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PAPER

Environmental and energy efficiency of a selected municipal wastewater treatment plant – a case study

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Abstract

Based on the analysis of environmental and energy efficiency in the years 2019–2021 in the selected sewage treatment plant (WWT) located in the southern Poland with mechanical-biological wastewater treatment, it was found that the highest level of pollution reduction of 98% enabled the highest BOD5 concentration to be reduced more than 800 times. The operation of the sewage treatment plant was characterized by variable efficiency of the treatment process, which was demonstrated by significant differences in chemical indicators (BOD5, COD, P, TSS and N). Low average concentration of total nitrogen below 4 mg l^{-1} occurred with a reduction of pollutants at a level not exceeding 90%. Noticeable energy consumption of 1.58 kWh m^{-3} related to the increase in the amount of treated sewage, confirmed by a moderate correlation, indicated the need to optimize the treatment process.

1. Introduction

Water is one of the main elements of life on earth [1]. About 71% of the world's total water content consists of about 2.5% pure water [2], but, it is important to save it, as well as protect it. Water pollutants are usually substances that alter the physical and chemical characteristics of water thus deteriorating their quality [3]. To the main major of water pollutants are categorized pathogens, organic and inorganic chemicals which include different contamination like heavy metals, dyes, volatile organic compounds, plastics, insecticides and pesticides [4]. Among the indicators of water pollution, the use of BOD 5 and COD are significant [5].

The wastewater treatment processes play an important role in the environmental quality e.g., surface water and sewage sludge disposal [4]. The increase in environmental awareness and the development of wastewater treatment technology have resulted in many regulations and standards that must be met today. The main EU document in wastewater management is the Council Directive of 21 May 1991 on urban wastewater treatment plants (91/271/EEC), the provisions of which had to be included in national regulations [6]. In Polish law, issues related to wastewater management, rational management, and water resource protection are regulated by the Act of 20 July 2017 [7]. Accordance to [8] wastewater is waterborne solids and liquids that discharged into sewers, which are a waste of social life. A well-functioning wastewater treatment plant with a developed sewage network significantly reduces the load of sewage discharged into the waters, which may result in the natural or artificial return of animals or plants to the ecosystem [9]. Over the years, a number of efforts have been made to treat various wastewater treatment technologies such as conventional filtration, coagulation-flocculation and biological treatment systems, as well as membrane technologies [10]. This indicates that most often wastewater treatment systems have two levels of treatment (physical settling of solids) and secondary (various forms of oxidation, e.g. activated sludge or trickling filters) [11].

The operation of WWT is closely related to the production of sewage sludge, the composition of which is closely related to the composition of sewage entering sewage treatment plants [12]. Some researchers have shown that the efficiency of wastewater treatment depends on the advancement of wastewater treatment technology and the load of pollutants [13].

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Figure 1. Location of the mechanical and biological wastewater treatment plant in southern Poland (South Małopolska).

Municipal wastewater is a potential source of chemical energy, i.e. organic carbon, which can be recovered in the form of biogas during sludge fermentation [14]. The energy demand of a wastewater treatment plant depends on the location of the treatment plant, its size (equivalent population, ecological, amount of wastewater, hydraulic load), type of treatment process and aeration system, wastewater quality requirements, and the age of the installation [15]. Electricity is one of the main costs incurred by the treatment plant; therefore such facilities during operation should optimize processes in such a way as to minimize energy consumption while maintaining the required parameters of treated wastewater. Wastewater treatment plants are energy-intensive, especially in terms of electricity requirements with around 90% of total energy consumption [16]. It is important to know the energy consumption of individual stages of wastewater treatment, as this allows you to choose the most effective solution during the construction or modernization of such facilities [17]. The aim of the paper was the efficiency of the environmental and energy of a selected municipal wastewater treatment plant in 2019–2021 located in the southern Poland.

2. Materials and methods

The work includes monthly qualitative and quantitative studies of wastewater before and after treatment and energy consumption of the treatment process in 2019–2021. The analysis used data from 12 months in 2019–2020 and 4 months (February, April, June, and October) in 2021, provided by the operator of the wastewater treatment plant. The following indicators were taken into account in the qualitative and quantitative analysis: biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (N), total phosphorus (P), and the amount of wastewater at the outflow. They used similar indicators in their research work [18]. In addition, the results of the work were related to the values of permissible concentrations of pollutants in wastewater specified in the Regulation of the Minister of Maritime Economy and Inland Navigation of July 12, 2019, on substances, particularly harmful to the aquatic environment and the conditions to be met when discharging sewage into waters or the ground as well as when rainwater or meltwater is discharged into waters or water facilities [19]. Collection and preparation of samples and psychic-chemical determinations were made by the relevant regulations [20]. The study determined the level of reduction (η) of the indicated indicators of wastewater pollution according to the following:

$$\eta = \frac{C_0 - C}{C_0} \tag{1}$$

were c_0 is wastewater concentration before treatment, c is wastewater concentration after treatment.

The energy consumption of the wastewater treatment process was also analyzed, which concerned the consumption of electricity, taking into account the amount of treated wastewater. Energy intensity (En) was calculated as the quotient of electricity consumed in a month (E_m) to the amount of treated wastewater (I_m) in the same month from the equation:

$$En = \frac{E_m}{I_m} \tag{2}$$

The analysis took into account the maximum, minimum, and arithmetic mean values of the indicated indicators. The data on collecting waste were subjected to statistical analyses considering the following descriptive statistics: minimum, maximum, mean, and standard deviation. Extreme values, mean values, and standard deviations are presented using box plots for selected elements that differ significantly from one point to another. The Pearson linear correlation coefficient method was used to determine the correlation meeting the condition of a normal distribution of data covering the amount of treated wastewater and energy consumption

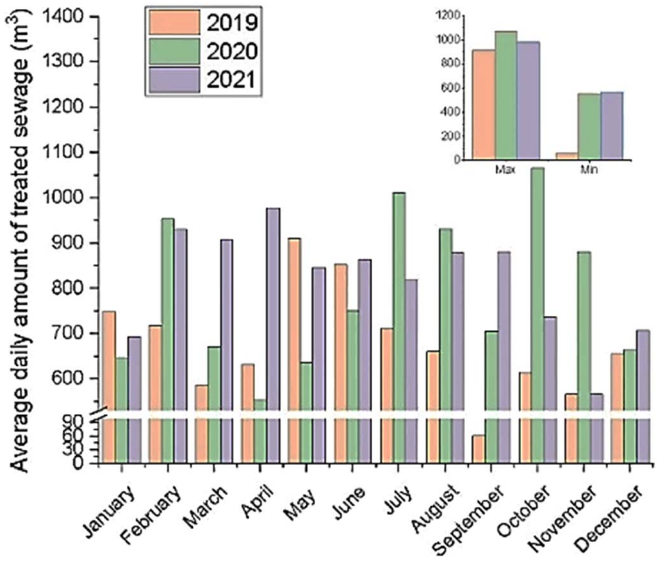

Figure 2. Average daily amount of treated sewage in individual months and years.

[21]. The significant differences between indicators of wastewater pollution before and after wastewater treatment were estimated, and Student's parametric t-test (for dependent samples) was used to compare the two dependent groups (on the base of averages). The test probability on the level of $p < 0.05$ was assumed to be significant (Przydatek 2019) [22]. The number of data points used for analytical purposes for each of the four variables (BOD5, COD, P, TSS, N) was $n = 28$. Statistica 13 (StatSoft Poland, StatSoft, Inc., USA) software was used to conduct the statistical analyses.

The research facility is located in the southern part of Poland in Lesser Poland (Southern Poland) and is used to treat domestic and economic sewage produced in the urban and community area. The wastewater treatment plant in X has a maximum capacity of 1288 $m^3\ d^{-1}$ and is located on the Poprad.

River, which is the receiver of treated sewage. The existing wastewater treatment facility (figure 1) is; a catchment station, sieve, emergency manual grate, sand trap, sand separator, sewage and rainwater pumping station, belt press, quicklime silo, BIOKOMPAKT reactors, blower station, excess sludge tank, retention tank, sewage quantity measurement, storm overflow sieve, treated sewage outlet.

The selected facility is a mechanical-biological treatment plant, the operation of which was based on technology-type BIOCOMPACT (BCT-S), associated with the process of low-load activated sludge with extended aeration time with biological removal of biogenic compounds and the use of wastewater filtration on activated sludge suspended in the separation zone.

Components of the wastewater treatment process:

- Mechanical treatment: Sieve; Sandbox; Sand separator;
- Biological treatment: BIOCOMPACT reactors; Anaerobic zone; Denitrification zone; Nitrification zone; Excessive sediment.

3. Results

3.1. Quantitative analysis of the wastewater results

The average amount of treated wastewater in the examined treatment plant is shown in figure 2.

In 2019, the lowest daily average of treated wastewater was 61.73 m^3 in September, while the highest in May was 910.87 m^3. In 2020, the highest value of 1,065.45 m^3 was recorded in October with the lowest value of 553.2 m^3 in April. In the following year, 2021, the average daily amount of sewage was slightly lower than the previous year by 86.72 m^3. The lowest result was higher than the previous one by 12.5 m^3.

3.2. Qualitative analysis of the wastewater results

The highest total suspended solids in raw wastewater occurred in July 2021 and amounted to 1,590 mg l^{-1}, while the lowest in February 2020 was at the level of 102 mg l^{-1} with an average of 403.07 mg l^{-1}. The highest COD value of 4.410 mg l^{-1} was founded in May 2020, and the lowest value of 234 mg l^{-1} was recorded in August 2019.

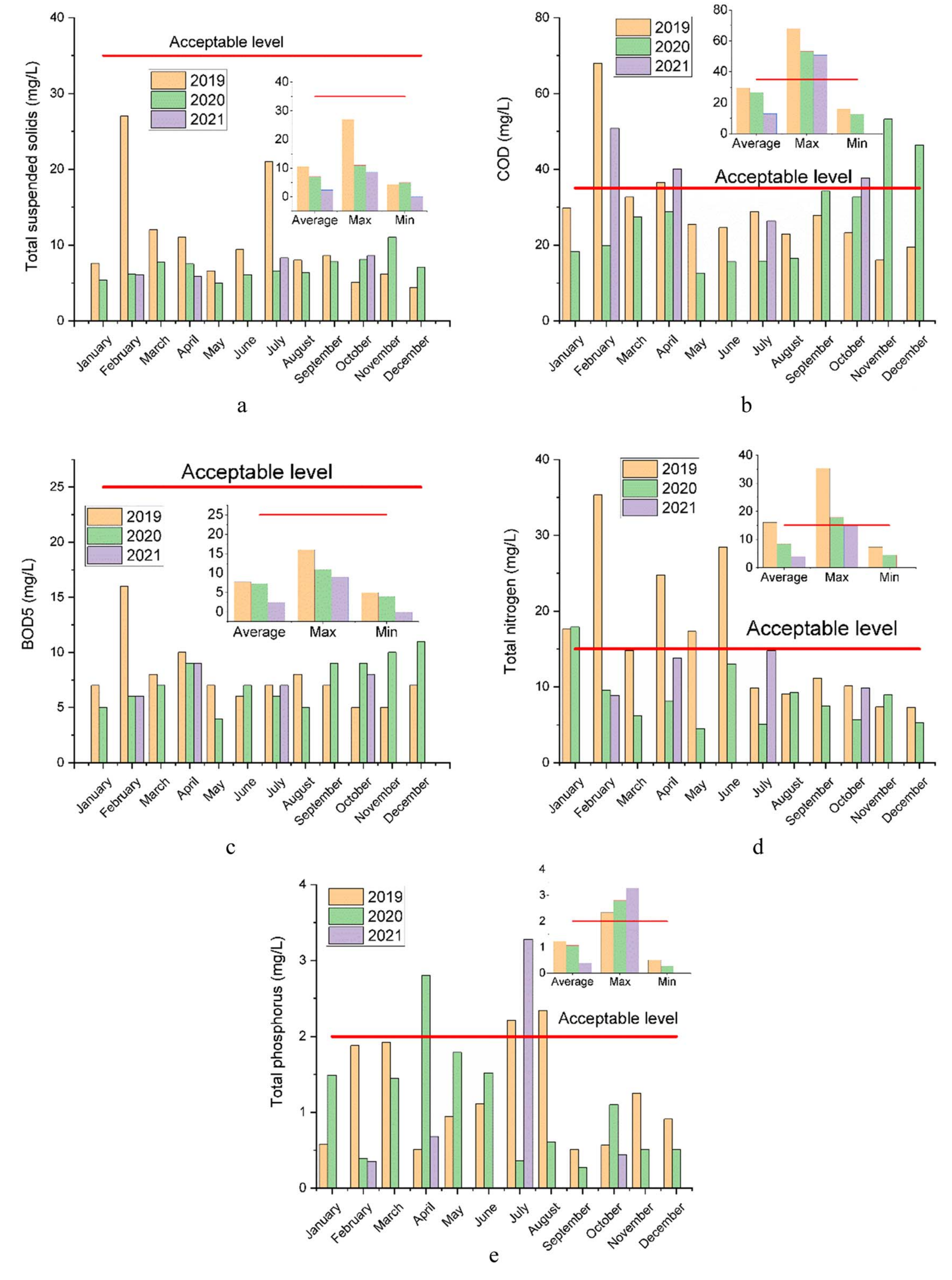

Figure 3. Composition of waste after treatment, including concentrations of (a) TSS; (b) COD; (c) BOD5; (d) N; (e) P.

The average, in this case, was 984.29 mg l^{-1}. COD distinguished the highest value of standard deviation exceeding 800 mg l^{-1}. The minimum concentration of BOD5 was recorded in August 2019–130 mg l^{-1}, and the highest in November 2020–3,583 mg l^{-1} with an average of 509.75 mg l^{-1}. Total nitrogen concentration ranged from 41.3 mg l^{-1} in June 2020 to 216 mg l^{-1} in October 2019, with an average of 102.69 mg l^{-1}. Most often, the 8-fold fluctuations concerned the concentration of N in the range of 17.9–35.3 mg l^{-1} with an average of 12.18 mg l^{-1} after purfication and showed the overflow of the permissible level 15 mg l^{-1}. In the purification process, the N content was reduced by 88.10%. The highest P content occurred in July 2021 at 3.28 mg l^{-1}, and the lowest was in September 2020 at 0.27 mg l^{-1} with an average of 1.15 mg l^{-1} and an acceptable level of

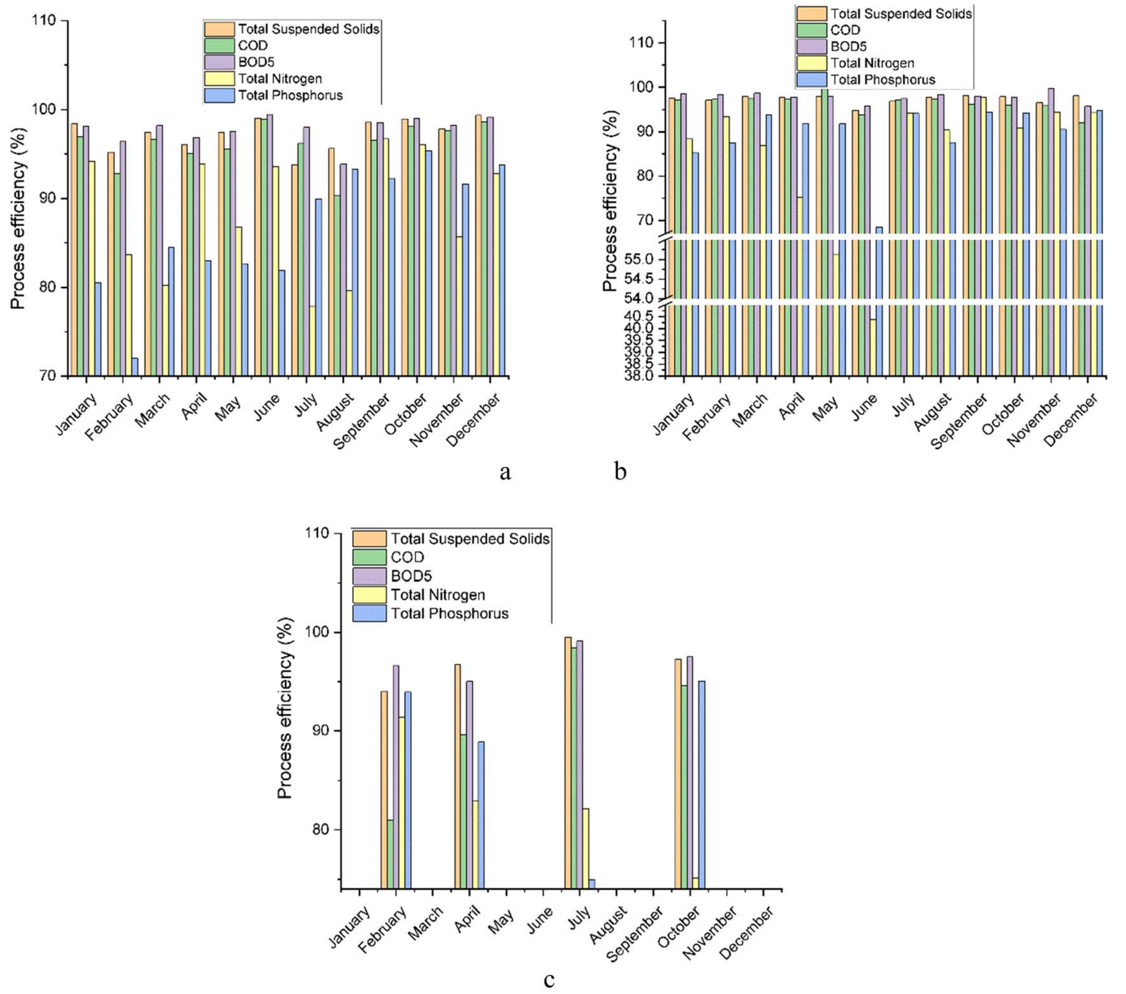

Figure 4. The efficiency of the wastewater treatment process: (a) 2019 (b) 2020 (c) 2021.

Table 1. Descriptive statistics results of wastewater treatment.

Variables	Unit	Descriptive statistics				
		N- important	Average	Min.	Max.	Stand. deviat.
TSS[a]		28	403.07	102,00	1,590,00	295.127
COD[a]		28	984.29	234.00	4,410.00	804.148
BOD5[a]	[mg/L]	28	509.75	130.00	3,583.00	638.851
P[a]		28	9.78	2.55	17.20	3.466
N[a]		28	102.69	39.40	216.00	36.512
TSS[b]		28	8.60	4.40	27.00	4.792
COD[b]		28	29.66	12.60	67.90	12.951
BOD5[b]	[mg/L]	28	7.54	4.00	16.00	2.396
P[b]		28	1.15	0.27	3.28	0.810
N[b]		28	12.18	4.47	35.3	7.32

[a] Wastewater before treatment.

[b] Wastewater after treatment.

2 mg l^{-1}. The P concentration was exceeded four times (mostly in 2019), which is confirmed by the results in the range of 2.21–3.28 mg l^{-1} with the lowest level of phosphorus content reduction in the research cycle by 88.24%. This indicator's highest standard deviation result of 23.535 mg l^{-1} occurred (figures 3 and 4, table 1).

3.3. Process energy consumption analysis

The energy consumption of the wastewater treatment process in the X treatment plant was shown in figure 5.

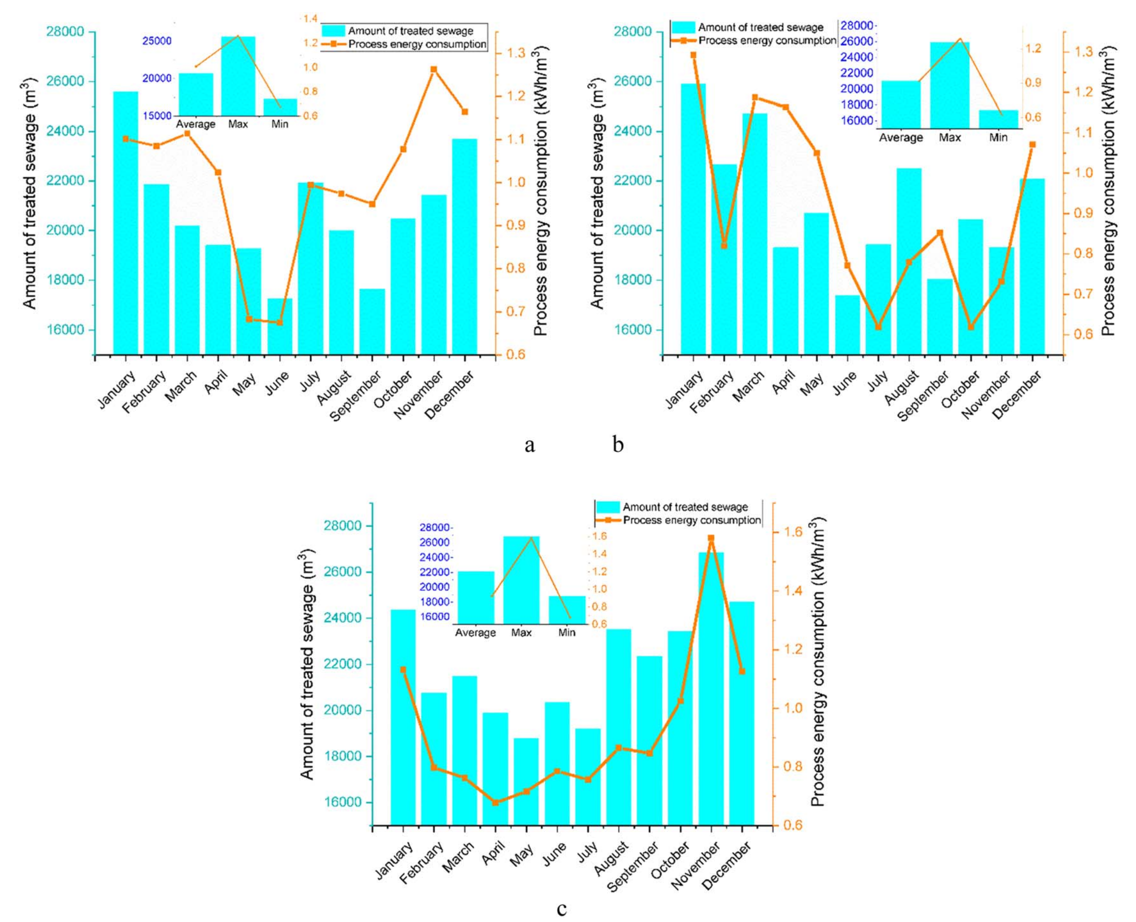

Figure 5. The energy intensity of the wastewater treatment process: (a) 2019 (b) 2020 (c) 2021.

In 2019, the lowest energy intensity of the process was obtained in November, 1.26 kWh m^{-3}, with the amount of treated sewage amounting to 21,423 m^3, with the highest average annual energy intensity of 1.01 kWh m^{-3}. It should be noted that the highest amount of treated sewage occurred in January, 25,597 m^3, and the lowest, 17,266 m^3, together with the lowest energy intensity in June, 0.67 kWh m^{-3}. In 2020, the lowest energy intensity of the process was 0.62 kWh m^{-3}, which occurred in October. On the other hand, the highest energy intensity took place in January and amounted to 1.29 kWh m^{-3}. The average energy intensity in 2020 was 0.91 kWh m^{-3}. The highest energy intensity in 2021 occurred in November and amounted to 1.58 kWh m^{-3} with the highest amount of treated wastewater – 26,839 m^3, and the lowest energy intensity of the process in 2021 was obtained in April, which amounted to 0.68 kWh m^{-3}. The average energy intensity in 2021 reached 0.92 kWh m^{-3}.

3.4. Statistical analysis

The highest value of pollution in wastewater before treatment was confirmed on the basis average concentration of COD – 984.29 mg l^{-1}. Similarly, the highest value amounted to the maximum and minimum between 234.00–4,410.00 mg l^{-1} and an additional of standard deviation 804.148 mg l^{-1}. Differently, the lowest values regarded of concentration of P from 2.55 to 17.20 mg l^{-1} at an average of 9.78 mg l^{-1}.

After wastewater treatment, the highest average value was 29.66 mg l^{-1}, and minimum concerned COD. Whereas of the highest values maximum and standard deviation regarded content N of 83.80 and 23.54 mg l^{-1}, respectively. On the other hand, the lowest values regarded P from 0.27 to 3.20 mg l^{-1} at an average of 1.15 mg l^{-1} (table 1).

The inflow and outflow contamination of wastewater was characterized by statistically significant differences, including BOD5, COD, P, TSS and N indices (figure 6) with significantly lower average concentrations after the wastewater treatment process.

A moderate correlation (figure 7) was noted in the case of an increase in the amount of treated wastewater and energy consumption (0.65). [23] also showed a positive correlation between the demonstrated variables. In turn, other researchers [24] achieved a similar correlation value.

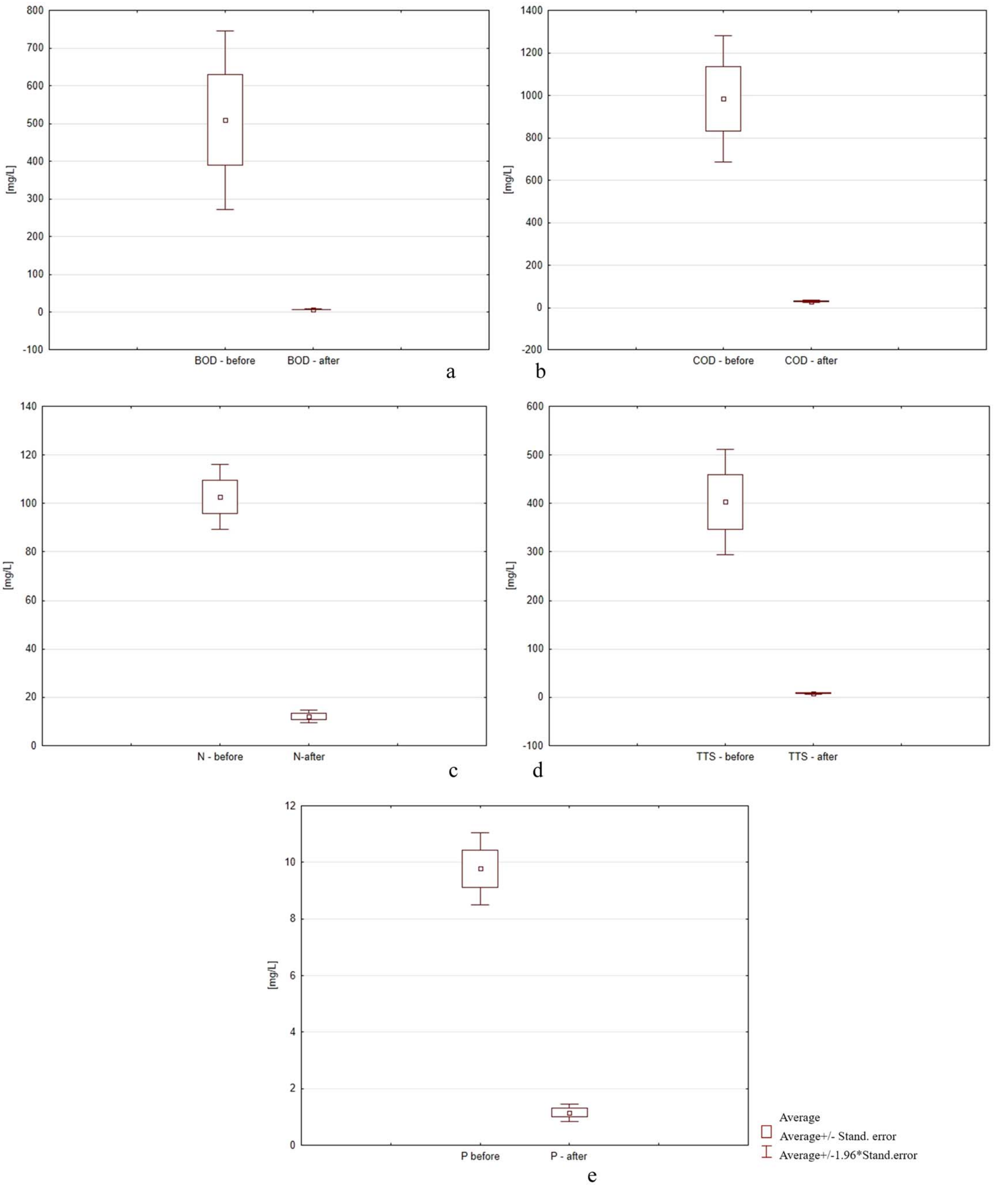

Figure 6. Significant differences between research points before and after wastewater treatment: (a) BOD5, (b) COD, (c) N, (d) TSS, (e) P.

4. Discussion

The efficiency of the sewage treatment plant is related to both the environmental aspect and energy efficiency. The functionality of such facilities is essential to maintain sustainable development in the context of minimizing the negative impact of sewage on the aquatic environment. On the other hand, controlling environmental factors are one way to prevent environmental degradation [25].

One of the basic indicators to be assessed during treatment is the total suspended solids. Its high content of 1,590 mg l^{-1} in raw sewage in 2021 was significantly reduced by 97.26%. One of the researchers [26] showed the impact of TSS on the course of the process depends on the physicochemical properties of the compounds. Another COD indicator tested in raw sewage was characterized by a content in the range of 32.6–50.8 mg l^{-1} with an average of 29.66 mg l^{-1}, which was exceeded mainly in the second half of 2020 and 2021. [27] wykazali, że ścieki o wysokim ChZT wyrządzą wielką szkodę środowisku. This result occurred despite the high concentration reduction during the purification process of 96.13%. A lower level of COD reduction in studies was shown by [28]. BOD5 is an important indicator for evaluating WWT functionality. The highest

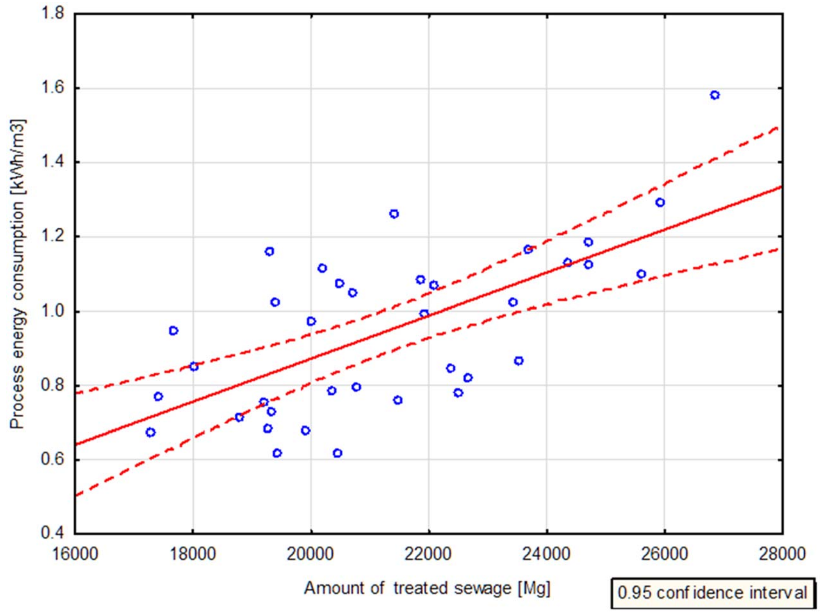

Figure 7. Significant correlation between variables of treated amount sewage and energy consumption.

concentration of BOD5 before purification was 3.583 mg l^{-1}, and after this process there was a significantly lower concentration of 4 mg l^{-1}. It should be emphasized that the level of reduction of this pollutant was the highest and exceeded 98%. [29] showed a lower maximum value of BOD5–1,320 mg l^{-1} in Poland.

From an environmental point of view, the efficiency of removing biogenic compounds during wastewater treatment is important. According to [30], the primary source of P in the environment is anthropogenic, and present a synthetic detergent in domestic wastewater. In the case of P, the permissible concentration of total phosphorus in treated wastewater was exceeded several times at concentrations ranging from 2.21 to 3.28 mg l^{-1}, with the average not exceeding 2 mg l^{-1} and the reduction level at the level of 88.24%. Wastewater is a significant source of nitrogen pollution in surface waters, hence the effective removal of nitrogen from wastewater is a great importance to prevent eutrophication processes [31]. Nitrogen occurs in various oxidation states, which makes the process of its removal complicated and difficult, resulting in increased costs of energy consumption and wastewater treatment [32]. The concentration of total nitrogen in raw sewage ranged from 39.4 to 216 mg l^{-1} with an average of 102.69 mg l^{-1}. [33] showed a lower average content of N in the research. Most often, the 8-fold fluctuations concerned the concentration of N in the range of 17.3–35.3 mg l^{-1} with an average of 12.18 mg l^{-1} and showed the overflow of the permissible level with the reduction of pollution at the level of 88.10%. [34] demonstrated a higher level of N reduction.

In this case, the use of a biological method is considered an effective solution in the removal of nitrogen compounds from wastewater [35]. Generally, the results of research confirmed the occurrence of significant differences between raw and treated wastewater. Similarly, [36] showed significant differences, which were associated with a significant reduction in pollutants contained in raw wastewater.

The environmental impact of energy consumption in wastewater treatment plants can be reduced by various strategies, such as energy efficiency measures, and the use of renewable energy. Sources and energy recovery from wastewater or its by-products [37].

According to [38], in order to effectively recover potential energy in a sewage treatment plant, it is advisable to fully use the excess sludge containing N with 60% of organic matter. It should be noted that the largest amount of treated wastewater in 2019–25,597 m^3 coincided with the average energy intensity of 1.01 kWh m^{-3}. In October 2020, the process had the lowest energy consumption of 0.62 kWh m^{-3} with the highest average daily amount of treated wastewater of 1,065.45 m^3. In turn, the higher energy intensity was recorded in November 2021 with the result of 1.58 kWh m^{-3} with the highest amount of treated wastewater. [39] showed similar amounts of energy consumption in the range of 0.3–2.1 kWh m^{-3} during wastewater treatment. There was a noticeably moderate correlation associated with energy consumption during wastewater treatment. [23] showed that wastewater with higher internal energy, determined by COD concentration and flow rate, results in higher energy consumption in treatment plants, and also causes an increase in the production of excess sludge, bioreactor surface and wastewater volume.

A noticeable increase in energy consumption indicates the need for efficiency optimization in WWT. According to [40], energy optimization at WWT is a key management issue for businesses. One of the sources of meeting the demand for electricity in a sewage treatment plant may be the recovery of biogas a fuel requirement, in the cogeneration unit [41].

5. Conclusion

Based on the analysis of the environmental and energy results of the operation of a selected wastewater treatment plant in southern Poland in 2019–2021, the following conclusions were drawn:

- The highest concentration of BOD5–3,583 mg l^{-1} before wastewater treatment and the lowest after treatment of 4 mg l^{-1} occurred at the highest level of pollution reduction exceeding 98%.
- COD and P concentrations were several times higher than the permissible level in treated wastewater, without affecting the higher average values, which were below 25 and 2 mg l^{-1}, respectively.
- Pollutants at the inflow and outflow of wastewater were characterized by statistically significant differences (BOD5, COD, P, TSS and N) with a noticeable decrease after treatment.
- A decrease in the increased average concentration of total nitrogen below 4 mg l^{-1} with a reduction of pollutants not exceeding 90% should be considered beneficial.
- A noticeable increase in energy consumption in the wastewater treatment plant to 1.58 kWh m^{-3} along with the increase in the amount of wastewater confirmed by moderate correlation indicated the need to optimize the treatment process.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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