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ENVIRONMENTAL IMPACT OF TWO WAYS OF TREATING DOMESTIC WASTEWATER WITH AN EXAMPLE OF A CONVENTIONAL TREATMENT PLANT VERSUS PLANT-POND SEWAGE TREATMENT

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ABSTRACT: One of the important metter of environmental care is effective sewage treatment. Centralised sewage treatment with high efficiency dominates in Poland. However, highly dispersed properties often require the use of other alternative solutions. The aim of the paper is to compare the impact of two sewage treatment methods on the environment: conventional (PWWTP) and plant-pond (PPST). To assess the operation of both treatment plants and their environmental impact, emergy calculation and emergy indicators such as ELR, EYR, and ESI were used. It was found that the PPST treatment plant burdens the environment less. The current operation of the conventional treatment plant absorbs over 87% of the total emergy, while in the case of the biological treatment plant it is 0.40%. ELR for PPST was 5.58, while for PWWTP it was as much as 1809.09. The efficiency of sewage treatment in both treatment plants is similar. BOD5 reduction was 87.5% for PPST and 96.7% for PWWTP. For both treatment plants, an attempt was made to identify other environmental benefits, such as the generation and use of by-products, the possibility of using treated sewage for irrigation purposes or creating a biodiversity site. An attempt was made to quantify some of the additional benefits.

KEYWORDS: emergy analysis, sewage treatment efficiency, conventional wastewater plant, plant-pond sewage treatment, environmental services

Introduction

Wastewater treatment systems are one of the basic elements of caring for environmental quality. In Poland, in urban areas, at the end of 2023, as much as 91% of the population used the sewage system, and in rural areas, 45.5% (Statistics Poland, 2024). Centralised wastewater treatment systems are used to a significant extent. Their construction enjoys the support of local authorities and is often supported by operational programs. This is supported by the level of wastewater treatment achieved, practical control over the entire process, and minimisation of the occupied land for treatment plant infrastructure. However, such systems can be impractical in some situations, such as distance to homes or terrain. Running a conventional wastewater treatment plant is also usually associated with high cost of construction, equipment and process monitoring, maintenance and operation (Serdarevic & Dzubur, 2019).

There are places of residence characterised by a large dispersion of buildings. In such cases, the only economically or technically feasible solution is to collect wastewater in non-drainage basins and dispose of it cyclically to the septage receiving stations, or to build domestic wastewater treatment plants (Jawecki et al., 2016; Wiśniewska-Kadżajan, 2013). These decentralised systems are an alternative and play a large role in wastewater treatment, mainly in small communities (United States Environmental Protection Agency, 2025; Wu et al., 2011). As at the end of 2023, there were nearly 2.5 million domestic sewage disposal systems in operation. Of these, 16.5% were domestic wastewater treatment plants, most of which, 91.7%, were located in rural areas (Statistics Poland, 2024). Plant-wetland treatment can be an alternative, both to centralised wastewater treatment systems and other individual domestic solutions. One can find studies comparing these systems in various respects: resource consumption, environmental impact, space occupation or treatment efficiency. In some of them, emergy accounting is used as a research and comparison tool. It allows the evaluation of the consumption of both construction, operating materials and energy, as well as the assessment of the environmental impact of such facilities. In comparisons of wastewater treatment plants, it is pointed out that traditional treatment methods are characterised by significant consumption of resources and energy, leading to a burden on the environment. Integrating energy and material recovery processes can significantly improve the environmental performance of wastewater treatment systems (Vassallo et al., 2009). Similar conclusions are presented by Zhang et al. (2010), highlighting that conventional wastewater treatment is characterised by a low proportion of local, renewable resources, which negatively impacts the environment. Therefore, there is a need to increase the share of local renewable resources and optimise technological processes to improve the sustainability of the wastewater treatment system (Ciobanu et al., 2022). In the work of Alizadeh et al. (2020), the potential for sustainability improvement of water treatment plants was studied in some scenarios, including the production of agricultural compost from sludge. The authors emphasise the importance of these processes and their impact on reducing environmental costs. At the same time, they point out that analysis using emergy accounting can be a useful tool for wastewater treatment plant managers, as well as citizens, to enhance urban water sustainability.

The use of local renewable resources is negligible in the operation of a conventional treatment plant. A possible change requires the reorganisation of human settlements and the landscape around them, but also a change in lifestyles so that there are enough spaces in residential areas to treat wastewater through nature. It is noted that there are no savings from using sludge biomass to produce energy at the wastewater treatment plant. (Björklund et al., 2001).

One way to increase the share of local renewable resources is to use a plant-pond sewage treatment system to treat domestic wastewater. Plant-pond technology has lower operating costs and simplicity of operation, making it attractive to small and medium-sized communities. However, land acquisition for this type of facility is a problem. Also, climatic factors can be a limitation. It is suggested that plant-pond technology be integrated with other treatment methods and that modern modelling and monitoring tools be used to optimise processes and increase the efficiency of pond systems. (Ho & Goethals, 2020)

As with recreational ponds, aquatic plants in wetland sewage treatment plants play an important role in maintaining a balanced ecosystem. In addition to their purification function, they provide suitable conditions for the existence of aquatic organisms. Carefully planned pond management, including plantings, contributes to maintaining a balanced ecosystem.

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The emergy accounting used (Zhou et al., 2009, Merlin & Lissolo, 2010) showed that a plant-pond wastewater treatment system has a lower environmental impact compared with a conventional treatment plant. The EYR, ELR and ESI indicators suggest that artificial wetlands are a more sustainable option for wastewater treatment.

The purpose of this paper is to compare two different wastewater treatment systems: domestic wastewater in the case of the plant-pond sewage treatment plant and municipal wastewater in the case of the conventional sewage treatment plant. The analysis concerns wastewater treatment plants located in the climatic conditions of southwestern Poland. In order to compare the expenditures associated with the construction and operation of the two treatment plants, the values of emergy indicators and the efficiency of wastewater treatment were taken into account. In addition, the fertilising potential accumulated in the sewage sludge and plant biomass of the denitrification ponds of the pond treatment plant was estimated. The comparison also highlighted additional environmental aspects of the plant-pond treatment system, including the biodiversity enclave created.

The analysis of the operation of both treatment plants concerns data and information for one year of their operation, 2024.

Materials and method

Characteristics of the studied objects

Plant-pond sewage treatment plant

The plant-pond sewage treatment (PPST) serves a household located in the village of Szczedrzyk, in southwestern Poland. The treated domestic sewage is a result of the daily functioning of the people living in the household. The facility is described by the coordinates 50°41’50.1 “N 18°10’08.8 “E. The treatment plant was built in 2004, mainly due to the lack of a sewage system in the village at that time. In addition to its direct function, the facility is also used for environmental education workshops conducted by the owners. The treatment plant covers an area of 77 m^2. According to the project, it is designed for 9 PEs (people equivalent). For several years, wastewater production and treatment have been for a family of 3 people. The number of people in the household varies periodically due to agritourism activities. The technology used uses mechanical and biological wastewater treatment processes. The treatment plant consists of the following components:

- A septic tank where wastewater undergoes mechanical and partially biological pretreatment.
- The pumping station is equipped with a submersible pump that pumps wastewater to the plant filter.
- A plant filter with an active area of 8 m^2, where the main process of wastewater treatment takes place. The filter was planted with vegetation.
- Denitrification pond No. 1 with an area of 46 m^2 and a water capacity of 25 m^3. Made in a trench and planted on the slopes with vegetation. The main task of the pond is to remove nitrate nitrogen by denitrification in the bottom sediments. Other organic compounds, phosphorus and pathogenic bacteria are also removed. Excess water drains into denitrification pond No. 2.
- Denitrification pond No. 2 with an area of 23 m^2 and a water capacity of 11m^3. The pond was planted with vegetation.

The ponds are additionally fed with rainwater, also from the 180 m^2 roof area of the house, which is connected to the treatment plant. The water drained from the roof dilutes the wastewater in the ponds. In addition, the use of rainwater in the ponds improves the condition of the biomass, especially in recent years of drought.

Conventional municipal wastewater treatment plant

The Prószków wastewater treatment plant (PWWTP) is located in southwestern Poland (50°34’59.4 “N 17°52’04.8 “E) and represents a comprehensive approach to sustainable wastewater management. More than 99% of the wastewater subjected to treatment is domestic sewage. Only 0.5% of the wastewater subjected to treatment comes from local production and service plants (Uchwała, 2020). By integrating advanced mechanical and biological processes as well as sludge treatment and the facility achieves high treatment efficiency and quality of treated wastewater compliant with environmental protection requirements (national and EU standards). The treatment process

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comprises mechanical and biological stages, supported by advanced automation and monitoring systems. The WWTP in Prószków, following its significant reconstruction and expansion in 2023, exemplifies a modernised approach to managing municipal and industrial wastewater. Designed for a population of 7,500 PEs, it currently serves 5,279. The PWWTP processes an average daily wastewater inflow of 970 m^3. The facility includes the following treatment stages:

- Mechanical treatment phase that includes an initial screening stage utilising a belt-hook screen with a 3 mm aperture. Grit and fat separation occurs in an aerated vortex grit chamber, which efficiently captures and isolates these substances. These initial steps ensure the removal of coarse contaminants and fats, safeguarding downstream processes.
- Biological treatment at the plant is conducted in two Sequencing Batch Reactors (SBRs). The reactors alternate in operation, undergoing cyclic phases of filling, aeration, sedimentation, and decanting; aeration is provided by screw blowers, which ensure energy-efficient oxygen transfer via fine-bubble diffusers. Aeration efficiency is enhanced by the use of variable frequency drives controlling the blowers, ensuring a consistent oxygen supply while minimising energy consumption; the reactors facilitate the removal of organic matter, nitrogen, and phosphorus. Organic matter is oxidised by heterotrophic bacteria, while nitrogen is removed through nitrification and denitrification processes. Phosphorus removal is enhanced through the dosing of coagulants such as PIX, which precipitate phosphate compounds, ensuring compliance with discharge limits, for this size of the treatment plant.
- The sludge management process at the PWWTP involves thickening, chemical conditioning, and dewatering. Chemical agents, such as coagulants and polyelectrolytes, are employed to enhance dewatering efficiency and ensure the removal of pathogenic microorganisms. The resulting biosolids are rich in nutrients essential for plant growth and can significantly improve soil structure by increasing its organic matter content and water retention capacity.

Treated wastewater is directed to a drainage ditch and then to the Prószków stream and then to the Odra river.

Emergy analysis

Emergy analysis (E_mA) is a useful tool in assessing the environmental impact of an activity, and despite rather complex data requirements or problems with the accuracy of the method (Ciobanu et al., 2022), it is applicable to the assessment of various activities, both at the macro and micro scales. The energy-oriented approach can be used successfully to analyse the forces of nature involved in the process of creating its resources or producing goods and services. It is significant to account for the services provided by nature in a given process. This distinguishes E_mA from other approaches used to measure environmental impacts. Some of them focus on emissions and their role, without considering the impact of ecosystems on human well-being and sustaining economic activity (Bakshi, 2000). Others attempt to place monetary values on environmental products and services by reference, for example, to the value of substitute goods (Hau & Baksh, 2004). This does not always reflect the actual value of the environment, its resources involved in the production process and the services provided by nature. Emergy ($E_{m)}$ is determined from the equation (Saladini et al., 2016) (1):

$$E_m = \sum_i f_i \cdot UEV_i, \tag{1}$$

where:
f_i – input of exergy flow, expressed in units of energy, mass or money,
UEV_i – unit emergy value, expressed in, for example, seJ/J (so called solar transformity), seJ/kg or seJ/$.

It denotes for example, the solar energy required to produce 1 J of service or product (Odum, 1996). Solar energy is the basis of all emergy calculations. To more accurately determine the environmental load of a process, indicators such as ELR, EYR, ESI, for example, are used, which we also use in our analysis (Table 1).

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Table 1. Emergy indicators used in emergy accounting

Indicator	Formula	Description
Environmental Loading Ratio	ELR = (LN+FN)/(LR+FR)	It determines the pressure on the environment. A higher value is a higher environmental pressure.
Emergy Yield Ratio	EYR = E_m/(FN+FR)	The higher the score, the less reliance the system has on purchased emergy, and the more competitive the system is.
Environmental Sustainability Index	ESI = EYR/ELR	A measure of sustainability with respect to minimizing the burden on the environment while promoting development. ESI< 1 indicates pressure on the environment and production using non-renewable resources.

Footnotes: LR – local renewable; LN – local nonrenewable; FR – purchased renewable; FN – purchased nonrenewable; E_m – emergy.
Source: Dong et al. (2008).

Data collected for emergy analysis

In the emergy analysis, we take into account the type and amount of resources consumed. For this purpose, we obtained data directly from the owners of both facilities. In the case of the PPST, information on the expenditures incurred in the construction of the treatment plant came from the documentation of the construction application (Zgłoszenie budowlane, 2004). Other data, related to the operation of the treatment plant, came from an interview with the owners of the household. Information and data on the construction and operation of the PWWTP were obtained directly from the Prószków Municipal and Housing Company, which oversees the treatment plant.

The data used for emergy analysis includes many elements, taking into account, for example: consumption of tap water, electricity, human labour input, chemicals, use of machinery and equipment, and means of transport. Using the emergy approach, inflows involved in the activities of the two systems have been divided into:

- local renewable inputs (LR), such as solar energy, wind, and rain, unpaid own labour (its caloric conversion and solar transformity were assumed (Ciobanu et al., 2022).
- local non-renewable inputs (LN), which include the area occupied by treatment plants.
- purchased inputs (investment and current operating inputs), for example: construction materials, steel, plastics used were assumed to be non-renewable purchased substances; an emergy monetary equivalent of 6.09E+12 seJ/$ was assumed for remunerated human labor (NEAD, 2024).

Data on quantity and quality of wastewater, active sludge, plant biomass

From both treatment plants, data were obtained on the amount of wastewater delivered for treatment. In the case of PPST, its current amount of wastewater (based on the construction declaration) was related to the three people currently permanently living in the household. For wastewater from the PPST, we conducted laboratory tests to the extent necessary, both for raw wastewater (sampling – pumping station before the filter) and treated wastewater (sampling – denitrification pond II): BOD_5, COD, total nitrogen concentration ($N_{tot.}$) (from 7 measurements in 2024).

PWWTP provided the results of laboratory analysis of incoming and treated wastewater. For this treatment plant, these are average data from one year, 2024. Table 2 shows the selected operating parameters of both treatment plants.

Both treatment plants produce potential fertiliser mass as a by-product: activated sludge at PWWTP and plant biomass at PPST. Fresh activated sludge mass produced at 15 tons/month is transferred for agricultural use. We estimated the amount of biomass from the Szczedrzyk wastewater treatment plant based on the biomass collected from 1m^2 and related it to the total area covered by vegetation. To determine the suitability and fertiliser value of the products, we performed:

a) determination of dry matter content;

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b) elemental analysis of sewage sludge and plant biomass: total carbon ($C_{tot.}$), total nitrogen ($N_{tot.}$) by catalytic combustion in a combustion tube;
c) P and K content analysis by ICP-OES emission spectrophotometry.

Among other things, the analyses made it possible to determine the C:N ratio. It is important during the production of compost, for example, as it affects the rate at which microbes process carbon and make nutrients available to plants, as well as the formation of stabilised soil carbon compounds. The knowledge of the nutrient content (N,P,K) allowed us to assess the fertiliser potential and monetary value of both fertiliser products, relating it to the value of the pure component of commercial fertilizers.

Table 2. Basic parameters of operation of wastewater treatment plants in Szczedrzyk and Prószków

PPST (Plant-pond sewage treatment)		
Area occupied by the treatment plant (filter+ponds) [m^2].	77	
Roof area supplying rainwater to the treatment plant [m^2].	180	
People equivalent (PE) – current	3	
Average daily volume of incoming/treated wastewater [m^3/d].	0,3	
Volume of treated wastewater [m^3/PE/year].	36.5	
	Fresh wastewater	Post-treatment*.
Biochemical oxygen demand (BOD_5) [mgO_2/L] – mean value	299.99	37.63
Chemical oxygen demand (COD) [mgO_2/L] – mean value	463.58	152.02
Total nitrogen concentration [mg N/L] – mean value	105.80	30.56
PWWTP (Prószków wastewater treatment plant)		
Area occupied by the treatment plant [m^2].	10 100	
People equivalent (PE)	5279	
Average daily volume of incoming/treated wastewater [m^3/d].	970	
Volume of treated wastewater [m^3/PE/year].	67.10	
	Fresh wastewater	Post-treatment
Biochemical oxygen demand (BOD_5) [mgO_2/L] – mean value	305.4	10.08
Chemical oxygen demand (COD) [mgO_2/L] – mean value	874.2	116
Total nitrogen concentration [mg N/L] – mean value	81.42	20

Footnotes: *on the 2nd denitrification pond.

Results and discussion

Emergy analysis, emergy indices

Figures 1 and 2 show the boundaries of the two systems in terms of inflows of emergy streams and produced products (biomass, sewage sludge).

In the PWWTP, the system boundaries include the treatment plant and the sludge storage site. The LN used is land permanently occupied for building structures. The remaining expenditures come from purchases (F). These are capital materials and expenses related to day-to-day operation, such as energy consumption, taxes and environmental fees. The sludge generated is transferred for agricultural use on local farms.

The PPST treatment plant is presented as a subsystem. It is part of a small horticultural farm, located next to the household, where measures are taken to create a closed cycle of matter and use plant biomass to enrich the soil with organic matter.

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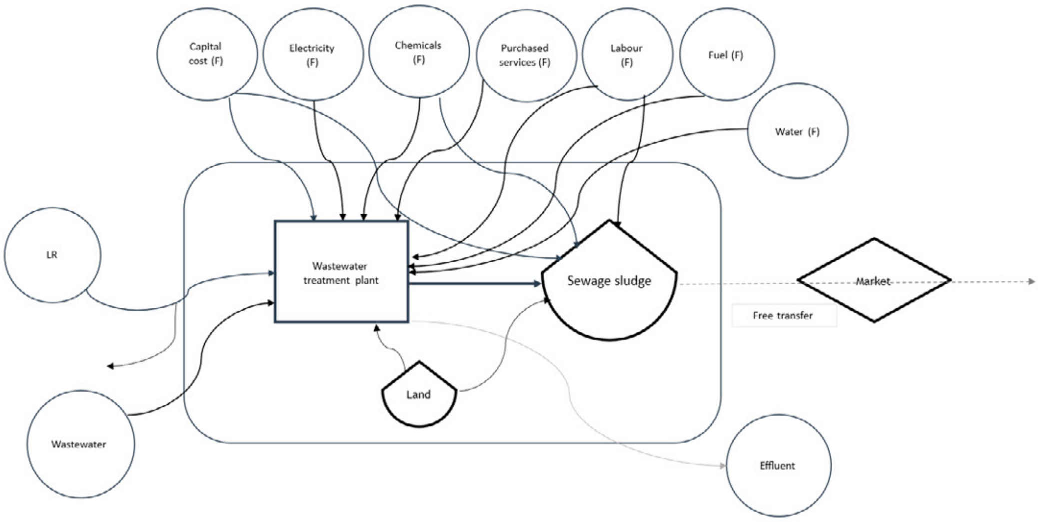
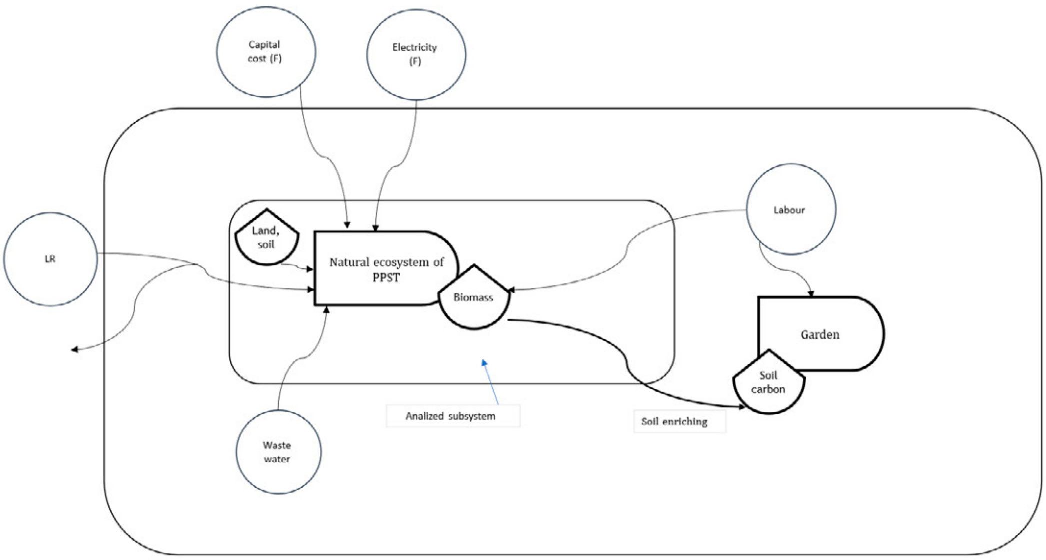


Footnotes: LR – local renewable; F – purchased;

Figure 1. Diagram of emergy flows in the PWWTP



Footnotes: LR – local renewable; F – purchased;

Figure 2. Diagram of emergy flow streams in PPST

Tables 3 and 4 show the results of emergy calculations for both treatment plants. Total emergy (TE_m) values at the same time represent the environmental cost of wastewater treatment. The inflows of renewable and non-renewable resources, including those from purchase, are summarised. We assumed that buildings, structures, as well as machinery and other equipment would be operated for a period of 20 years (depreciation period). They have been assigned the corresponding amounts of materials from which they were made. For these inputs, we provide – either data taken from the literature or calculated solar transformity. These were referenced or recalculated by adjusting for a baseline of 15.83E+24 seJ/year (Brown et al., 2016). We also calculated the emergy contributions they make. These are values related to one year of operation of both wastewater treatment plants.

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Table 3. Emergy calculation for PPST

Item	Unit	Raw data	R	UEV [seJ/unit]*	TE_m [seJ/year]	Ref. UEV
Renewable local resources – environment						
Sunlight	J	2.774E +11	1	1.00E+00	2.774E+11	Odum (1996)
Wind, kinetic	J	4.151E+07	1	2.47E+03	1.025E+10	Odum (1996)
Rain, chemical	J	7.617E +08	1	2.68E+04	2.041E+13	Odum (1996)
Geothermal heat	J	1.699E+08	1	1.015E+04	1.725E+12	Odum (1996)
Own labor – PPST construction	J	1.760E+07	1	1.238E+07	2.178E+14	Odum (1996)
Renewable local resources – exploitation input – own work						
Own labor – current work	J	5.028E+07	1	1.238E+07	6.223E+14	Odum (1996)
Total local renewable: environment + own work					**8.627E+14**	
Non-renewable local resources – environment						
Land occupation	m^2	7.70E+01	0	1.6753E+09	1.290E+11	Ciobanu et al. (2022)
Total local non-renewable: environment					**1.290E+11**	
Non-renewable – investment inputs – purchased (divided by a life time of 20 years):						
Sand	g	1.948E+06	0	1.694E+09	3.298E+15	Odum (1996)
Stone	g	4.590E+04	0	1.694E+09	7.774E+13	Odum (1996)
PCV pipe	g	3.863E+03	0	9.569E+09	3.696E+13	Björklund et al. (2001)
PEHD foil	g	4.000E+03	0	9.569E+09	3.828E+13	Björklund et al. (2001)
Concrete products	g	3.564E+05	0	1.930E+06	1.153E+15	Björklund et al. (2001)
Machinery (pump)	g	5.000E+02	0	4.100E+06	3.438E+12	Björklund et al. (2001)
Excavator work service	$	3.081E+01	0	6.090E+12	1.876E+14	NEAD (2024)
Project – document	$	3.081E+01	0	6.090E+12	1.876E+14	NEAD (2024)
Total purchased constructed materials					4.796E+15	
Non-renewable – exploitation inputs – purchased:						
Electricity	kWh	2.237E+01	0	2.680E+12	2.309E+13	Björklund et al. (2001)
Total emergy inputs in wastewater treatment:						
Total emergy in treated wastewater					**5.68E+15**	

Footnotes: R – share of renewability; UEV – transformity; TEm – total emergy; *baseline = 15.83E+24 seJ/year; 1 $ = 4.0576 PLN.

The results in Tables 3 and 4 and Figures 3 (a, b) show that non-renewable emergy shares are dominant at both WWTPs (99.94% at PWWTP: 1.953E+18 seJ/year; 84.82% at PPST: 4.819E+15 seJ/year). Its significant share is due to the purchase of materials and services from outside the system. In a conventional wastewater treatment plant, the largest share of non-renewable emergy is associated with ongoing operation and is as high as 87.91% of TE_m. It depends on a variety of costs, including labor wages (39.25% of total TE_m), taxes, other indirect and direct costs of operations (28.06% of TE_m), or chemical agent consumption (2.386E+16 seJ/year; 1.22% of TE_m). In other conventional wastewater treatment plants, non-renewable emergy inflows also account for a significant share, almost 100% (Zhou et al., 2009; Björklund et al., 2001; Ciobanu et al., 2022).

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The contribution of LR and LN (occupied land) to the treatment plant's operations is significantly lower (0.055% in PWWTP and 15.183% for PPST). This is also confirmed by other results (Zhou et al., 2009), where the share of LN and LR is about 1.5% in the root treatment plant and less than 1% in the conventional one. It is important to note that in PPST, the running costs are very low. Only electricity consumption has an impact: 2.309E+13 seJ/year and own labor 6.223E+14 seJ/year; a 14.82% share of TE_m. We further consider the latter as a renewable resource in the household. This confirms once again that the facility is essentially a fully self-sustaining ecosystem, using the forces of nature.

Table 4. Emergy calculation for PWWTP

ITEM	Unit	Raw data	R	UEV [seJ/unit]*	TE_m [seJ/year]	Ref. UEV
Renewable local resources – environment:						
Sunlight	J	3.745E+13	1	1.00E+00	3.745E+13	Odum (1996)
Wind, kinetic	J	5.454E+09	1	2.47E+03	1.347E+13	Odum (1996)
Rain, chemical	J	2.994E+10	1	2.68E+04	8.023E+14	Odum (1996)
Geothermal heat	J	2.229E+10	1	1.015E+04	2.263E+14	Odum (1996)
Total local renewable					**1,080E+15**	Odum (1996)
Non-renewable local resources – environment:						
Land	m^2	1.01E+04	0	1.675E+09	1.692E+13	Ciobanu et al. (2022)
Total local nonrenewable					**1.692E+13**	
Non-renewable – investments inputs – purchased (divided by a life time of 20 years):						
Machinery and equipment:						
Grating for removal of mechanical debris – steel	g	2.00E+05	0	4.13E+09	8.26E+14	Zhou et al. (2009)
Mechanical debris removal device – steel	g	1.50E+05	0	4.13E+09	6.195E+14	Zhou et al. (2009)
Grit chamber with fat separator – steel	g	2.50E+05	0	4.13E+09	1.033E+15	Zhou et al. (2009)
Blowers – steel	g	4.00E+04	0	4.13E+09	1.652E+14	Zhou et al. (2009)
Controlled gates – steel	g	2.24E+05	0	4.13E+09	9.251E+14	Zhou et al. (2009)
Press – steel	g	4.00E+05	0	4.13E+09	1.652E+15	Zhou et al. (2009)
Agitators – steel	g	3.00E+04	0	4.13E+09	1.239E+14	Zhou et al. (2009)
Control automation – steel	g	1.25E+04	0	4.13E+09	5.163E+13	Zhou et al. (2009)
Grid aerators – steel	g	3.50E+03	0	4.13E+09	1.446E+13	Zhou et al. (2009)
Buildings and structures:						
Sink station – concrete	g	7.838E+05	0	2.55E+09	1.995E+15	Ciobanu et al. (2022)
Pipelines – plastic	g	4.188E+04	0	9.66E+09	4.045E+14	Ciobanu et al. (2022)
Mechanical treatment station – concrete	g	3.90E+06	0	2.55E+09	5.251E+15	Ciobanu et al. (2022)
Measuring chamber – concrete	g	9.75E+05	0	2.55E+09	2.482E+15	Ciobanu et al. (2022)
Pump house – concrete, bricks	g	1.913E+06	0	3.72E+09	7.115E+15	Ciobanu et al. (2022)
SBR tanks – concrete	g	5.639E+07	0	2.55E+09	1436E+17	Ciobanu et al. (2022)
Secondary settling tank – concrete	g	2.219E+07	0	2.55E+09	5.65E+16	Ciobanu et al. (2022)
Utility room – bricks	g	3.238E+06	0	2.55E+09	8.243E+15	Ciobanu et al. (2022)

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ITEM	Unit	Raw data	R	UEV [seJ/unit]*	TE_m [seJ/year]	Ref. UEV
Sludge dewatering water tank – concrete	g	1.633E+06	0	2.55E+09	4.158E+15	Ciobanu et al. (2022)
Total investment inputs					**2,351E+17**	
Non-renewable – operation inputs – purchased:						
Electricity	kWh	9.00E+ 03	0	1.032E+12	9.823E+16	Odum (1996)
Fuel	l	6.60E+09	0	2.295E+05	1.515E+15	Zhou et al. (2009)
Chemicals: for sewage and sludge	l	9,00E+03	0	2.65E+12	2.385E+16	Björklund et al. (2001); Zhang et al. (2010)
Lime for decontamination	kg	1.20E+01	0	1.00E+12	1.200E+13	Björklund et al. (2001); Zhang et al. (2010)
Chemicals: cleaning agents	l	1.30E+02	0	2.65E+12	3.445E+14	Björklund et al. (2001); Zhang et al. (2010)
Water	m^3	2.52E+02	0	1.09E+06	1.481E+15	Zhang & Ma (2020)
Human labor	$	1.259E+05	0	6.09E+12	7.669E+17	NEAD (2024)
Services	$	5.954E+05	0	6.09E+12	3.626E+17	NEAD (2024)
Taxes, fees (environmental)	$	7.531E+03	0	6.09E+12	4.586E+16	NEAD (2024)
Other costs	$	8.30E+04	0	6.09E+12	5.055E+17	NEAD (2024)
Total operation inputs					**1.718E+18**	
Total emergy inputs in wastewater treatment:						
Total emergy in treated wastewater					**1.9541E+18**	

Footnotes: R – share of renewability; UEV – transformity; TE_m – total emergy; baseline = 15.83E+24 seJ/year; 1$ = 4.0576 PLN.

For both treatment plants, the ELR value is above 1 (Table 5), which indicates an environmental load. The ELR value for the PWWTP is over 320 times higher than that for the PPST. This is due to the high share of emergy of investment materials, but also to current emergy flows related to high costs of paid labour, service costs, taxes, and fees.

Table 5. Selected emergy indicators of treatment plant operation

Indicator	PPST	PWWTP
TE_m of treated wastewater [seJ/year]	5.6818E+15	1.9541E+18
TE_m of treated wastewater [seJ/m^3]	5.1889E+13	5.5191E+12
ELR	5.5864	1809.0897
EYR	1.1790	1.0006
ESI	0.2111	0.0006

Footnotes: ELR – Environmental Loading Ratio, EYR – Emergy Yield Ratio, ESI – Environmental Sustainability Index, TE_m – total emergy.

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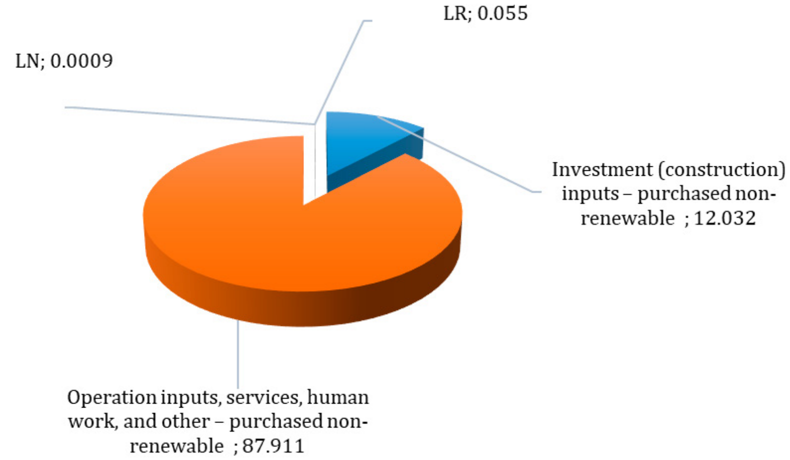
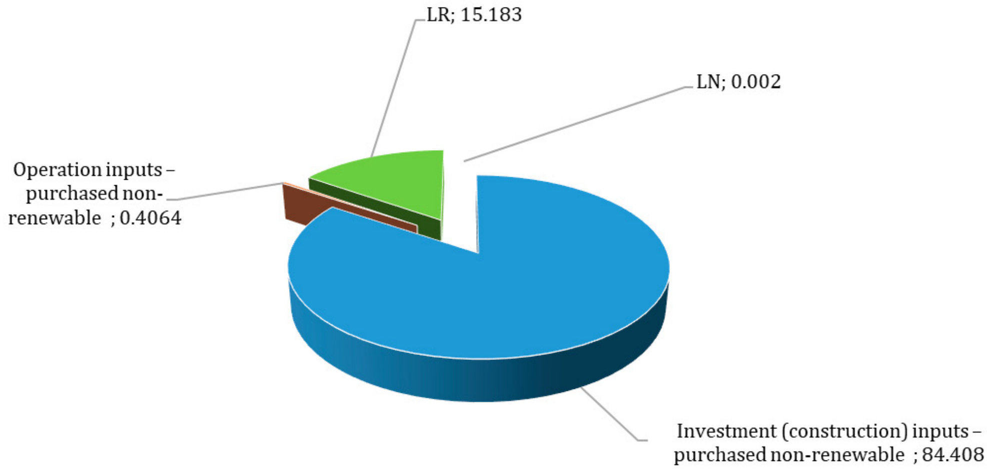
a)



b)



Footnotes: LR – local renewable, LN – local non-renewable.

Figure 3. Share of emergy flows [%], a) PWWTP and b) PPST

In studies by other authors (Table 6), ELRs for wastewater treatment plants also take values sometimes much higher than 1. This reflects the significant use of non-renewable resources, mainly from purchase (Cao & Feng, 2007), during the operation of such systems. Emergy consumption per unit of treated wastewater is higher at PPST (5.1889E+13 seJ/m^3 for PPST and 5.5191E+12 seJ/m^3 for PWWTP). The value of this indicator would be clearly lower (and therefore more favourable) if the number of residents assumed in the project (PE = 9) were using the treatment plant. For several years, the household has only periodically had more residents, due to its agritourism activities. However, the peculiarity of wastewater treatment at PPST, consisting in a slower treatment process, is also advantageous, with a clearly variable pollutant load.

Table 6. Comparison of different treatment plants in terms of selected emergy indicators

Sewage Treatment Plant	seJ/m^3/year	ELR	EYR	ESI	Ref.
PPST	5.1889E+13	5.5864	1.1790	0.2111	This study
PWWTP	5.5191E+12	1 809.089	1,0006	0.0006	This study
Municipal Wastewater Treatment Plant – Romania, (C)	5.30E+10	57.52	1.002	0.02	Ciobanu et al. (2022)
Sewage treatment plant – China, (C)	3.444E+12	9 881.841	10.885	0.0011	Zhang & Ma (2020)
Sewage treatment system + treated water discharge + sludge landfilling – China, (C)	7.78E+11	1.802	1.632	0.905	Zhang et al. (2010)

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Sewage Treatment Plant	seJ/m³/year	ELR	EYR	ESI	Ref.
Sewage treatment subsystem + reclaimed water reuse subsystem + aerobic compost production subsystem – China, (C)	2.72E+11	1,904	1.590	0.835	Zhang et al. (2010)
Cyclic Activated Sludge Technology + sludge storage – China, (C)	2.06E+12	1.57	1.43	0.91	Liu et al. (2022)
Wastewater treatment plant – Sweden, (C)	9.243E+11	3 234.2	1.001	0.0008	Björklund et al. (2001)
Wastewater treatment system – China, (CW)	1.08E+12	748.0	1.293	0.002	Zhou et al. (2009)
Cyclic activated sludge system – China (C)	4.38E+11	135.84	1.007	0.007	Zhou et al. (2009)
Italy, (C)	2.14E+14	59.83	1.0167	0.017	Vassallo et al. (2009)
Italy, (C)	3.852E+11	---	1.00	---	Siracusa and La Rosa (2006)
Italy, (combination C+CW)	3.852E+11	13.11	1.077	0.082	Siracusa and La Rosa (2006)

Footnotes: C – conventional; CW – constructed wetland.

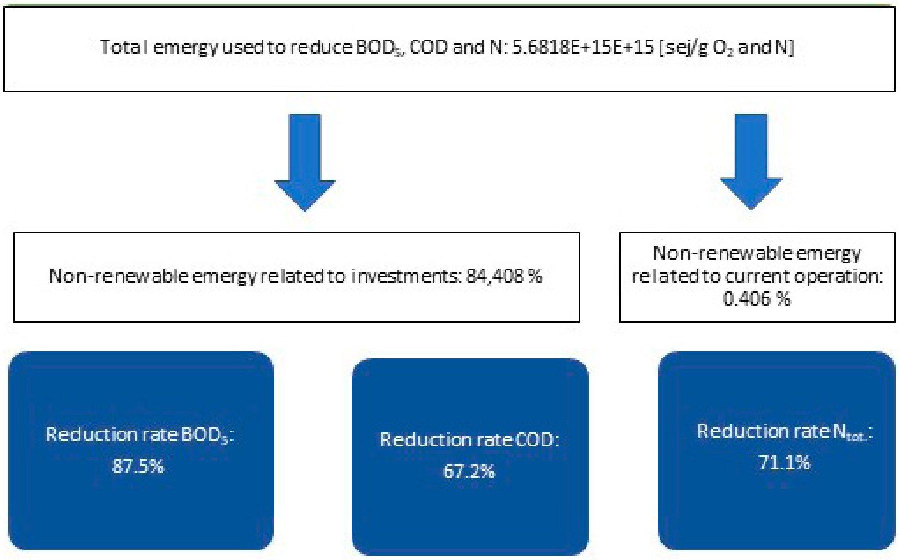
We believe that for this type of plant, the ELR is not entirely appropriate in assessing environmental impact. The capital expenditure and – in a conventional treatment plant – the purchase of consumables significantly increase the ELR. It is high wherever the system in question requires a higher level of technology and there is high environmental stress. It is most often associated with the low use of local renewable resources and the import of materials and raw materials from outside the local system (Merlin & Lissolo, 2010).

Also, from the calculated EYR and ESI indicators, it is apparent that both WWTPs carry an environmental load. Although, as with ELR, PPST has a much lower environmental pressure. A higher EYR value indicates that a process makes better use of local renewable and non-renewable resources, with an investment of external economic resources (Zhang et al., 2011). Thus, it can be concluded that both treatment plants operate more as an industrial process than as an environmental process. ESI values significantly lower than 1 indicate that wastewater treatment plants, however, very important in the functioning of households and entire agglomerations, represent a pressure on the environment. In contrast, if one were to compare the operation of the two treatment plants themselves and the associated inputs, the PPST example is essentially a 'self-sustaining', functioning ecosystem in which plants actively participate in relieving the pressure on the environment due to the inflow of treated wastewater.

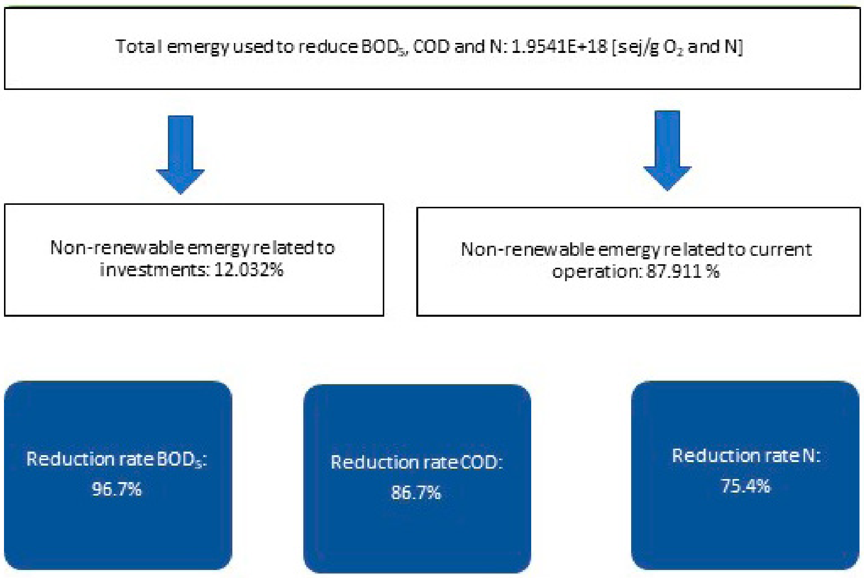
Treatment efficiency

The pollutant reduction rate (BOD_5 and COD) at the conventional treatment plant meets the requirements of the Ordinance of the Minister of Maritime Affairs and Inland Navigation (Rozporządzenie, 2019). In the case of PPST, the parameter COD was minimally exceeded (permissible maximum concentration: 150 mg O_2/L in the effluent after treatment). The standards for $N_{tot.}$ in treated effluent discharged to the environment were slightly exceeded at both treatment plants (standard for PWWTP 15 mg N/L; for PPST 30 mg N/L). However, these values only apply to wastewater discharged into lakes and their tributaries and directly into artificial water bodies located on flowing waters. Therefore, they do not apply to both treatment plants.

In our considerations, we verify the effectiveness of the work done by the environment in reducing pollution. Pollutant removal efficiency is slightly higher in the PWWTP. However, achieving the required effects involves a high outlay of emergy of current operations. Nearly 100% of TE_m is non-renewable emergy, of which nearly 88% is the cost of ongoing operations. At the PPST treatment plant, the situation is reversed. In order to achieve a similar level of pollutant reduction, the non-renewable emergy of ongoing inputs amounted to only 0.406% of TE_m (Figure 4). This also implies a small ongoing environmental cost of the treatment compared to the PWWT.



PPST (Plant-pond sewage treatment)



PWWTP (Prószków wastewater treatment plant)

Figure 4. Total emergy and share of non-renewable emergy in the reduction of BOD_5, COD and $N_{tot.}$

Additional considerations – ecosystem services, area opportunities for pond treatment plants

Ecosystem services

Each wastewater treatment system provides measurable social benefits, and the choice of the appropriate system is often dictated by the available space and treatment time (Geber & Björklund, 2002). Water and wastewater treatment technologies reveal multifunctional potential in terms of providing additional benefits, known as secondary ecosystem services. These go beyond the treatment processes themselves (Zawadzka et al., 2019). These services are defined as "the benefits that human populations obtain, directly or indirectly, from ecosystem functions" (Costanza et al., 1997). They include, for example, the protection of drinking water resources from fecal contamination and waterborne diseases, protection against eutrophication, chemical pollution, promoting climate

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change mitigation (Alabaster et al., 2021), but also participation in carbon storage, pollination, water retention, sedimentation, nutrient retention, and the creation of habitats for biodiversity (Zawadzka et al., 2019). In this section, we would like to identify selected environmental services provided by the two wastewater treatment plants we analysed. We have grouped the benefits into the following categories:

- **Provisioning services** (applies to both treatment plants):
  - *Water supply*. Treated wastewater can be reused, e.g., in agricultural irrigation. Constructed wetlands have higher pathogen removal efficiency and can convert wastewater into a resource for agricultural irrigation (Shingare et al., 2019). Reused wastewater can be treated as so-called additional income for avoided production losses due to drought (García-Herrero et al., 2022; Verlicchi et al., 2012). Based on the analysis proposed by Siracusa and La Rosa (2006), if the TE_m for treated wastewater in the PPST was 5.6818E+15 seJ/year, this represents the environmental cost of the system for treating 109.5 m^3 of wastewater. If we assume that we use the same amount of surface water (e.g. for irrigation), the required emergy will be: 1.32E+05 seJ/g · 1.10E+08 g = 1.45E+13 seJ/year. This value is an environmental benefit. Therefore, if the treated wastewater is reused, there is an environmental saving of 1.45E+13 seJ/year. The benefit-cost ratio is 0.0026. In the analysed PPST, the wastewater treated in the ponds is a direct benefit for the growing plant biomass, which is then used as fertiliser. Treated wastewater from the PWWTP ultimately ends up in the Odra River. Therefore, we are dealing exclusively with environmental waste that generates an environmental cost of 1.9541E+18 seJ/year. However, if the treated wastewater were used as irrigation water, the benefits alone would amount to 4.68E+16 seJ/year, with a benefit-to-cost ratio of 0.024.
  - *Production of plant biomass, sewage sludge.* The treatment plants provide by-products used as fertiliser. Vegetable biomass at PPST is cut annually and used as mulch in the garden. Sewage sludge is donated free of charge for local agricultural use. The results of laboratory determinations of both organic materials are given in Table 8.

Table 8. Characteristics of sludge and plant biomass

Parameter	PPST – plant biomass	PWWTP – sludge
Fresh weight kg/year	540	180 000
Dry matter content [%]	22.66	16.60
$N_{tot.}$ content [g/kg d.m.]**	20.30	66.90
P content [g/kg d.m.]*	1.29	22.48
K content [g/kg d.m.]*	12.90	5.50
$C_{tot.}$ content [g/kg d.m.]	463.70	442.60

Footnotes: * pure component; ** we treat total nitrogen as a nutrient available to plants.

The fertiliser potential of both by-products was related to the N, P, and K content in dry matter. The fertiliser potential is higher for sludge, but mainly due to the amount of sludge produced. Each m^3 of wastewater treated in the PPST provides: 0.02 kg of N, 0.001 kg of P, and 0.01 kg of K, contained in biomass. In turn, in the PWWTP, each m^3 of treated wastewater generates 0.005 kg of N, 0.002 kg of P, and 0.0005 kg of K in the sewage sludge.

When converting the nutrient content to PE, the values are in favour of the treatment plant in Szczedrzyk (production: dry plant mass 40.8 kg, 0.82 kg N, 0.053 kg P, and 0.53 kg K). Even if there were 9 people using the PPST treatment plant, these indicators would still be favourable. In the case of sewage sludge, per 1 PE there is: 5.66 kg of dry matter, 0.37 kg of N, 0.13 kg of P, and 0.03 kg of K.

It should be emphasised that plant biomass in PPST is used every year as a soil improver in gardens, mulch to protect the soil from erosion, water loss and weed growth. Therefore, this product should be considered not only as a potential fertiliser, but also in terms of soil protection.

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The monetary value of the components contained in the fertiliser materials was also estimated. For this purpose, we assumed the average prices per kg of single-component fertilisers in 2024: saltpetre 34%, superphosphate 40%, and potassium salt 60%. The monetary value of the N, P, and K components contained in the total dry biomass of PPST = \$3, and in PWWTP – \$3041.70. This means that 1 m^3 of treated wastewater in PPST generated \$0.02 in biomass nutrient value, and in the case of PWWTP sewage sludge – \$ 0.01. The monetary value of fertiliser from the PPST treatment plant per 1 PE is \$0.96, while that from sewage sludge is \$0.60.

- **Supporting services** (for plant-pond sewage treatment):
  - *Habitat formation.* The PPST is a nature-based solution, mimicking the functions of natural wetlands while also being a wildlife habitat. We have identified plant species that inhabit the treatment plant: *Carex elata* All., *Scirpus* L., *Glyceria maxima* (Hartm.) Holmb, *Typha latifolia* L., *Typha angustifolia*, L., *Schoenoplectus lacustris* (L.) Palla, *Acorus calamus* L., *Sagittaria sagittifolia* L., *Iris pseudacorus* L., *Lemna* L., *Carex acuta*, *Urtica dioica L.*

  The importance of natural habitats has been monetized, and the estimated benefits are \$197/ha/year in New Zealand (Kirkland, 1988), or 24 573 euro/ha/year in Greece (Birol et al., 2006).
  - *Nutrient cycling*. Vegetation in the PPST treatment plant acts as phytoremediators using nutrients, including N, P, K (Gersberg et al., 1986; Wathugala et al., 1987; Herath & Vithanage, 2015).
  - *Supporting the hydrological cycle.* By recycling stored water (Zhao et al., 2020).

- **Regulating services** (both analysed systems):
  - *Wastewater treatment*. This is the most important function of any wastewater treatment plant in light of the removal of environmental pollutants and the consequent delivery of treated wastewater for economic use. Chen et al. (2009) estimated that for a large wetland treatment plant in Beijing, the total value of its ecosystem services is \$2 067 740/ha/y, and the treatment service accounts for as much as 63.82% of this value.
  - *Climate regulation*. Service linked to greenhouse gas emissions. The results of the analysis by Mander et al. (2014) indicate that natural wetlands used for wastewater treatment are net absorbers of C and not radiative sources of climate change, even when the originating CH_4 emissions are taken into account. However, good management is required in created wetlands with high CH_4 emission potential. Solutions based on the use of microalgae are proposed for conventional wastewater treatment plants, the operation of which results in direct greenhouse gas emissions as well as indirect emissions, resulting from energy generation. Their cultivation is considered an attractive alternative for CO_2 gas sequestration. (Meier et al., 2015). Microalgae ponds however, occupy large land areas, which limits their use to rural areas (Campos et al., 2016).
  - *Erosion control and enrichment of soil in carbon*. Wetlands, which we can include PPST, have a protective effect on the soil and help prevent soil erosion. Plant roots prevent soil reduction due to wind or water action. (Agaton & Guila, 2023) Furthermore, the plant biomass produced, when used as mulch and fertiliser, participates in humus formation. Similarly, sewage sludge, when used agriculturally, serves to improve soil structure and provides nutrients to plants. Agricultural use of the by-products of both treatment plants can contribute significant amounts of organic material, reproducing soil organic matter. This is of great importance under Polish conditions, as the quality of soils is among the lowest in Europe (Doroszewski et al., 2012) with low water holding capacity and low organic carbon content (Skłodowski & Bielska, 2009). Analyses of $C_{tot.}$[1]. and $N_{tot.}$ content in plant biomass from PPST and in PWWTP sewage sludge allow us to assume that both products can be useful as soil conditioners with a favourable C:N ratio of 22.8 (PPST) and 6.6 (PWWTP). If the C:N ratio is less than 25 (Grzebisz, 2008), the microorganisms release excess nitrogen and make it available to the crop. For green manures and sewage sludge at a dry matter content of 20%, the reproduction rate of soil organic matter is 16 kg/ton of applied fertiliser (Kuś, 2015). This is how much soil organic matter will increase following the application of 1 ton of fresh manure. Plant biomass from

1 We assume that $C_{total} = C_{org}$.

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PPST can provide about 2 kg C org. (0.7 kg/PE). The amount of sludge produced therefore provides as much as 478 kg C org. (but 0.1 kg/PE).

- **Cultural services** (for PPST).

Wetland-type treatment plants can provide many valuable benefits of educating young people and conducting scientific research at them. The PPST treatment plant is also an educational facility. The benefits are therefore tangible for both visitors and the owners themselves, who have been actively pursuing environmental education and cooperating with universities for many years.

Potential for wetland treatment plants in Poland

According to the provisions of the National Programme for Sewage Treatment (Ministry of Infrastructure, 2021), the rate of collection of pollutants through the sewage network should reach 98% in agglomerations of 100 000 PE and over and 95% in the remaining ones. It has therefore been calculated that in agglomerations of more than 100 000 PE, of which there are 91 in Poland and which represent 67% of the total number of PE, the load corresponding to 620 000 PE will not be collected through the sewer network. In smaller agglomerations, of which there are 1 544 in Poland and representing 33% of the total number of PE, the load corresponding to 750 000 PE will not be collected through the sewerage network. Therefore, it will be necessary to use other forms of wastewater collection: no-outflow tanks or household wastewater treatment plants. Taking into account that plant treatment plants represent a small percentage of the solutions used in Poland, we estimate that 5% (68 500 PE) of the total wastewater load that will not reach the sewerage system can be handled by plant treatment plants.

Conclusions

This paper discusses and compares two different wastewater treatment systems; the PPST plant-pond system and the PWWTP conventional system. Both systems are different in their operating principle as well as in the amount of wastewater treated. In the analysis, an emergy accounting was used, which, among other things, allows the degree of environmental impact of both treatment plants to be assessed.

- It was found that in the case of the plant-pond sewage treatment, the total emergy consumption was 5.6818E+15 seJ/year, while in the conventional treatment plant it was as high as 1.9541E+18 seJ/year.
- Non-renewable emergy dominates both treatment plants. In the PWWTP, over 99% of TEm is non-renewable emergy, while in the PPST it is nearly 85%. Expenditures from outside the system (purchased) clearly dominate in this type of emergy.
- Considering the amount of wastewater treated and the level of technology, emergy consumption per unit of wastewater treated is lower in the conventional treatment plant, amounting to 5.5191E+12 seJ/m3 for the PWWTP and 5.1889E+13 seJ/m3 for the PPST.
- Emergy indicators are much more favourable for the plant-pond sewage treatment. The PE indicator is three orders of magnitude lower and amounts to 5,5864. The other indicators presented in Table 5 also show that the plant-pond system has a lower environmental impact.
- Calculations have shown that in the case of a plant-pond sewage treatment, the relatively highest costs are incurred at the time of its construction. They account for 84.4% of TE_m. During operation, it is a virtually maintenance-free system and the running costs are minimal. This feature distinguishes it from a conventional system. In the latter system, nearly 88% of TE_m is emergy related to ongoing operating costs.
- The parameters characterising raw and treated wastewater were presented for both treatment plants. It was indicated that the wastewater treatment efficiency is similar in both analysed treatment plants. The percentage reduction of BOD_5, COD, and N_{total} is slightly higher in PWWTP. However, treatment efficiency should also be considered in the context of the scale of expenditure, especially non-renewable emergy (Fig. 4), including that related to current operation.

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- An attempt was made to identify the ecosystem services provided by both treatment plants. The fertilisation potential of by-products was compared per 1 m^3 of treated wastewater. Each 1 m^3 of treated wastewater in the PPST translates into a slightly higher N, P, and K content in the biomass compared to their content in the sewage sludge. When converting the nutrient content to PE, the pond-root system is more advantageous. 1 m^3 of treated wastewater in the PPST generated $0.02 in biomass fertiliser value, compared to $0.01 in the case of PWWTP sewage sludge.
- The by-products of the treatment plant have a C:N ratio that makes them suitable for use as organic fertiliser. The C:N ratio is more favourable in sewage sludge (6.6). However, it should be emphasised that plant biomass, apart from its potential fertilising function, also protects the soil by covering it as mulch.
- Treated wastewater in the PPST is directly used by the plants of the treatment plant's ecosystem. Therefore, if we consider treated wastewater as irrigation water, the treatment plant generates 1.45E+13 seJ/year of environmental benefits. In the case of PWWTP treatment plants, the wastewater treated is ultimately discharged into rivers and is therefore not used for irrigation.
- Many plant species have been identified on the surface of the PPST. They form a very rich phytocenosis, creating conditions for the colonisation of various fauna species.
- The plant-pond system has other environmentally significant features. It can provide multiple ecosystem services, as indicated in the article. It is clear that the magnitude of these services is commensurate with the size of such treatment plants. However, taking into account the indicated potential possibilities of their application in the country, it is an environmentally valuable solution.
- Plant-based treatment plants represent a small percentage of the solutions used in Poland. This is mainly due to the limited availability of land. Greater opportunities arise in rural areas. We estimate that in Polish conditions, 5% (68 500 PE) of the total wastewater load that does not enter the sewage system could be treated by plant-based treatment plants.

The contribution of the authors

Conceptualisation, A.K. and J.P.; literature review, A.K.; methodology, A.K. and J.P.; formal analysis, A.K., J.P. and I.K.-B.; writing, A.K., J.P. and I.K.-B.; data collection, A.K. and I.K.-B.; conclusion and discussion, A.K., J.P. and I. K.-B.

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ODDZIAŁYWANIE ŚRODOWISKOWE DWÓCH SPOSOBÓW OCZYSZCZANIA ŚCIEKÓW BYTOWYCH NA PRZYKŁADZIE OCZYSZCZALNI KONWENCJONALNEJ I ROŚLINNO-STAWOWEJ

STRESZCZENIE: Jednym z istotnych elementów dbałości o środowisko jest skuteczne oczyszczanie ścieków. W Polsce dominuje scentralizowane oczyszczanie ścieków o dużej skuteczności. Jednak nieruchomości o dużym rozproszeniu często wymagają zastosowania innych alternatywnych rozwiązań. Celem pracy jest porównanie oddziałyływania na środowisko dwóch sposobów oczyszczania ścieków; konwencjonalnego (PWWTP) oraz stawowo-roślinnego (PPST). W ocenie działania obu oczyszczalni i ich środowiskowego oddziaływania wykorzystano rachunek emergetyczny oraz wskaźniki emergetyczne takie jak ELR, EYR, ESI. Stwierdzono, że oczyszczalnia PPST mniej obciąża środowisko. Bieżące funkconowanie oczyszczalni konwencjonalnej pochłania aż ponad 87% całości emergii, podczas gdy w przypadku oczyszczalni biologicznej jest to 0.40% całości emergii. ELR dla PPST wyniósł 5.58 podczas gdy dla PWWTP 1809.09. Skuteczność oczyszczania ścieków w obu oczyszczalniach jest zbliżona. Redukcja BZT_5 wyniosła dla PPST 87.5%, a dla PWWTP 96.7%. Dla obu oczyszczalni dokonano próby identyfikacji innych, środowiskowych korzyści, jak np. wytwarzanie i wykorzystanie produktów ubocznych, możliwość wykorzystania oczyszczonych ścieków dla potrzeb nawadniania czy tworzenie miejsca różnorodności biologicznej. Podjęto próbę ilościowego oszacowania niektórych dodatkowych korzyści.

SŁOWA KLUCZOWE: analiza emergetyczna, efektywność oczyszczania ścieków, konwencjonalne oczyszczanie ścieków, roślinno-stawowe oczyszczanie ścieków, usługi ekosystemowe

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