_4^+ (Ammonium)	mg L^{-1}	<0.5
NO_2^- (Nitrite)	mg L^{-1}	1
NO_3^- (Nitrate)	mg L^{-1}	<1
P_2O_5 (Phosphates)	mg L^{-1}	<2
Temperature	°C	<30
Color	-	Colorless
Odor	-	Odorless

Note: Source: World Health Organization (WHO, 2006).

The most recent evaluation of wastewater treatment facilities in Hungary, as detailed in the UNECE (United Nations Economic Commission for Europe) and WHO (World Health Organization Regional Office for Europe) document [23], emphasizes a number of important points:

- Wastewater treatment improvement: The percentage of treated wastewater undergoing tertiary treatment rose from 88% in 2018 to 95% in 2020, indicating notable improvements in wastewater treatment efficiency.
- High compliance in sensitive areas: All wastewater treatment facilities in designated sensitive catchment areas employ tertiary treatment, which effectively eliminates phosphorous and nitrogen. By 2019, the removal rates of nitrogen and phosphorus were 81–69% and 86–14%, respectively.
- Focus on small agglomerations: Hungary is concentrating on extending wastewater treatment to smaller agglomerations (those with populations under 2000), in order to address small settlements. This initiative aligns with the sustainable development goals (SDGs) aimed at protecting the aquatic habitat. A pilot project is planned for the 2021–2027 planning cycle to install wastewater systems in a few small municipalities.
- New goals and research: By 2030, Hungary aims to further reduce pollutant loads, particularly phosphorous, and may consider implementing a fourth stage of treatment for the removal of micro pollutants that impact drinking water sources in some regions.

The objective of this systematic study was to comprehensively evaluate the performance of 14 wastewater treatment plants in Hungary by analyzing key parameters, including total chemical and physical metrics and heterotrophic plate counts (HPC). The analysis focused on determining compliance with the stringent standards outlined in the EU wastewater treatment directive. The inclusion of HPC as an additional parameter provided further vision into the operational efficiency of the treatment processes [10,24]. The findings were analyzed by computing the average removal efficiency (ARE) and testing the hypothesis through statistical analysis performed using R software (R 4.2.2).

2. Material and Methods

In any wastewater treatment plant, it is essential to analyze the raw wastewater (the inlet) and the treated water (the outlet). This analysis helps to determine the different physicochemical and bacteriological parameters, making it possible to evaluate the pollution levels at each treatment plant and the effectiveness of pollution removal. Such evaluations provide valuable insights into the purification performance of the WWTP. In December 2019, we collected samples from the effluents of 14 treatment plants in Hungary. The parameters analyzed included ammonia (NH_3), nitrate (NO_3), nitrite (NO_3), total phosphorus (TP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), total suspended solids (TSS), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD). This comprehensive analysis was carried out to ensure a thorough understanding of the treatment plants' efficacy in managing wastewater.

2.1. Study Area

The current study was carried out in December 2019 in northeastern Hungary, where most of the targeted treatment plants are located. These facilities were selected due to their great representation of municipal wastewater treatment operations in this area and because they serve a wide range of local communities. These plants are responsible for treating raw wastewater for approximately 26,000 residents living in this plain area. The total capacity of treated wastewater is 598,000 m^3, though this figure is not available for each individual plant. Out of the total number of facilities, only three plants were located during the study, while the others were not found.

2.2. Sampling Processes

The samples were collected over a predetermined time frame to give an overview of the performance of the wastewater treatment plants under normal operating circumstances. While this method does not capture seasonal variations, it allows for a baseline evaluation of treatment effectiveness. Although wastewater treatment plants routinely collect daily monitoring data, this study did not have access to those datasets. The analysis concentrated on the independently collected samples in order to guarantee consistency and dependability in measuring both physicochemical and microbiological parameters.

2.2.1. Procedures and Analysis

Samples were taken from both influent and effluent points at rural wastewater treatment plants (WWTPs) located in the northern plains of Hungary. Samples were promptly transported to the laboratory at a temperature of 4 °C and were analyzed within a day.

2.2.2. Equipment for Physicochemical Analysis

BOD_5 (biochemical oxygen demand) was measured using a calibrated dissolved oxygen (DO) probe in a BOD incubator set at 20 °C for a duration of 5 d.

The COD (chemical oxygen demand) was assessed following digestion with potassium dichromate, by using a spectrophotometer. To measure TN (total nitrogen), a total organic carbon/nitrogen analyzer was used, while total Kjeldahl nitrogen (TKN) was quantified through Kjeldahl digestion and titration.

To measure ammonia, nitrate, and nitrite, the following specialized techniques were used: ion-selective electrodes or spectrophotometry with Nessler's reagent for ammonia, cadmium reduction for nitrate, and sulfanilic acid for nitrite.

TP (total phosphorus) was determined through digestion with ammonium molybdate, and measured spectrophotometrically. Total suspended solids (TSS) were measured by filtering, drying, and weighing the samples. The reagents used included ammonium molybdate (for phosphorus), sulfanilic acid (for nitrite), potassium dichromate (COD), Nessler's reagent (for ammonia), and common digestive aciprovids. This comprehensive methodology provided a thorough evaluation of WWTP performance, ensuring reliable and repeatable physicochemical measurements.

The samples needed to be analyzed within a maximum of 24 h in order to avoid any change in the concentrations of the sample [25]. Thus, they were stored at a temperature of 4 °C after they were transported to the lab.

2.3. WWTPs Characteristics

The capacity and functionality of the 14 wastewater treatment plants (WWTPs) in this study vary. Among them, Plant 4, with a 400 m^3/day capacity, Plant 11, with a 388 m^3/day capacity, and Plant 14, with a 2000 m^3/day capacity, report specific daily treatment capacities. The capacity information for the remaining WWTPs was unavailable. With the exception of Plant 11, which lacks specialized treatment procedures, all 14 WWTPs use biological treatment processes and implement procedures for the removal of nitrogen and phosphorus forms.

2.4. Laboratory Methods

After the sample collection, different physicochemical parameters were measured at the Debrecen testing laboratory (Tiszamenti Regional waterworks, Debrecen, Hungary), which is known as one of the most significant water utility facilities in Hungary. This facility strives to achieve consumer satisfaction, while taking into account environmental and economic factors. At this laboratory, the most important parameters required to determine the efficiency and operation of wastewater treatment plants were prioritized in the study [26–28]. Using standards methods, we identified the essential parameters that need to be measured using advanced machines and new instruments.

2.5. Heterotrophic Plate Count

We used the pour plate method to calculate the heterotrophic plate count (HPC). Water samples were collected from every wastewater treatment facility, including both influent and effluent. In sterile Petri dishes, we introduced 1 mL of each water sample. Then, we added melted and cooled R2A agar, which is a low-nutrient medium ideal for the growth of heterotrophic bacteria. The plates were then incubated for 48 h at temperature of 28 °C. After the incubation, we counted the visible colonies and expressed the results as colony-forming units per milliliter (CFU/mL) of the water sample.

2.6. Statistical Analysis

Paired *t*-tests were performed to evaluate the wastewater treatment process's effectiveness in lowering different water quality parameters. The analysis involved comparing concentrations of key pollutants in treatment wastewater (TW) from 14 sewage treatment plants with those in raw wastewater (RW). The study focused on several parameters, including nitrate-N, Kjeldahl nitrogen, total inorganic nitrogen, ammonia-N, and total phosphorus.

In addition, another calculation, along with benchmarks, is generally used by governments and health associations, among others, to assess the adequacy of effluents from the WWTP in accordance with the guidelines and current environmental conditions [29]. Efficiency was calculated for four of the most important parameters: BOD, COD, total-P, and total-N. To calculate the reduction efficiencies of different parameters, we used the following equation:

$$\text{Percentage change} = (\text{TW} - \text{RW}) \div \text{RW} \times 100$$

3. Results and Discussion

3.1. Physicochemical Parameters

Ammonia-N demonstrated an average reduction efficiency of 81.08%, indicating a noteworthy decrease in the concentration of ammonia-nitrogen (Figure 1). The significant reduction showcases the treatment effectiveness in removing ammonia, which is a major nitrogenous pollutant.

Total phosphorus levels also showed a substantial decrease, with an average reduction efficiency of 11–25% (Figure 1). The treatment process effectively mitigated phosphorus concentrations, enhancing the overall efficiency of nutrient removal.

Kjeldahl nitrogen, which expresses nitrogen from both organic and ammonia sources, showed a significant decrease, with an average efficiency of 102.87% (Figure 1). This result indicates the treatment plant's capability to handle complex nitrogen compounds with remarkable efficacy.

Total inorganic nitrogen concentrations were significantly reduced, achieving a mean reduction efficiency of 67.1%. This outcome underscores the plant's ability to target various inorganic nitrogen species.

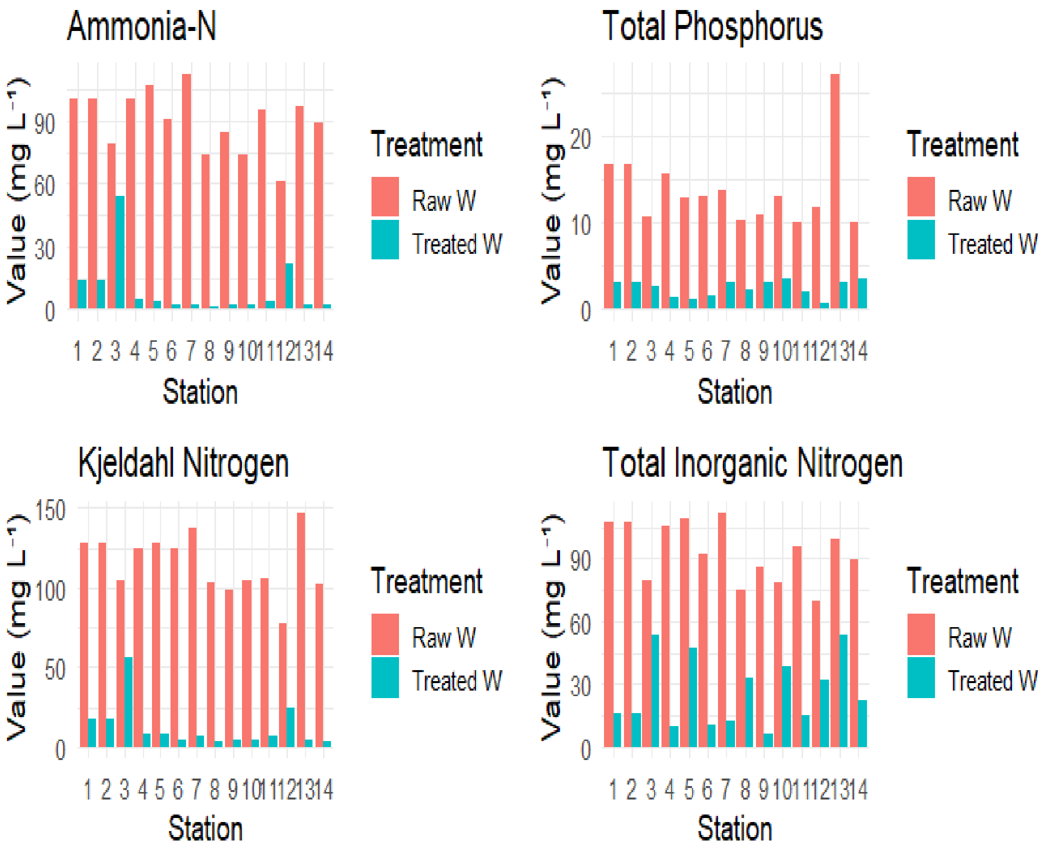

Figure 1. NH_3, TP, TIN, and TKN reduction in wastewater treatment process: percentages of removal prior and after purification. (Raw W: raw water, Treated W: treated water).

Total N concentration concentrations significantly decreased after wastewater treatment, with the reduction further supported by a 95% confidence interval (74.76, 102.91), and with a mean reduction efficiency of 88.84% (t = 13.632, $p < 0.001$).

Biochemical oxygen demand (BOD). The wastewater treatment process effectively removed organic pollutants, as indicated by a significant decrease in biochemical oxygen demand (BOD). The water quality significantly improved, as evidenced by the mean reduction efficiency of 47.45% (t = 10.802, $p < 0.001$) and a 95% confidence interval of 37.96 to 56.94. This is consistent with the findings of a study conducted to assess the satisfaction of wastewater treatment plants at different levels of treatment units using the activated sludge process [30].

Chemical oxygen demand (COD): A significant reduction in chemical oxygen demand (COD) was observed, reflecting the effective treatment of wastewater. The mean reduction efficiency reached 79.14% (t = 10.244, $p < 0.001$). This outcome highlights the plant's successful removal of oxidizable substances, as indicated by the 95% confidence interval (62.66, 96.62).

According to Howard et al., suspended solids, BOD_5, and COD are useful parameters for controlling wastewater treatment, while other parameters may not be as effective. Their study found that, during treatment, parameters such as total suspended solids (TSS), total nitrogen (Total N), total phosphorus (Total P), and organic matter (COD, BOD_5) were considerably diminished in the effluent during treatment [31]. These results emphasize the importance of these indicators for monitoring treatment efficiency and are compatible with the findings of other researchers [32,33]. Furthermore, Maguvu et al. reported evidence of the usefulness of these indicators in evaluating the effectiveness of water treatment processes, highlighting the decrease in total dissolved solids, turbidity, phosphates and nitrates in wastewater. They also discussed the use of surrogate organisms as indicators for assessing treatment efficiency [33] (Figure 2).

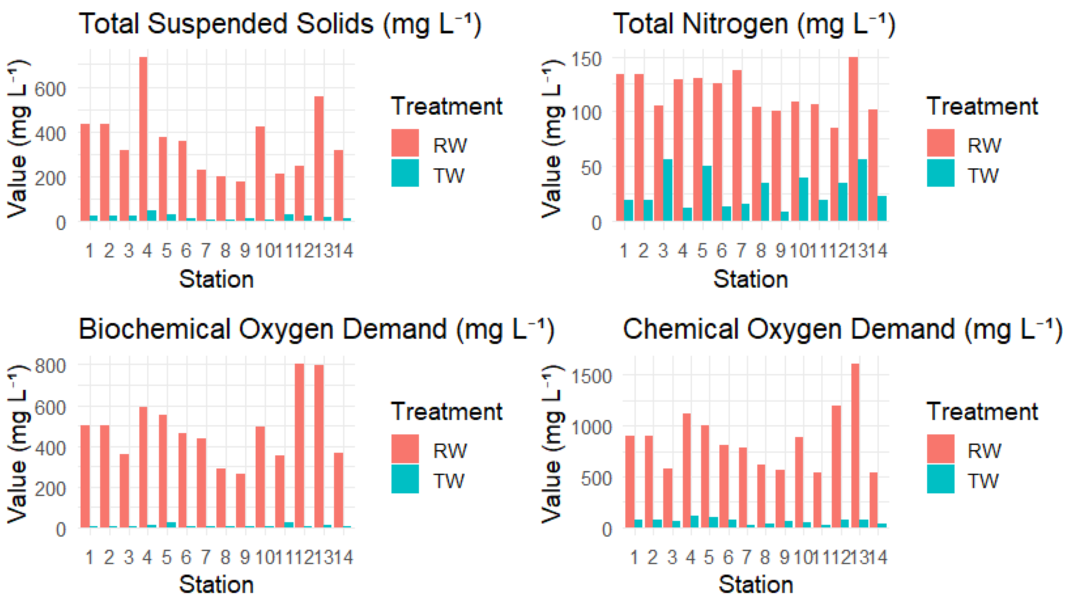

Figure 2. COD, BOD, TSS, and TN reduction in wastewater treatment process percentages of removal prior and after purification.

Figure 3 displays the alterations in performance between 14 municipal wastewater treatment plants (WWTPs) based on a thorough comparison of their removal efficiencies for total phosphorus (TP), total suspended solids (TSS), total nitrogen (TN), biochemical oxygen demand (BOD), and chemical oxygen demand (COD).

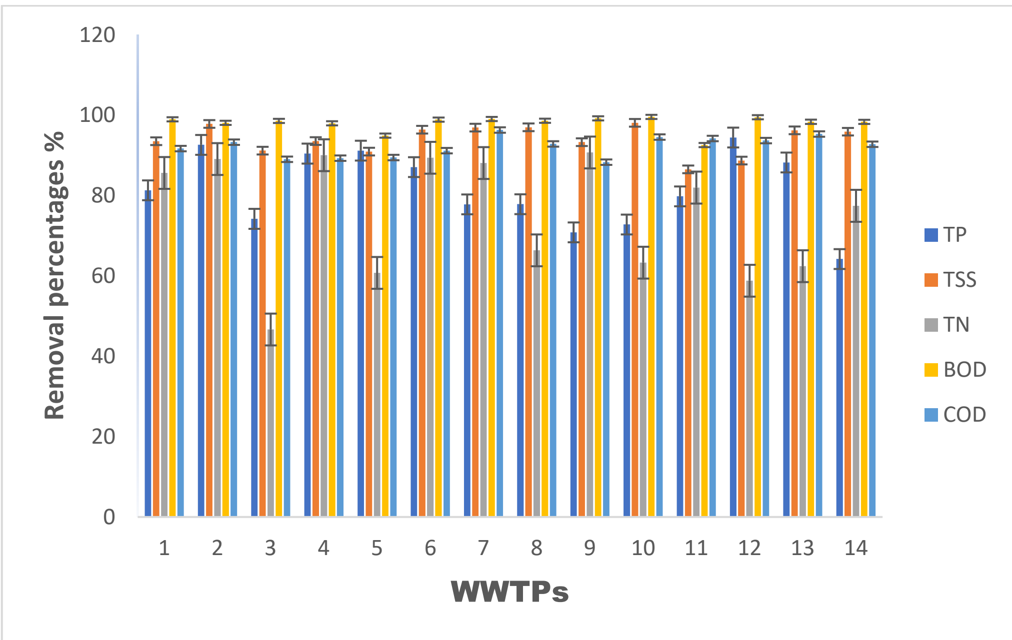

Figure 3. Comparison of 14 municipal WWTPs' total phosphorus (TP), total suspended solids (TSS), total nitrogen (TN), biochemical oxygen demand (BOD), chemical oxygen demand (COD) removal efficiencies.

Table 2 summarizes the concentrations of physicochemical parameters (e.g., ammonia-N, nitrate-N, and total phosphorus) before and after treatment in 14 sewage treatment plants, illustrating the significant improvements achieved. Table 3 further presents the mean removal efficiencies of key parameters such as NH3, TSS, and COD, which reinforce the effectiveness of the treatment processes across the studied facilities.

3.2. Nitrite-N and Nitrate-N Results

It is possible that the treatment procedure had little effect on nitrate levels because nitrate-N concentrations did not significantly change after treatment ($p = 0.2619$). Following treatment, there was no discernible change in nitrite-N concentrations ($p = 0.9613$), suggesting a strong level of treatment effectiveness for this dimension.

These findings indicate that most wastewater treatment plants were ineffective in reducing nitrate-N concentrations, as evidenced by the notable differences between inflow and outflow concentrations. In many instances, these concentration differences were either minimally reduced or, more frequently, increased in the treated effluent.

Only three wastewater treatment plants (Plant 1, Plant 3 and Plant 4) demonstrated the ability to reduce nitrate levels, although the removal efficiency was limited and did not achieve significant reductions (Table 4). The nitrate-N concentrations at Plant 1, Plant 3 and Plant 4 were 5.49 mg/L, 0.54 mg/L, 4.59 mg/L in the raw water, respectively, and were reduced to 2 mg/L, 0.23 mg/L and 1.88 mg/L, respectively.

The contents of the treated water in the other WWTPs increased in comparison to the raw wastewater; the highest treatment plant level being 50.3 mg/L, whereas the lowest one was 2.02 mg/L in Plant 13. Nonetheless, the increase in nitrate-N concentrations was not as significant in some of the WWTPs (Table 4).

The presence of nitrogenous compounds in the effluent, such as thickener and nitrocellulose resin, may contribute to the elevated nitrate content when the effluent is discharged into a receiving watershed [29]. This nutrient loading can subsequently lead to eutrophication, and could be adversely affecting aquatic ecosystems and potentially resulting in oxygen depletion in water bodies [34].

At the level of all the treatment plants, the values of nitrates content are higher in treated water than in raw water, mostly with a slight increase except in Plant 7, which shows a constant value (<0.03 mg/L) in both inflow and outflow.

Table 5 presents the concentrations of nitrite-N (NO_2^-) in the influent and effluent, showcasing the variations across the treatment plants. The highest concentration (2.35 mg/L) was observed in Plant 4, despite the very low concentration (0.07 mg/L) found in the effluent; however, it significantly increased during treatment (Figure 4).

In general, this noticeable increase of nitrate and nitrite in our results is mainly due to the oxidation of nitrogen through the nitrification process [35], as mentioned above. The high levels of nitrate and nitrite in the outflow could indicate deficiencies in the denitrification process. This suggests that denitrification does not appear to have occurred properly, leading to higher levels in the wastewater. This could be explained by several factors, including environmental ones like temperature fluctuations and high influent nitrogen loads, which could be particularly significant if the sampling was performed in the winter, when denitrification efficiency decreases. According to the WHO and ENECE, numerous crucial elements related to process design and operational constraints in WWTPs in Hungary are responsible for the observed inefficiency in denitrification [23]. The possible limitation of easily accessible carbon sources is a major concern. Additionally, insufficient anoxic zones, which are necessary to create the low-oxygen conditions required for effective denitrification, pose significant challenges. Hydraulic overloading, which reduces the oxygen retention time, exacerbates the issue by increasing the limited time available for biological processes. This ultimately results in incomplete nitrogen removal, as the denitrification process is severely hampered by insufficient carbon availability.

Table 2. Physicochemical parameters concentration prior and after treatment of wastewater from 14 sewage treatment plants.

	1		2		3		4		5		6		7		8		9		10		11		12		13		14	
Parameters	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**	**RW**	**TW**
Ammonia-N (mg/L)	101	14	101	14	79	54	101	5.3	107	3.7	91	2.1	112	2.6	74	1.62	85	2	74	2.3	95	3.7	61	22	97	2.4	89	2.1
Nitrate-N (mg/L)	5.49	2	5.49	2	0.54	0.2	4.56	1.88	1.55	42.7	0.83	8.61	0.24	9.51	1.07	31.1	1.2	4.3	4.8	34.6	0.3	11.2	8.26	9.4	2.02	50	0.23	20
Total phosphorus (mg/L)	16.8	3.14	16.8	3.14	10.7	2.8	15.7	1.5	12.8	1.13	13	1.68	13.7	3.04	10.3	2.28	11	3.2	13	3.59	10	2.08	11.7	0.7	27.1	3.2	10	3.58
Kjeldahl-nitrogen (organic N+ammonia-N) mg/L	128	17.1	128	17.1	104	56	124	8.59	128	7.7	124	4.29	137	6.77	103	3.38	99	4.8	104	4.63	106	7.53	77	25	147	4.6	102	3.27
Total inorganic N (mg/L)	107	16.2	107	16.2	79.5	54	106	9.5	109	47	91.8	11	112	12.1	75.1	33	86	6.4	79	38	96	15.3	69.5	32	99.1	54	89.2	22
Total suspended solids (mg/L)	433	28	433	28	318	28	730	47	375	34	361	13	228	7	199	<7	179	12	423	8	215	29	248	28	557	21	317	13
Total N (mg/L)	134	19.3	134	19.3	105	56	129	12.8	130	51	125	13.2	137	16.3	104	35	100	9.3	109	40	106	19.1	85	35	149	56	102	23
Biochemical oxygen demand (mg/L)	502	5	502	5	358	5	594	12	550	28	464	5	435	4	290	4	263	<3	492	<3	350	26	804	4	797	13	365	6
Chemical oxygen demand (mg/L)	905	75	905	75	584	64	1112	119	1008	106	815	72	787	<30	616	44	564	66	883	48	535	31	1191	75	1609	75	541	39
Nitrite-N (mg/L)	0.09	0.17	0.09	0.17	<0.03	0	0.07	2.35	<0.03	1.03	<0.03	0.33	<0.03	<0.03	<0.03	0.3	0.1	0.2	0	0.87	0.1	0.36	0.21	0.4	0.05	1.6	<0.03	0.06

Note: RW: Raw Water, TW: Treated Water.

Table 3. Mean removal efficiency of physicochemical parameters in wastewater treatment plants.

Physicochemical Parameters	**Removal Efficiency %**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
NH_3	86.14	95.37	31.65	94.75	96.54	97.69	97.68	97.81	97.65	96.89	96.11	63.93	97.53	97.64
NO_3^-	63.57	0.00	57.41	58.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TP	81.31	92.62	74.21	90.45	91.17	87.08	77.81	77.86	70.83	72.80	79.81	94.44	88.23	64.20
TKN	86.65	57.18	46.15	93.07	93.98	96.54	95.06	96.72	95.12	95.55	92.90	67.53	96.85	96.79
TI	84.80	86.59	32.08	91.01	56.72	88.02	89.22	56.06	92.58	51.78	83.98	53.96	45.51	75.34
TSS	93.53	97.84	91.19	93.56	90.93	96.40	96.93	96.98	93.30	98.11	86.51	88.71	96.23	95.90
TN	85.63	89.08	46.67	90.06	60.77	89.42	88.10	66.35	90.74	63.30	81.99	58.82	62.42	77.45
BOD_5	99.00	98.10	98.60	97.98	94.91	98.92	99.08	98.62	99.24	99.59	92.57	99.50	98.37	98.36
COD	91.71	93.31	89.04	89.30	89.48	91.17	96.32	92.86	88.30	94.56	94.21	93.70	95.34	92.79
NO_2^-	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4. Concentrations of nitrate-N (NO_3^-) in both influent and effluent of the studied plants.

WWTPs	Raw Water	Treated Water
1	5.49	2
2	1.48	9.06
3	0.54	0.23
4	4.59	1.88
5	1.55	42.68
6	0.83	8.61
7	0.24	9.51
8	1.07	31.08
9	1.17	4.27
10	4.78	34.59
11	0.33	11.2
12	8.26	9.43
13	2.02	50.3
14	0.23	19.95

Table 5. Concentrations of nitrite-N (NO_2^-) in both influent and effluent of the studied plants.

WWTPs	Raw Water	Treated Water
1	0.09	0.17
2	0.08	0.59
3	<0.03	0.03
4	0.07	2.35
5	<0.03	1.03
6	<0.03	0.33
7	<0.03	<0.03
8	<0.03	0.3
9	0.06	0.16
10	0.03	0.87
11	0.14	0.36
12	0.21	0.39
13	0.05	1.55
14	<0.03	0.06

In the case of phosphate, the results can be attributed to the discharge of industrial and domestic wastewater that contains phosphate detergents, providing about 3 g of phosphorus per person per day [36].

In this section, the average reduction efficiency percentages of all studied wastewater treatment plants are stated, taking into account BOD, COD, TSS, TP, and TN. The analysis adopted the parameters outlined in the EU directive. Our findings indicate that only four plants are highly effective in reducing all parameters, including BOD, COD, TSS, TP and TN, and meet the wastewater discharge standards mandated by the EU Urban Wastewater Treatment Directive [37]. Plant 1, Plant 2, and Plant 4 achieved their goals and reduced concentrations by 90.23%, 94.19%, and 92.26%, respectively. As previously mentioned, all wastewater treatment plants significantly and effectively remove BOD, COD, and TSS. For TN and TP, the removal efficiency varies from plant to plant. Some plants almost manage to eliminate TP while significantly removing the other pollutants. Plant 7, Plant 9, and Plant 11 recorded TN removal efficiencies of 77.81%, 70.82%, and 79.80%, respectively, falling short of the directive's required 80%. However, their overall pollution reduction efficiencies were acceptable, standing at 91.64%, 88.47% and 87.01%, respectively. In contrast, Plant 5, Plant 12, and Plant 13 did not meet the TN removal goal, although they achieved substantial reductions for other parameters, with efficiencies of 85.44%, 87.03% and 88.01%, respectively. Lastly, Plant 3, Plant 8, Plant 10, and Plant 14 failed to remove both TP and TN. Their reduction percentages were 79.94%, 86.53%, 85.67% and 85.73%, respectively.

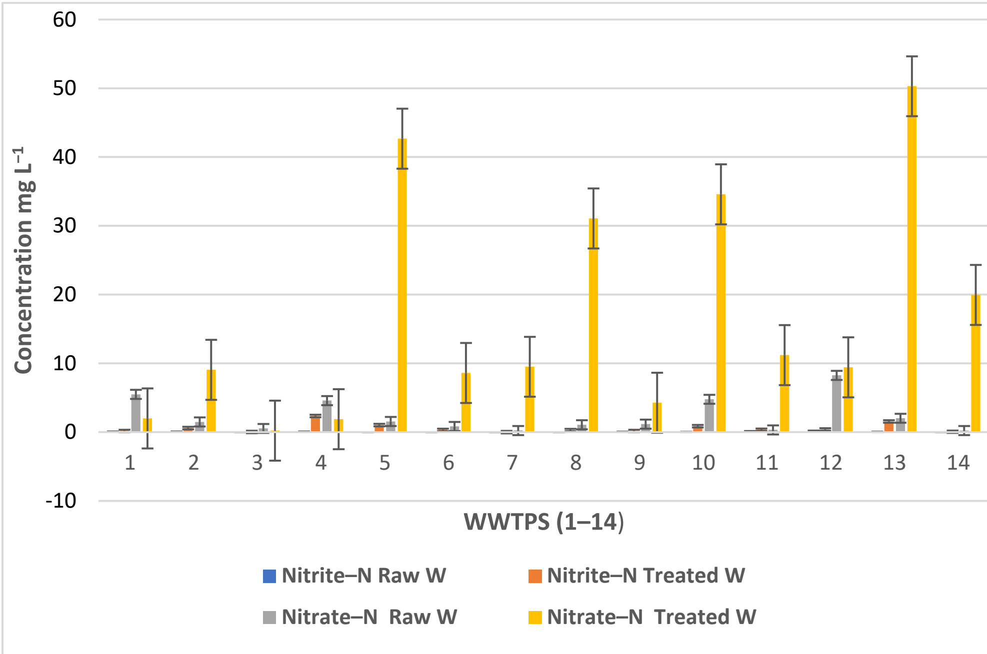

Figure 4. Amount of nitrate-N and nitrate in (mg/L) (incoming and outgoing wastewater): failure in removing pollutants.

This study explored the effectiveness of wastewater treatment using BOD, COD, total nitrogen (Total-N), and total phosphorus (Total-P). The importance of these parameters is outlined by the EU Urban Wastewater Treatment Directive (Directive 91/271/EEC) and other directives, which highlight their significance as crucial indicators in evaluating the performance of wastewater treatment plants. Their relevance lies in their direct impact on water quality and their role in inhibiting eutrophication.

However, we acknowledge that other significant pollutants that are becoming more widely accepted as major environmental contaminants, such as heavy metals, pharmaceuticals, and microplastics [38], may not be captured by this limited focus. Including these factors could provide a more comprehensive assessment of treatment efficiency.

Figure 5 highlights the failure of some WWTPs to sufficiently remove nitrate and nitrite pollutants, emphasizing the deficiencies in denitrification processes across certain facilities. While the findings of this study provide important information about the efficacy of wastewater treatment facilities in northeastern Hungary, the observed issues with denitrification, such as the insufficient availability of carbon sources and inadequate anoxic zones, may be specific to the plants studied. Their performance could be impacted by the differences in these plants' capacity, design, and operating procedures. Therefore, it is important to exercise caution when extrapolating the findings to other wastewater treatment facilities that might have distinct technologies, operational limitations, or geographical settings.

The significant variation in removal efficiencies among the 14 wastewater treatment facilities can be attributed to multiple factors, including variations in plant design, treatment methods, and operational procedures. This variability is consistent with findings from other studies in Europe. For example, researchers found that insufficient maintenance and out-of-date infrastructure led to inefficient performance in 50% of Spain's small WWTPs [13]. Similarly, other researchers discovered that only 55% of Greece's small municipal treatment plants met the necessary standards, indicating performance variability across facilities [14].

Ultimately, all the plants have been classified based on their performances on all the physicochemical parameters Table 6. Based on the Figure 4, we note that most systems in most cases give good results that meet European standards.

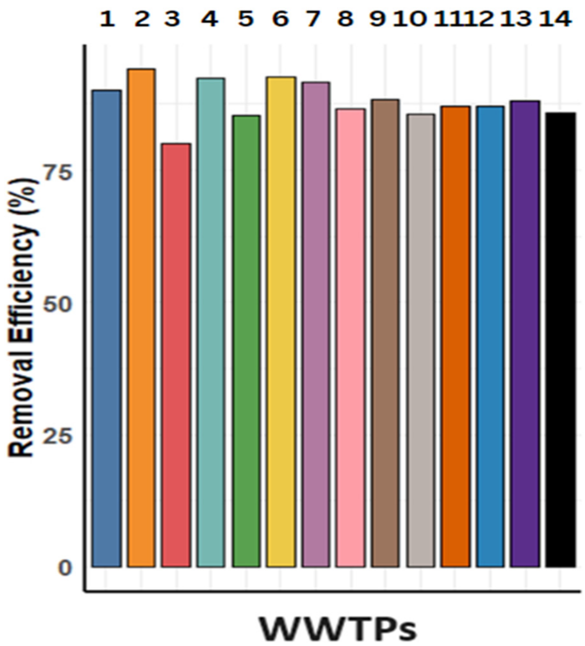

Figure 5. Percentages of physicochemical parameters that are removed efficiently in the studied sewage treatment plants.

Table 6. Classification of sewage treatment plants.

Classes	Sewage Treatment Plants in Order	Removal Efficiency (RE)
A	1.2.4.6.7.9	Excellent
B	5.8.11.12.13	Very good
C	3.10.14	Sufficient

3.3. Microbiological Parameter HPC (Heterotrophic Place Count)

Figure 6 illustrates heterotrophic values in the effluents of the 14 plants; these evaluated plants recorded first, second, fifth and tenth recorded logical values, where the number of heterotrophic plates heated to 22 °C is higher than the heterotrophic number heated to 35 °C.

The heterotrophic plate count (HPC) parameter has been introduced as an additional tool for monitoring wastewater treatment plants (WWTPs) [10]. Since many regulations set limits on bacterial concentrations in water to protect public health, the inclusion of this parameter helps to improve the understanding of treatment processes, assess their effectiveness, and ensure compliance with regulatory standards.

The planned sewage treatment at Plant 1, Plant 2, Plant 5, and Plant 10 seems to have worked. In contrast, the other sewage treatment plants recorded the opposite. The data show that the number of heterotrophic germs at 35 °C is higher than at 22 °C. Notably, Plant 5 recorded the highest value, with a 1,780,000 CFU at 35 °C, which decreased to 1,310,000 CFU at 22 °C, demonstrating a significant difference between the two temperatures. Conversely, Plant 7 recorded the lowest value, at 44,000 CFU, which increased to 180,000 CFU, indicating less significant variations between the two temperatures. A significant difference in colony numbers between the two temperatures was noted at most wastewater treatment plants. However, to examine a broader range of bacterial types as well as other organisms such as molds, yeasts and fungi, further heating treatment at 45 °C may be warranted, although this focus is beyond the scope this article.

Furthermore, a coincident resemblance observed in heterotrophic plate count and physicochemical results was recorded; for example, the WWTPs with excellent physicochemical removal efficiency also displayed relatively low HPC values under both temperature conditions, except for Plant 6. However, a notable reduction in the number of colonies was observed in Plant 1 and Plant 2, while no significant differences were observed in Plant 4, Plant 7, and Plant 9. This is consistent with previously reported findings by Carter et al. [39]; for instance, they examined the relationship between water quality parameters and heterotrophic bacteria (HPC) levels in water distribution systems. Their investigation found that HPC counts might be helpful in determining the water quality of systems that distribute drinking water [40].

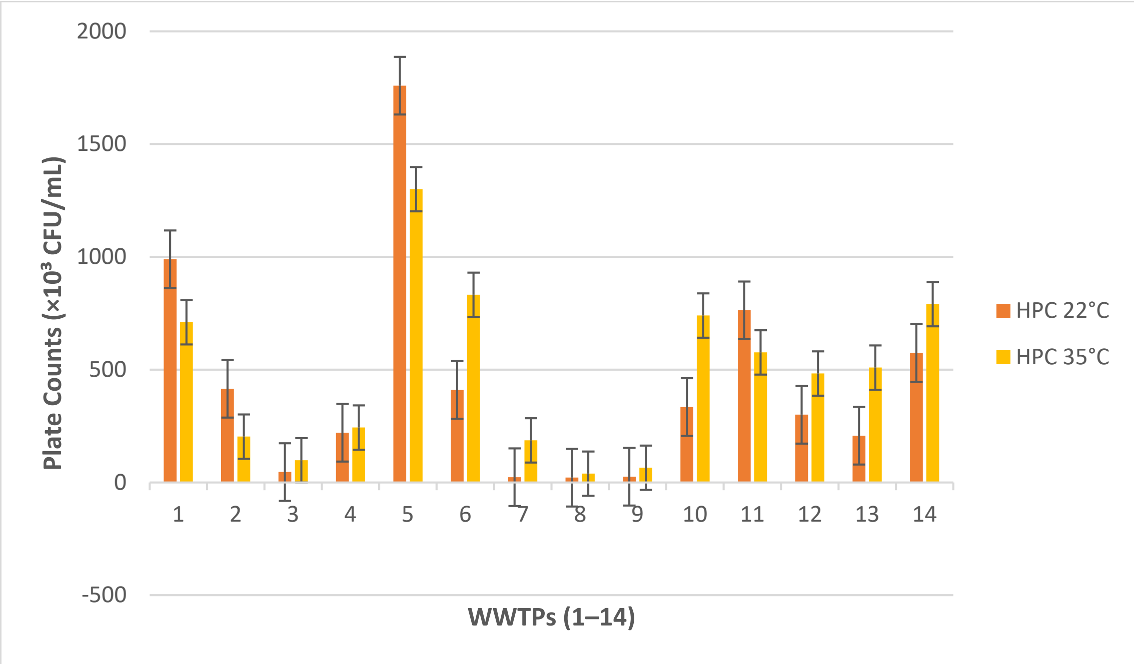

Figure 6. Heterotrophic plate counts (HPC) in the effluent at 22 °C and 35 °C of 14 WWTPs.

According to HPC, the disinfection process in certain plants may still require enhancement, especially to ensure microbial contaminant removal, even though physicochemical treatment is generally effective.

An additional research endeavor examined the correlation between heterotrophic bacteria and water quality parameters within a drinking water distribution system. The objectives of this investigation were to ascertain the factors that account for the spatiotemporal distribution of heterotrophic bacteria and to develop a model of their establishment within the system [41]. The results of this study are consistent with considerable variation in the effectiveness of microbial removal across different wastewater treatment systems. Despite their success in lowering BOD_5, activated sludge systems frequently fall short of microbial removal requirements, as demonstrated by Ghoreishi et al., as a result of operational issues including poor management and the production of bulk sludge [39]. According to Decamp and Warren, wetland systems exhibit variable microbial removal rates, despite being economical, achieving reported efficiencies of between 41 and 98% in 2000. Both biological and chemical factors influence this variability [42], which is similar to the suboptimal HPC results we found in our study. Hashemi et al. have pointed out UV disinfection systems, which are very good at eliminating microorganisms; however, they need to be pre-treated to handle suspended solids, which is another disadvantage that is visible in our WWTPs [43]. These comparisons show that design limitations and operational shortcomings are common issues among different treatment systems, highlighting the necessity of focused improvements in Hungarian WWTPs.

Our results are consistent with earlier research that examined at the relationship between heterotrophic bacteria and physicochemical parameters. For instance, a study suggested that HPC measurements could be used as a marker of microbial contamination. This study highlighted the applicability of HPC counts in assessing water quality in distribution systems [44]. Another study identified factors explaining the spatiotemporal distribution of heterotrophic bacteria, and modelled their occurrence in the distribution system [45]; these researchers observed that microbial dynamics in these systems could be modelled using HPC level.

In most of the treatment plants, abnormal results recorded can be attributed to the rapid multiplication and propagation of bacterial colonies that have the ability to adapt to high temperature [46]. The presence of these bacteria in effluent suggests that the disinfection process was not effective. Ideally, there should be a significant reduction in bacterial numbers after a second heating at 35 °C, but the results indicate otherwise. Conversely, the heating treatment at 22 °C appears to yield more acceptable results, suggesting that, while the disinfection is not entirely ineffective, it still requires significant improvement. Therefore, it is clear that adhering strictly to HPC standards is not currently feasible [47,48].

These parameters provide a thorough understanding of the reduction of organic load, the efficiency of nutrient removal, and overall improvements in water quality, all of which are crucial for assessing how well treatment systems work.

Despite providing crucial information, physicochemical parameters are occasionally insufficient on their own to fully capture the safety and quality of treated water, particularly when evaluating the possible microbial risk. As an additional measure, the heterotrophic plate count (HPC), a microbiological parameter, was introduced. The purpose of incorporating HPC was to give a more comprehensive view of the quality of treated water and to support the confirmation and cross-verification of the results from the physicochemical data. Here, it was thought to be beneficial to check for any residual microbial presence after treatment, even though HPC is typically used in surface and drinking water evaluations. The purpose of tracking the HPC levels was to determine whether the microbiological conditions matched the enhancements shown by the physicochemical parameters. A more thorough and reliable evaluation of the overall treatment effectiveness of each plant is made possible by this extra layer of analysis, which helps to guarantee that the treated effluent satisfies standards for both chemical and microbiological safety.

In conclusion, even though the heterotrophic plate count method offers insightful information about the microbial quality of treated wastewater, it is evident that certain plants require improved disinfection procedures to confirm adherence to stringent environmental regulations. A more thorough understanding of the microbial dynamics in WWTP effluents may be possible with the use of sophisticated microbiological techniques in future research, such as measuring respiration rates and dehydrogenase activity.

4. Conclusions

The reliability of organic matter (COD, BOD_5) and TSS as treatment indicators was confirmed by our analysis, which was based on both physicochemical parameters and heterotrophic plate count (HPC). This analysis demonstrated consistent removal efficiencies across various wastewater treatment plants. However, the removal of TP and TN varied among the plants, and some met EU standards while others did not. The observed ranges for TP removal were 70–83% to 79–80%, while TN removal varied from 46–66% to 77–45%. Efficiency measurement was made impossible by the rise in nitrate and nitrite levels in the effluent.

The study highlights operational challenges in the denitrification process. Future research should aim to confirm these results in diverse regions and treatment plant types, evaluate whether the operational limitations are common, and ascertain whether the suggested enhancements, such as retrofitting anoxic zones and adding carbon supplementation, are effective in other contexts.

Overall, the microbiological and physicochemical results were aligned well, and the majority of the parameters met discharge requirements. This suggests that these Hungarian WWTPs were effectively treating wastewater.

Additionally, the research greatly demonstrated compliance to various regulatory standards. Nonetheless, several recommendations can help enhance wastewater treatment processes:

- Apply advanced oxidation processes (AOPs): AOPs are used to treat wastewater by eliminating organic compounds, micro pollutants, and other contaminants that may not be effectively removed by conventional methods. These include ozone, hydrogen peroxide, and ultraviolet (UV) combined with hydrogen peroxide. The goal is to purify the wastewater and make it suitable for residential use [47,48].
- Implement membrane bioreactors: Wastewater can be treated more effectively and compactly when biological treatment and membrane separation are combined (MBRs) [48].
- Utilize micro screening (to eliminate suspended solids from wastewater), ultrafiltration (to effectively eliminate toxic materials, suspended solids, and dissolved solids from wastewater), advanced carbon adsorption (to eliminate organic pollutants, hazardous materials, and persistent organic pollutants), as well as phosphorus and nitrogen elimination to optimize treatment outcomes [49].
- Focus on managing substantial quality emissions of nitrogen compounds, particularly from industrial discharges and agriculture activities.
- Explore novel treatment approaches such as modified wetlands, while maintaining operational effectiveness by comparing different technologies [50].
- Improve treatment procedures by using the enhanced biological nutrient removal (EBNR) method, which has shown excellent removal efficiencies for phosphorus, nitrogen, and carbon [51], such as the Modified Ludzack–Ettinger (MLE) process, which could further improve nitrogen and phosphorus removal efficiency.
- Employ anaerobic ammonium oxidation (anammox) and partial nitritation procedures for economical nitrogen removal. Even though the anammox process is successful with a variety of wastewater streams, more research is necessary to determine its suitability and how it handles various industrial effluents [51].
- Incorporate advanced methodologies to assess a broader range of pollutants, including heavy metals, persistent organic pollutants, and microplastics.

These recommendations can help address weaknesses in current treatment systems and improve overall wastewater management strategies.

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