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Assessment of the Efficiency, Environmental and Economic Effects of Compact Type On-Site Wastewater Treatment Plants—Results from Random Testing

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Abstract: This study presents the results of random testing of selected on-site wastewater treatment plants (WWTPs) constructed in Poland in Masovia Voivodship in the years 2011–2016. The vast majority of tested on-site WWTPs were compact (container) type treatment plants, based on low rate activated sludge (AS), sequencing batch reactors (SBR), or a hybrid (activated sludge supported with biological film, AS + BF) method. Compact type plans are becoming more and more popular in single households in Poland, due to the option of co-financing. According to certificates provided by producers and distributors, container on-site wastewater treatment plants are efficient in BOD_5 removal, with the expected removal rate being over 80%. The aim of this study was (1) to analyze BOD_5 in effluents sampled from randomly selected on-site WWTPs, (2) to evaluate predicted and real environmental effects of the implementation of on-site WWTPs in selected communes within Masovia Voivodship, and (3) to calculate unit environmental and economic effects of container on-site WWTPs in three different technologies. Results of this study show that in most cases, there is a gap between the declared and the real BOD_5 removal efficiency. There is also a difference between the performance of different container type technologies. The lowest real environmental effect was obtained for AS technology, and the highest for the hybrid one. The predicted environmental effect has only been almost achieved in the case of hybrid systems. Based on net present value (NPV) benefits, technologies can be set up as follows: AS > SBR > AS + BF, making the AS method the most effective technology from the point of view of the economy.

Keywords: wastewater; on-site treatment; activated sludge; SBR; hybrid systems

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1. Introduction

Small wastewater treatment plants (WWTPs) must treat domestic wastewater before it can be discharged into a receiver. For small WWTPs, a wide range of different cleaning methods is available for use e.g., single-stage trickling filter systems, rotary dipping body plants, plants with submerged fixed bed, systems with freely movable growth bodies, activated sludge plants in the stock-up operation, combination systems, pass-activated aeration plants, and membrane-activated aeration plants [1] which are commonly known as compact or container type on-site wastewater treatment plants. The most popular solutions for single households are low-rate activated sludge (AS), sequencing batch reactors (SBR), and plants with submerged fixed bed or freely movable growth bodies known as hybrid plants (AS + BF). Activated sludge and biofilm are characteristics forms of biomass used in wastewater treatment [2]. Activated sludge is a suspension composed of microorganisms, which at a suitable oxygen supply level are capable of organic substance mineralization from sewage. In SBR, the whole treatment process occurs in a single tank with the use of an automatic control system ensuring the realization of subsequent treatment cycles composed of succeeding phases of filling, aeration, sedimentation and decantation, and periodical excessive sewage discharge. Hybrid systems are a combination of biofiltered and activated sludge. Sewage in the bioreactor is aerated and organic constituents contained in the inflowing sewage are food for aerobic bacteria, which attach themselves to a medium submerged inside the container [3]. The species composition of microorganisms present in the suspended biomass as well as in the immobilized biomass is different. Filamentous bacteria, ciliates, and rotifers are frequent in the suspended biomass, while free-swimming ciliates were mainly observed in the immobilized biomass [2]. Technical solutions which combine activated sludge and biofilter methods are increasingly becoming more popular. Hybrid treatment plants incorporate advantages of both methods, which is of primary importance for on-site system working conditions (involving changes in the quality and quantity of supplied wastewater). During the period of low hydraulic or organic loading or when no sewage outflow is registered, biocenosis in the form of activated sludge will not end quickly because the substrate necessary for microorganism development is obtained by forming biofilm covering the biofilter [4].

The advantage of compact systems over natural-based ones (e.g., constructed wetlands, hydroponic plants or sand filters) is the possibility of obtaining a certificate of compliance with EN 12566-3:2016 (Small wastewater treatment systems for up to 50 PT—Part 3) and thus the possibility of co-financing the installation from public sources. The number of on-site WWTPs in Poland has been growing in recent years (Figure 1). In 2019, 235,000 of such plants were documented [5]. The perspective of future construction of such systems is also significant, as only just over 70% of the population uses the collective sewage system [6].

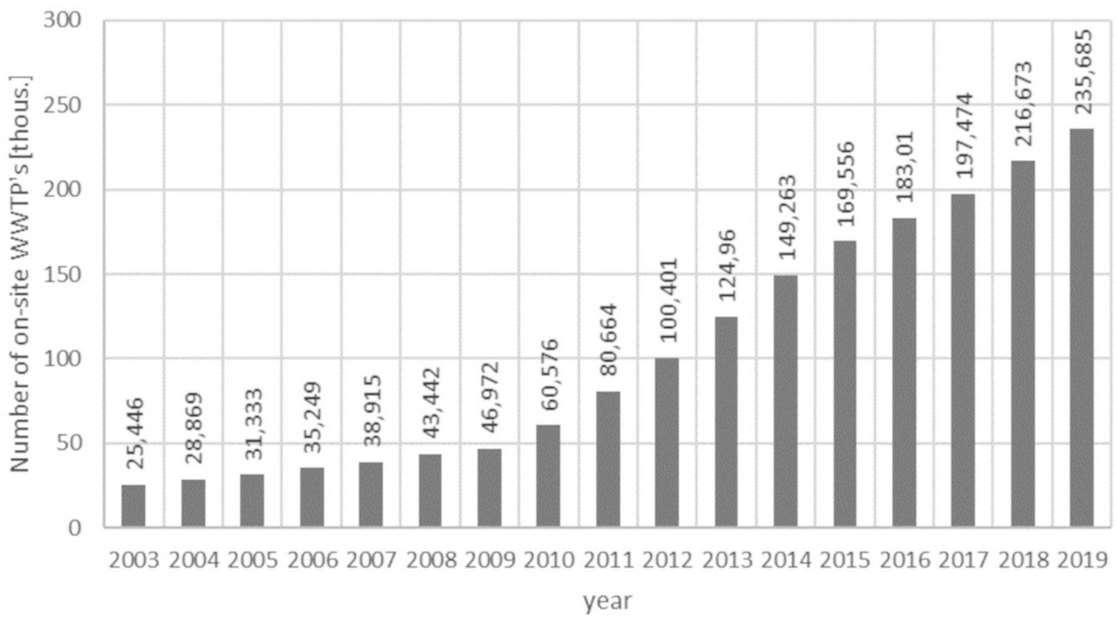

Figure 1. Number of on-site wastewater treatment systems constructed in Poland in years 2003–2019 (based on data from [5]).

Compact type on-site WWTPs are not "self-maintaining" systems. The operation of small WWTPs can be subdivided into process management measures (activities to be carried out by the plant operator and the sludge disposal responsible units) and inspection (measures for determining and assessing the actual condition), maintenance, and repair (measures to restore the target state) [1]. The maintenance of small WWTPs must be carried out by qualified persons. If necessary, repair must be ordered separately by the operator. Daily control should check whether the system is in operation. Monthly checks should focus at least on: visual inspection of the process for sludge output, control of inflows and outflows for blockages, reading the operating hours counter of the electrical units, and checking the infiltration unit (to see if the effluent is being directed to the soil) [1].

Operation, periodical control of the level of sludge in the septic tank and the reactor chamber, and control of the blower and the pump are all very important in small biological wastewater treatment plants [2,7,8]. Compact type on-site WWTPs require permanent access to power. Electricity is necessary to run the pumps and aeration of the wastewater. Temporary power shortages or the desire to minimize electricity bills by users are a frequent cause of ineffective operation of treatment plants.

Installation of compact type on-site WWTPs that have a certificate of compliance with PN-EN 12566-3 + A2: 2013-10 or newer [9] can be co-financed in Poland using public sources (The funds available in 2020 for this purpose come from Rural Development Program 2014–2020 "Measure 7. Basic services and village renewal in rural areas, 7.2.2. Water and sewage management" or from Regional Funds for Environmental Protection and Water Management (WFOŚiGW) within "Nationwide water and sewage management program outside the agglomerations included in the National Program for Municipal Sewage Treatment for years 2015–2020"), reducing the purchase cost by at least 50%. The imperfection of current and previous programs is the assessment of project effectiveness in terms of quantity and not a quality. For example, in an analyzed program, investment settlement requires: a certificate or declaration of compliance with the PN-EN 12566-3: 2016-10E standard or (PN-EN 12566-3 + A2: 2013 standard until 31 December 2017), in which there will be treatment efficiency indicators (following the current Regulation [10]) and photocopies of the notification to the communal registry of on-site wastewater treatment plants. A water-legal permit (the permit determining the required quality of wastewater discharged to the receiver; it is issued pursuant to the national Water Law Act and is not required for on-site wastewater treatment plants with a capacity of less than 5 m^3/d) for sewage discharge into waters or into the soil and the results of effluent quality tests performed by an accredited laboratory are not required for treatment plants with a capacity of less than 5 m^3/day [8]. The environmental effects provided by this program are the number of additional people benefiting from the improved waste water treatment or capacity of modernized facilities. They are explained as: "the environmental effect presents the result of the implementation of projects in the field of wastewater management and determines the amount of pollutant load, expressed in population equivalent (P.E.), subject to treatment in accordance with Directive 91/271/EEC [11], originating from new users and existing users, when they were previously served by a system that did not meet the standards specified in the Directive" [12]. In such an approach, the number of people/households equipped with wastewater disposal systems is more important than the real efficiency of pollutants removal from these sources. This approach is continued during on-site wastewater treatment system operation due to the lack of obligatory monitoring of systems performance.

This paper presents the gap between predicted and real environmental effects of implementation of on-site wastewater treatment systems on the example of selected communes in Masovia Voivodship in Poland. Economic analysis of three most popular compact type on-site wastewater treatment technologies was also performed. The aim of this study was (1) to analyze BOD_5 in effluents from randomly selected on-site WWTPs, (2) to evaluate predicted and actual environmental effects of implementation of on-site WWTPs, and (3) to calculate unit environmental and economic effects of container on-site WWTPs for three different technologies.

2. Materials and Methods

2.1. On-Site WWTPs Selection Procedure

Sampling sites (23 in total) were selected based on a list of municipalities that received funding for the construction of on-site treatment plants from the Regional Fund for Environmental Protection and Water Management in Warsaw in the period of 2011–2016. The number of communes that received co-financing in the following years was 14 in 2011, 13 in 2012, 7 in 2013, 9 in 2014, 5 in 2015, and 1 in 2016. As some municipalities obtained funding for the implementation of subsequent construction stages in the following years, the total number of co-financed municipalities in this period was 39.

Monitoring of on-site WWTPs constructed between 2014 and 2016 was performed in the years 2017–2019. Effluent samples from different types of WWTPs were collected and analyzed for BOD_5 by the manometric method [13]. Obtained results were compared with a predicted BOD_5 effluent concentration of 40 mg/L (based on the assumptions of the on-site WWTPs implementation programs) and a declared removal efficiency of 80%. Data were also evaluated with analysis of variance to show statistically significant differences between technologies. Also, the information about the number of on-site WWTPs constructed in the commune and applied wastewater treatment technology was collected (Table 1).

Table 1. Data for calculations of environmental effects of implementation of on-site wastewater treatment plants. AS—activated sludge; SBR—sequencing batch reactor; AS + biological film (BF)—hybrid method (activated sludge supported with biological film); HP—hydroponic system; SF—sand filter; IS—infiltration system (septic system).

On-Site WWTP	Technology	Total Number of Systems	Number of People Served	Unit Water Use [m^3/P·yr]	Unit Load of BOD_5 * [g/P·d]	Receiver
1	AS	145	435	27.2	60	Effluent is discharged to the soil via infiltration system
2	AS	80	240	30.7		
3	AS	89	267	35.0		
4	AS	37	111	30.5		
5	AS	122	366	29.0		
6	SBR	140	420	29.0		
7	SBR	35	105	41.0		
8	SBR	26	78	35.6		
9	SBR	38	114	41.0		
10	SBR	51	153	35.2		
11	AS + BF	168	504	43.0		
12	AS + BF	156	468	48.9		
13	AS + BF	210	630	43.0		
14	AS + BF	457	1371	36.9		
15	AS + BF	175	525	48.9		
16	AS + BF	175	525	29.0		
17	AS + BF	49	147	32.3		
18	AS + BF	365	1095	40.3		
19	AS + BF	110	330	42.9		
20	HP	28	84	39.1		
21	HP	98	294	30.1		
22	SF	30	90	29.0		
23	IS	300	900	30.7		

* adapted from ATV-DVWK-A 198 [14].

2.2. Calculation of Environmental Effect

Data for calculation of environmental effects of implementation of on-site wastewater treatment plants (Table 1) were collected from the following sources:

- Total number of constructed on-site wastewater treatment systems was obtained from communes (personal communication)
- Total number of population connected to on-site wastewater treatment systems was obtained from communes or calculated based on the average number of inhabitants in a household (average number of people in a household located in rural areas 3.01 [15])
- Unit water use was obtained from communes or from Local Databanks [5]
- Unit BOD_5 load in wastewater was adapted from ATV-DVWK-A 198 [14]

The assumed indicator that was used to determine the environmental effect is the reduction of the load of pollutants introduced into the environment calculated based on the formula:

$$EE = L_{before} - L_{after} \quad (1)$$

where: EE—environmental effect equal to reduction of BOD_5 load discharged to the environment [kg/yr]; L_{before}—load of BOD_5 [kg/yr] before the installation of on-site WWT system (the "background" variant); L_{after}—load of BOD_5 [kg/yr] after the construction of on-site wastewater treatment plant (variants A, B, or C).

Environmental effects of implementation of on-site WWT systems in different communes were calculated in the following variants:

- Variant "A"—effluent from on-site wastewater treatment plant reaches the formal limits required in appropriate legal regulation [10]. As all tested on-site plants are located outside agglomerations and discharge effluent to the soil, in this variant, minimal reduction of BOD_5 of 20% was assumed.
- Variant "B"—effluent from on-site wastewater treatment plant reaches the level assumed in the program of on-site systems construction. The level for BOD_5 was set as 40 mg/L and is equal to the limit required for wastewater discharged to water bodies [10].
- Variant "C"—real BOD_5 concentration of effluents from tested on-site wastewater treatment plants was taken for calculations.

For all calculations, the "background" variant was assumed to be "storing of the wastewater in holding tank without the control of hauled liquid waste". A detailed description of legal status of on-site wastewater treatment systems in Poland is given in [16].

2.3. Unit Annual Costs

The unit annual costs (C_u) of compact on-site WWTPs were calculated for three different technologies (AS—activated sludge; SBR—sequencing batch reactor; AS + BF—hybrid method) based on the investment costs (I) and annual operating costs (C_o). Investment costs were estimated based on eighteen price lists provided by manufacturers or dealers of tested technologies. Annual operating costs were estimated based on the annual electricity consumption costs, cost of bio activators, and cost of system cleaning.

The unit annual cost (C_u) was calculated based on the equitation [17]:

$$C_u = \frac{I\,\alpha + C_o}{E} \quad (2)$$

where: I—investment costs (€); C_o—annual operating costs (€); α—the return on capital factor (-).

The return on capital factor α is calculated by the formula:

$$\alpha = \frac{r(1+r)^t}{(1+r)^t - 1} \quad (3)$$

where: r is the discount rate (%) and t is lifetime of WWTP (years); E—utility effect, in our case it is the environmental effect equal to the load of BOD_5 removed by the single system (kg), the load of 1 kg BOD_5 removed (kg), the load of BOD_5 removed per person (P), and the load of BOD_5 removed per volume of treated wastewater (m^3).

The assumptions for economic analysis are shown in Table 2. The value of the discount rate was adapted from previous studies concerning ecological services [18–20]. The lifetime of WWTPs was calculated based on the depreciation rate specified in Polish law [21]. An exchange rate of €1 = 4.5411PLN was used [22].

Table 2. Assumptions for the economic analysis.

Assumption	Value
Discount rate, r	5%
Depreciation rate, s	10%
Life of WWTP, t	10 years

2.4. NPV of On-Site WWTP Investments

Economic analysis of profitability of on-site WWTP investments was based on the net present value (NPV) and was calculated using the standard financial formula:

$$NPV = -I + \frac{CF_1}{1+r} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_t}{(1+r)^t} \quad (4)$$

where: I is the initial investment (€), CF is the cash flow (€), r is the discount rate (%), and t is time [years].

The assumptions for the NPV analysis are set in Table 2. Usually, cash flows (CF) are defined as a difference between inflows and outflows. In our case, we do not report any inflows. For that reason, the final NPV value is negative. However, from an environmental point of view, it is important to reduce the contamination and for that reason we used the absolute value of NPV (|NPV|). The most effective technology is the use which obtains the lowest NPV.

3. Results

3.1. Efficiency of Compact Type On-Site Wastewater Treatment Plants

Among 23 analyzed on-site WWTPs, 19 were the container type (5 of AS, 5 of SBR, and 9 of AS + BF), two were hydroponic (HP), one was a sand filter (SF), and one was a septic system (IF, septic tank with infiltration). HP, SF, and IF systems were constructed before 2013, and as they are not currently qualified as technologies that are subject to certification, they were not included in the further analysis.

The concentration of BOD_5 observed in effluents from selected plants is presented on Figure 2. Six of the 19 analyzed container type on-site systems discharged wastewater with BOD_5 below 40 mg/L, which is a limit for effluents discharged to water bodies, and was also the predicted result of on-site WWTPs implementation programs. The highest mean concentration of BOD_5 in effluent was observed for AS plants and the lowest for hybrid systems (AS + BF). Between those two groups, there was a statistically significant difference at the 95% confidence level (Figure 2).

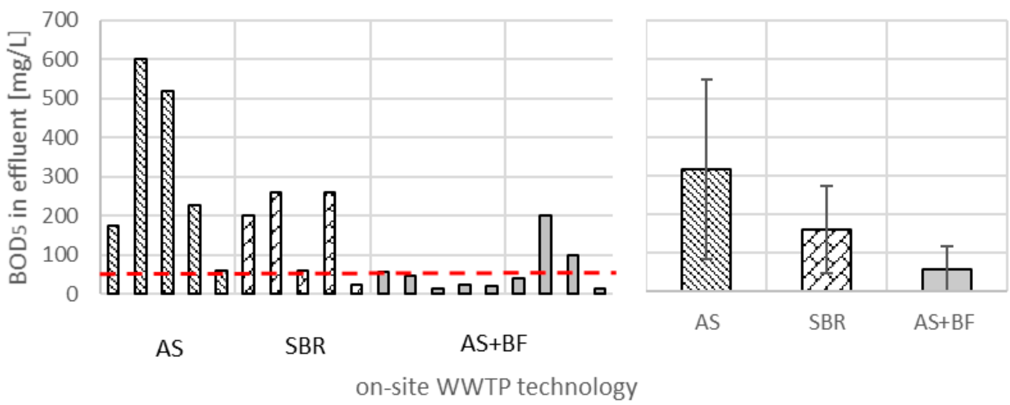

Figure 2. Concentration (left) and mean and SD (right) of BOD_5 in effluents sampled from selected on-site wastewater treatment plants (WWTPs). Dotted line denotes the limit of 40 mg/L, as analyzed in variant B. AS—activated sludge; SBR—sequencing batch reactor; AS + BF—hybrid method (activated sludge supported with biological film). Between AS and AS + BF, there is a statistically significant difference at the 95% confidence level.

The operational efficiency of household WWTPs is defined as the percentage of the reduction of pollutants, e.g., BOD_5 and is an often used indicator of on-site systems performance. Bearing this in mind, that removal efficiency is always connected with initial BOD_5 concentrations. In our study, the BOD_5 concentration in raw wastewater was rather high, with an average of 623 mg/L and within a range of 448–805 mg/L. Those values are higher than the 190–500 mg/L reported by Jawecki et al. [16]; however, our results are reasonable from the point of view of measured BOD_5 concentrations of effluents. For the calculations of environmental effects, we adapted the unit load of BOD_5 from ATV-DVWK-A 198 [14] with a value of 60 g/P d. This is the correct value, which was stated by Bugajski [23] on the basis of research on the quality of domestic wastewater in two sewage systems located in rural communes. However, he also showed that there is a high probability of the occurrence of lower or higher values. Values in the range from 40 to 60 g/P d and from 20 to 40 g/P d dominate, but values in the range from 60 to 80 g/P d also occur quite often [23]. The other factor influencing BOD_5 concentration is unit water use (Table 1), which in our study is also higher than the 80 L/P d reported in statistical reports [24] and which amounted to 99 L/P d (75–134 L/P d).

The declared rate for most compact type on-site plants' minimum BOD_5 removal efficiency of 80% was reached in case of 8 out of 9 analyzed hybrid systems, 2 out of 5 analyzed SBR systems, and only 1 out of 5 analyzed AS based systems (Figure 3). As the on-site plants were randomly selected, it can be stated that hybrid technology is the most effective and reliable one.

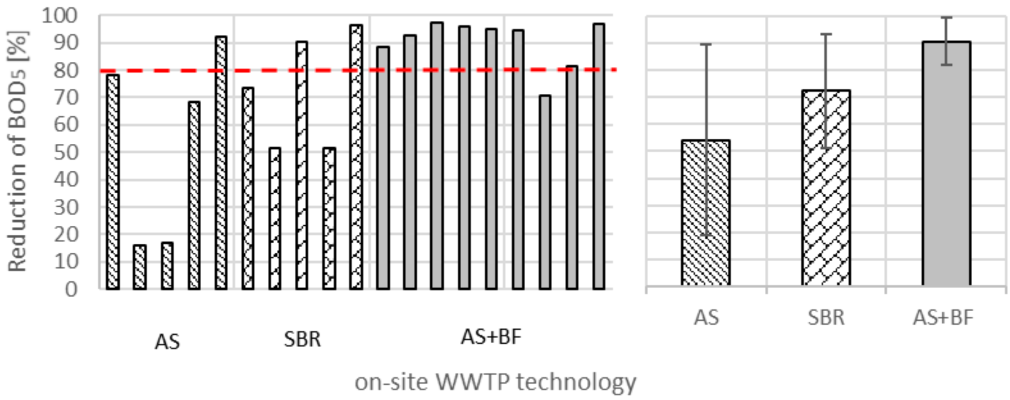

Figure 3. Reduction of BOD_5 in effluents sampled from selected container type on-site WWTPs. Dotted line denotes a minimum reduction of 80%, as declared by manufacturers. Mean BOD_5 reduction and SD are shown on the right. Between AS and AS + BF there is a statistically significant difference at the 95% confidence level. AS—activated sludge; SBR—sequencing batch reactor; AS + BF—hybrid method (activated sludge supported with biological film).

The results of this study confirmed the previous findings of other authors [4,25]. Greater reduction of organic substances in the hybrid bioreactor compared to the reactor using conventional activated sludge was reported by Krzanowski and Wałęga [4]. They achieved BOD_5 removal of between 90% and 99.7%, while in a comparable AS bioreactor, BOD_5 reduction was only 52.6%. These authors stated that a greater number of packets per filter bed and an increase in sewage recirculation from the secondary settlement tank lead to an improved efficiency of BOD_5 removal from wastewater. For an AS system, a notable improvement in the efficiency of organic substance removal was noted when the recirculation degree is increased to 20% of mean daily sewage inflow [4].

In case of the systems operating on a classic active sludge (AS) basis, severe exploitation problems may occur, such as sludge rinsing during significant hydraulic frictions or a lack of stability in activated sludge biocenosis development due to considerably irregular sewage inflow, which as a consequence influences the treated sewage quality [3,25]. Fluctuations in pollutant loading, in the volume of wastewater, and also variable environmental conditions typical for on-site wastewater treatment plants negatively affect the operation of systems using AS. Systems with biofilm-forming microorganisms are considered to be more advantageous and have a greater potential for on-site treatment [4]. Introduction of the biomass immobilized on the carriers as the submerged or mobile bed into the classic bioreactor with the active sludge increases the effectiveness of pollutant removal from the sewage [25]. The introduction of the moving bed into the reactor of activated sludge should be made in the summertime, because the rate of biomass growth is much lower and may fall by half in the winter [2].

3.2. Environmental Effect

In practice, the environmental effects are determined as a difference between the emissions for the state before and after the implementation of activities, accepting the omission of the environmental significance of the emissions. This method is used particularly in the assessment of the environmental effects of measures covered by aid programs with defined evaluation criteria that relate only to the substance load. Loads of BOD_5 calculated for different variants (A, B, C, and a background variant), and connected environmental effects calculated for a one on-site wastewater treatment system serving three people (which is the average number of people in a household located in rural areas in Poland [12]) for three different container type technologies are set up in Tables 3 and 4, respectively.

Table 3. Loads of BOD_5 [kg/yr] calculated for different variants.

Load of BOD_5 [kg/yr]							
Background Variant		**Variant A (Minimum)**		**Variant B (Predicted) Mean (min ÷ max)**		**Variant C (Real) Mean (min ÷ max)**	
Per person	Per plant	Per person	Per plant	Per person *	Per plant *	Per person	Per plant
21.9	65.7	17.5	52.6	1.4 (1.1 ÷ 2.0)	4.3 (3.3 ÷ 5.9)	4.7 (0.3 ÷ 18.4)	14.1 (0.9 ÷ 55.3)

* value depended on water use in the household.

Table 4. Environmental effects [kg/yr] calculated for a one on-site wastewater treatment system serving three people. Calculations were made for three different technologies used in compact type on-site wastewater treatment systems: AS—activated sludge; SBR—sequencing batch reactor; AS + BF—hybrid method (activated sludge supported with biological film). To obtain unit environmental effects (per one person served by on-site WWTP), values from the table have to be divided by 3.

Environmental Effect [kg/yr] of One On-Site WWTP Serving 3 People			
Variant	**Technology**		
	AS Mean (min ÷ max)	**SBR Mean (min ÷ max)**	**AS + BF Mean (min ÷ max)**
A (minimum) min. 20% reduction of BOD_5		4.3 (3.3 ÷ 5.9)	
B (predicted) concentration of BOD_5 in effluent limited to 40 mg/L		61.4 (59.8 ÷ 62.4)	
C (real) measured quality of the effluents from tested on-site systems	35.7 (10.4 ÷ 60.5)	47.6 (33. 7 ÷ 63.2)	59.4 (46.3 ÷ 63.9)

The background variant is an example of unproper wastewater management, which is still present in many cases. The volume of wastewater transported from holding tanks and discharged to WWTPs was estimated to be 27% in a previous study [26]. Nowak and Imperowicz [27] reported values of between 0.25% and 31% for selected settlements. Following the official statistical data, in 2016 and 2018, 23.1 and 46.2 hm^3 of liquid waste were collected and delivered to sewage treatment plants from septic tanks, respectively. Thus, the unit amount of sewage per one inhabitant was only 6 and 12 L/P d [28]. At the same time, the average level of domestic water use in rural areas in 2016 was estimated to be 80 L/P d [24]. Possible reasons for such small amounts of collected sewage are: leaks from septic tanks, high prices for transportation of liquid waste, unreliable reporting, and a lack of documentation of the collection and delivery of liquid waste to catchment points and collective sewage treatment plants [28]. Increased sustainability of wastewater collection and transport is a key issue under general discussion, with potential for vast improvements in energy efficiency and resource recovery potential for decentralized wastewater systems [29].

The environmental effect calculated for variant A was extremely low, but nevertheless is permitted by law if effluent is discharged to the soil. From the technical point of view, variant A represents a septic system which consisted of a septic tank and a drain field, or any other on-site wastewater management system without biological treatment being introduced. The negative environmental impact of such systems is widely known and has been undertaken in previous research. Already in the 1980s and 1990s, higher pH levels and concentrations of nitrate, total organic carbon, and dissolved organic carbon were detected in unsewered areas compared to severed areas [30,31]. The high density of septic systems in the watershed results in elevated concentrations of TDN and PO_4-P in streams relative to low density and control watershed streams [32]. Septic systems are also a source of bacteria and micropollutants in the environment, e.g., in underground water [33–35]. The septic system's effect on the environment can be difficult to measure. Sustainable on-site treatment solutions must be developed to replace many of the older types that are still in use and are having undesired effects on water bodies and groundwater [36]. For the protection of the environment, the construction of new septic systems should be prohibited, and the old septic systems should be replaced by biological treatment plants. This is already mandated by regulations in agglomeration areas [10], but is still permitted in scattered development areas [16].

Variant B, limiting the concentration of BOD_5 in the effluent to 40 mg/L, presents the environmental goal at a reasonable level and ensures an adequate level of protection of wastewater receivers. The environmental effect calculated for one on-site WWTP serving three people assumes that around 60 kg BOD_5/yr will be removed by the system. The hybrid container type treatment plant is very close to this level (Table 4, Figure 4). What is more, 5 out of 9 randomly tested on-site systems in AS + BF technology reached the level of 40 mg/L or lower for effluent results. The results also showed that the lowest real environmental effect was obtained for AS technology, and that there is a significant statistical difference between AS and AS + BF performance at the 95% confidence level (Figure 4). The SBR method could be placed in the middle in terms of the BOD_5 removal efficiency and the environmental effect obtained (Figures 2–4).

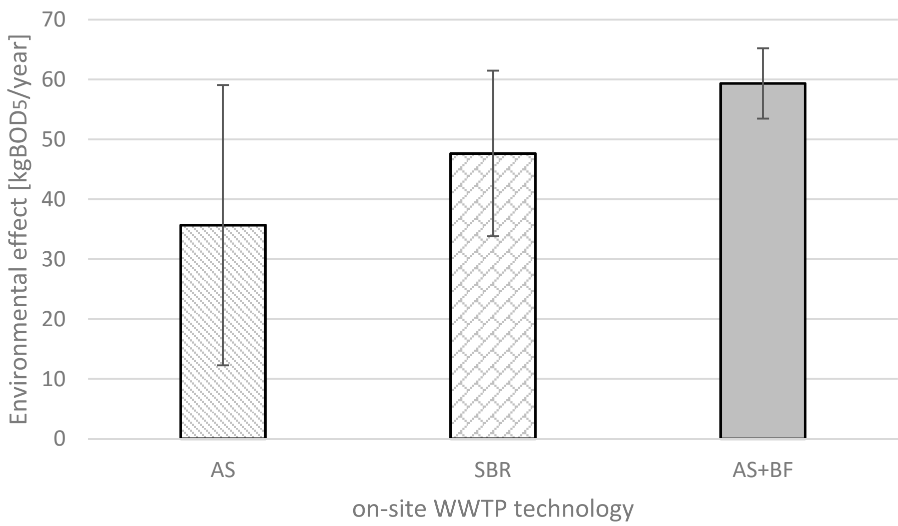

Figure 4. Environmental effects (mean and SD) [kg BOD_5/year] calculated for one on-site wastewater treatment system serving three people. AS—Activated sludge; SBR—Sequencing batch reactor AS + BF—Hybrid method (activated sludge supported with biological film). Between AS and AS + BF there is a statistically significant difference at the 95% confidence level.

3.3. Unit Annual Costs of Compact On-Site Wastewater Treatment Plants

A statement of annual operating costs and investment costs for tested on-site WWTP is presented on Figure 5. The cheapest technology is AS (1664€). The rest of the tested technologies are on similar cost level at 2058€ and 2103€ for SBR and AS + BF, respectively. The set of unit annual cost are presented in Table 5. The annual unit cost for environmental effect equal to the reduction of BOD_5 and removed load of 1 kg of BOD_5 are the lowest in the case of AS + BF technology (6.50 and 19.50 €/kg, respectively), which is justified by the highest degree of wastewater treatment. AS + BF technology has the highest unit cost per person (128.59€) in contrast to AS and SBR technologies. However, considering the unit costs of 1 m^3 of wastewater treatment, all technologies were found to be comparable (9.66–9.89 €/m^3). On the other hand, Jóźwiakowski et al. [37] analyzed the operating costs of six different on-site WWTPs and found that the AS costs was the highest ones and were equal to those of a tested hybrid system (activated sludge + trickling filter). Lower operating costs characterized the technologies: trickling filter > drainage system = sand filter = constructed wetland (VF-HF type) [37].

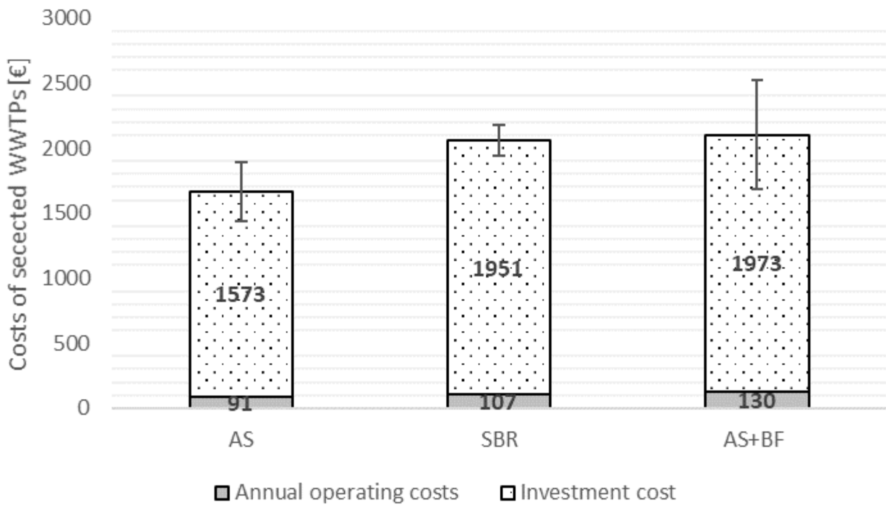

Figure 5. Costs of on-site WWTPs. Bars indicate SD value for investment cost, n = 6. Between AS and SBR and between AS and AS + BF, there are statistically significant differences at the 95% confidence level.

Table 5. Unit annual costs for tested on-site WWTP.

Unit Annual Costs on:	AS	SBR	AS + BF
environmental effect equal to reduction of BOD_5 (€/kg)	8.26	7.55	6.50
removed load of 1 kg BOD_5 (€/kg)	24.77	22.64	19.50
person (€/P)	98.18	119.86	128.59
volume of treated wastewater (€/m^3)	9.66	9.89	9.87

3.4. NPV of On-Site WWTP Investments

The NPV for 10 years of operation of an on-site WWTP is presented in Table 6. NPV considers the change of monetary value over time. The value reported in single year (from 1 to 10) means the annual costs of WWTPs operation that are changing over time. The results of NPV depend not only on the annual operating costs but also on the value of discount rate taken to calculation. The higher the discount rate, the most effective and profitable NPV. Boyer et al. [18] claim that the discount rate of 5% reflects the current common discount rate, but this rate can vary between the regions.

From the economical point of view, the most profitable method is using AS technology, which confirms the results of unit annual costs per person. However, after recalculations of the NPV result by assessing the environmental effects as being equal to the reduction of BOD_5, the most effective method is AS + BF technology (50 €/kg BOD_5). The effectiveness of other technologies equaled to 58 and 64 €/kg BOD_5 for SBR and AS, respectively. Also, Nowak and Wawryca [38] used the NPV method for assessment of the efficiency of three different on-site WWTPs (septic system (IS), SBR, and constructed wetland (CW)). For tested technologies, they obtained a NPV sequence as follow: IS < SBR < CW. According to Sowińska and Makowska [2], it is possible to modify AS technology into a hybrid one (AF + BF) through e.g., implementation of a moving bed. In this way, an increase in the BOD_5 removal efficiency of AS does not prevent the cost of WWTPs from being affordable.

Table 6. Result of the net present value (NPV) (€) for tested on-site WWTP.

	Year											∣*NPV*∣
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
AS	−1573	−87	−82	−78	−75	−71	−68	−65	−61	−59	−56	**∣2274∣**
SBR	−1951	−102	−97	−92	−88	−84	−80	−76	−72	−69	−66	**∣2777∣**
AS + BF	−1973	−124	−118	−112	−107	−102	−97	−93	−88	−84	−80	**∣2979∣**

4. Discussion

Small wastewater treatment plants have begun to play an important role at the global level in the management of water quality of rivers, lakes, estuaries and aquifers, with a larger numerical growth compared to centralized systems [39]. At least 26% of the population in most countries is served by on-site systems [40]. According to statistical data, there are around 235,000 on-site wastewater treatment plants in Poland [5], one third of Ireland's population is served by on-site wastewater treatment systems [41], and there are nearly one million on-site WWTPs in Sweden [42]. Although in many cases septic systems consisting of a septic tank and soil attenuation system have dominated this area [28,41], the number of biological on-site treatment plants has been increasing in recent years. Biological treatment plants can be of two types: the natural based type (e.g., constructed wetland or sand filter) or the container type. Natural based systems are very effective in BOD_5 and suspended solids removal and with some modifications can also remove nutrients efficiently [36,43,44]. However, they usually have high land requirements and as since the treatment process is not controlled there, they cannot be certified. Compact type biological on-site plants have been becoming more and more popular in recent years. Despite the unquestionable high efficiency of the activated sludge and biological film technology in centralized municipal wastewater treatment plants, the miniatures of these technologies used in on-site systems operate under specific conditions of hydraulic and organic load. This causes difficulties in the operation of these systems. This study has shown that in the group of container biological treatment plants, there are less and more efficient technologies, which is the result of different levels of resistance to changes in the composition and amount of sewage discharged from individual households. AS plants showed great variety in treatment efficiency, while hybrid systems were characterized by rather stable performances. Considering the fact that the majority of users of on-site treatment plants expect their effectiveness with user intervention to be limited to periodic services, in the future, hybrid technology should be recommended for individual users.

While the major investments costs in centralized wastewater systems are absorbed by the collection system, in decentralized systems they are absorbed by the treatment technology [39]. In case of on-site system investments, costs must be borne by the users of the treatment plant. Therefore, the choice of treatment technology often depends on the investor's financial resources. From this study, it is seen that investment costs of AS compact type systems are significantly lower than for AS + BF based container plants. In the case of the analyzed systems, lower costs also means a lower treatment efficiency.

The highest operation costs in decentralized treatment systems are generated by the aeration system and in our study, it was estimated to represent 44.2–61.1% of total operation costs. The unit cost of treated organic load is usually higher in on-site systems compared to centralized systems. Unit cost of BOD_5 removed in on-site systems analyzed in this study varied from 19.50 to 24.77 €/kg while for six medium size WWTPs with P.E. between 614 and 2338, it ranged from 0.46 €/kg (for 2338 P.E.) to 0.84 €/kg (for 614 P.E.)

with an average cost of 0.62 €/kg [45]. Similar costs (0.71 €/kg) were reported for nine wastewater treatment plants in EU member countries [46]. Also, the cost of treatment of the volume of wastewater decreases with increasing P.E. in centralized systems and ranged from 0.93 €/m^3 (P.E. 2338) to 1.80 €/m^3 (P.E. 614) with an average cost of 1.32 €/m^3 [45]. This shows that the cost of the treatment of 1 m^3 of wastewater in centralized treatment systems is over 7 times lower than in the decentralized systems analyzed in this study. A similar relation exists when considering the cost of wastewater treatment per person. In medium size centralized WWTPs, the cost ranged from 20 €/person (P.E. 2338) to 38 €/person (P.E. 614) with average cost being 28 €/person [45] while in analyzed on-site systems, the cost amounts to 98.18–128.59 €/person.

Despite the significant cost of wastewater treatment in compact type on-site treatment plants, there are many benefits from decentralization, with the one particularly important in the aspect of depletion of global resources. Small WWTPs may assure a greater level of environmental sustainability by supporting the potential reuse of treated wastewater, as well as nutrients recovery [47]. This aspect was not analyzed in our study, as all container type systems provide similar options for effluent reuse. However, if the water/nutrient recycling option would be included, then the operation costs will decrease. Considering the ten-year life-time, the operating costs of the system will reach around 30% of the total costs of the on-site treatment system, and this may be limited by saving fertilizers and the tap water e.g., for garden irrigation.

5. Conclusions

On-site treatment systems are considered as a cost-effective option of domestic wastewater management in unsewered areas. In current practice, the selection of treatment system depends upon the cost of construction, land requirement, and operation and maintenance expenses [48]. The necessary purchase cost is also very often a driving force for selection of the type of the on-site wastewater treatment plant. Thus, compact on-site wastewater treatment systems, with the option of co-financing, are receiving growing interest. High efficiency of wastewater treatment should be guaranteed by a certificate; however, this study shows that different technologies used in container treatment plants provide different environmental effects. The lowest environmental effect of implementation of on-site WWTP serving 3 people was obtained for AS plants, and the highest (almost doubled) was for hybrid systems. In case of treatment efficiency, AS plants showed great variety, while hybrid systems were characterized by a rather stable performance. Only in the case of hybrid systems was the predicted environmental effect almost completely achieved. The SBR method was placed between those two technologies, and is also the most advanced one in terms of wastewater treatment process control. In the future, hybrid systems should be promoted as the most reliable container type on-site wastewater treatment system, and existing AS systems should be upgraded into hybrid systems.

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