PAN POLSKA AKADEMIA NAUK
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.155319
2025, No. 66 (VII–IX): 244–253

Opportunities and constraints for effective treatment of domestic wastewater in rural onsite wastewater treatment systems operating in a foothill climate

Andrzej Jucherski[1)], Andrzej Walczowski[1)], Beata Grabowska-Polanowska[1)], Agnieszka Operacz*[2)], Piotr Bugajski[2)]

[1)] Institute of Technology and Life Sciences – National Research Institute, Al. Hrabska 3, 05-090 Raszyn, Falenty, Poland

[2)] University of Agriculture in Krakow, Faculty of Environmental Engineering and Land Surveying, Department of Sanitary Engineering and Water Management, Al. Mickiewicza 24/28, 30-059, Kraków, Poland

* Corresponding author

RECEIVED 19.05.2025 ACCEPTED 04.08.2025 AVAILABLE ONLINE 26.09.2025

Highlights
- Effective alternative to wastewater treatment plants with activated sludge
- Recommended for environmentally valuable areas without collective sewerage systems
- Innovative quasi-technical systems with lower energy consumption
- Foothill climatic conditions slightly affect the treatment processes efficiency

Abstract: This paper presents the results of a study of two innovative quasi-technical installations designed for high-quality treatment of domestic wastewater in rural areas. The installations are equipped with similar technological devices arranged in sequences consisting of: three-chamber flow septic tanks, biological sprayed beds filled with granular (10–20 mm) calcined clay materials, special slope biofilters with soil-grass beds and infiltration ponds as recipients. The sites are located at an altitude of more than 600 m a.s.l. in a foothill climate, in southern Poland. For both sites, the analysis showed a high elimination efficiency for pollutants expressed as biochemical oxygen demand over five days, chemical oxygen demand and total suspended solids. In the case of total nitrogen, the reduction rate was 79.4% for facility No. 1 and 84.3% for facility No. 2, respectively. A high level of ammoniacal nitrogen removal was achieved at both analysed sites, at 98.7% for facility No. 1 and 92.1% for facility No. 2. The PO_4-P were removed at 88.0% at facility No. 1 and 69.1% at facility No. 2. The correlation analysis showed no significant relationship between the removal efficiency of the analysed pollutant indicators and the temperature of the treated wastewater, with the exception of total nitrogen. Thus, it is concluded that the climatic conditions did not affect the wastewater treatment processes. They are an effective alternative to treatment plants based on activated sludge technology and are recommended for use in rural areas with high environmental values, without sewage systems, which require special protection.

Keywords: individual wastewater treatment plants, innovative soil-grass biofilters, LECA-filled sprayed biological beds, organic and nutrient removal efficiency

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

INTRODUCTION

Among the many important needs that determine people's modern living standards, the need to provide them with adequately effective wastewater sanitation systems must be considered the most important and expected by the majority of the European population. There are still large differences in the population's access to collective sewage systems across the EU Member States.

For example, the rate of population access to sewerage systems is 100% in Luxembourg, 99% in the Netherlands and Malta, 97% in Spain, and 96% in Germany. In Poland, the rate is 72%, higher than in Slovenia (68%), Romania (53%), Croatia (52%) and Cyprus (30%) (GUS, 2022). Eliminating these disparities requires significant and costly investment, both because of the large scale of projects needed, the unfavourable geographical and environmental conditions, as well as the unfavourable spatial and demographic characteristics, especially in rural areas, where low building density requires the extension of costly sanitary sewerage networks.

The example of Poland shows a significant disparity between urban and rural sewerage levels. In urban areas, 91% of the population uses the sewerage system, with 44% in rural areas (GUS, 2022). The disadvantages in rural areas affect more than 8,420,000 people, which is about 55% of the total rural population of Poland. For these reasons, the widespread implementation of centralised sanitation projects both in Poland and in all EU countries is a very difficult challenge. Therefore, the construction of individual wastewater treatment systems, especially in rural areas with low building density, is the most viable alternative and even an unavoidable necessity (Jóźwiakowski *et al.*, 2018; Bugajski, Kurek and Jóźwiakowski, 2019; Jucherski *et al.*, 2019; Istenič *et al.*, 2023). However, solving the problem will not be easy, as according to the new EU Wastewater Directive (Directive, 2024), the use of individual wastewater treatment systems will only be possible "where it can be demonstrated that the establishment of an urban wastewater collecting system or the connection to a collecting system would produce no benefit for the environment or human health, would not be technically feasible or would involve excessive costs, and only in those cases". Furthermore, individual treatment systems must be designed, operated and maintained to provide the same level of environmental and human health protection as "secondary and tertiary treatment". Thus, scientific and technical progress in wastewater treatment processes must lead to the development of only such individual treatment plants that are able to provide treatment quality comparable to that of those serving centralised sewerage systems. This is a very difficult task, mainly due to the unfavourable characteristics of wastewater discharged from individual properties in rural areas. Compared to wastewater discharged by collective sewerage systems, they are characterised by significant variability in generation and discharge volumes over time and, very significantly, by much higher concentrations of the pollutant components they contain. Comparing the limit values of pollutant components in treated wastewater according to the Polish law (Rozporządzenie, 2019) for the population equivalent (PE) < 2000 – i.e.: biochemical oxygen demand over five days (BOD_5) = 40.0 (mg $O_2\cdot dm^{-3}$), chemical oxygen demand (COD) = 150.0 (mg $O_2\cdot dm^{-3}$), total nitrogen (TN) = 30.0 (mg$\cdot$dm^{-3}), total phosphorus (TP)/phosphates PO_4-P = 5.0/4.4 (mg$\cdot$dm^{-3}), total suspended solids (TSS) = 50.0 (mg$\cdot$dm^{-3}) – to the average values of pollutant components in wastewater flowing from rural settlements (Jucherski and Walczowski, 2020) – 511.2 (mg $O_2\cdot dm^{-3}$), 837.2 (mg $O_2\cdot dm^{-3}$), 136.1 (mg$\cdot$dm^{-3}), 15.1 (mg$\cdot$dm^{-3}), 156.9 (mg$\cdot$dm^{-3}) respectively, – we can conclude that the "individual systems or other solutions" listed in the Directive (2024) have to provide a minimum treatment efficiency of BOD_5 = 92%, COD = 82%, TN = 78%, PO_4-P = 70.8%, TSS = 68%. This is a major challenge for the designers and operators of these installations.

Individual wastewater treatment programmes in rural areas in Poland are currently dominated by various types of prefabricated micro-treatment plants with activated sludge reactors. The advantage of these plants is in their compact design, which facilitates their location on plots with limited space, as well as quick installation using typical earth-moving machinery. Their disadvantage, however, is the frequent instability of the process, due both to their high sensitivity to harsh environmental conditions and to the highly variable quantity and quality of wastewater generated per day in rural buildings, as stated above. With a relatively small range of manufactured units available, it is a very important (and difficult) task to select the unit best suited to the specific conditions of individual wastewater management, as the adjustment possibilities to adapt the operating parameters to the highly variable conditions of domestic use are very limited. As a result of poor type selection, the wastewater treatment quality indicators of these units – even those with a very high technical level – are very often lower than those declared by manufacturers and expected by users (Steinhoff-Wrześniewska *et al.*, 2020). The use of suitable, biologically active soil-plant receivers could be useful to reduce this risk (Jucherski *et al.*, 2024). Ultimately, however, the success or defeat of any implementation depends decisively on the technical and technological potential of the equipment used. For example, the results of several years of testing of two modern individual activated sludge treatment plants showed that, even when operating under stabilised and controlled conditions of the physical and chemical characteristics of the effluent and a fixed hydraulic load typical of 4–6 PE, the analysed installations could only meet the requirements for the basic indicators: BOD_5, COD and TSS (Jucherski and Walczowski, 2020). At the same time, a decrease in treatment efficiency was found in the autumn and winter periods in all analysed components. The removal efficiency of TN dropped significantly, by as much as 55%. The required TN concentrations in the treated effluent (up to 30 mg$\cdot$dm^{-3}) were only achieved during short periods of summer when the effluent temperature exceeded 15°C. The average annual phosphate removal efficiency was also insufficiently low, ranging from 34.5 to 36.9%. This means that biological methods of phosphorus removal in activated sludge wastewater treatment plants are ineffective and require the use of additional chemical precipitation equipment. In conclusion, it was found that the containerised domestic wastewater treatment plants offered to date, operating with activated sludge technology, have considerable difficulties in meeting all quality requirements throughout the year, especially under foothill climatic conditions.

The aim of the study was to determine the reliability of two household wastewater treatment plants in terms of the removal of organic and biogenic compounds. Both systems represent innovative and original solutions for wastewater disposal. The

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

novel aspect lies in the biological treatment system, which consists of a vertical trickling biological bed and a sloped horizontal wetland bed, also known as a cascading system.

MATERIALS AND METHODS

The subject of the study was two innovative plants built in accordance with Figure 1 and the block diagram in Figure 2. These facilities are located on mountain farms and meet the domestic needs of their wastewater management. From 2008 to the present, they have been under the constant research supervision of the Mountain Research and Education Centre in Tylicz (Pol.: Górskie Centrum Badań i Edukacji w Tyliczu) belonging to the Institute of Technology and Life Sciences National Research Institute (Pol.: Instytut Technologiczno-Przyrodniczy – Państwowy Instytut Badawczy).

The basic element of this plant is a classic multi-chamber flow-through septic tank with a unit active volume of about 800 dm^3 per person, which allows high efficiency of pretreatment processes, especially sedimentation of total suspended solids (Philip *et al*., 1993; Jucherski, 2000). The next element is a vertical flow biological reactor with a filter bed filled with granular (10–20 mm) calcined clay materials (LECA), fed cyclically with wastewater by means of a pumping unit installation equipped with a sprinkler. The sprinkler distributes the wastewater droplets evenly over the bed surface, which promotes the intensification of the mineralisation and nitrification processes of the treated wastewater. Special shallow biofilters with soil-grass beds are a key element of the installation, located on slopes in the form of grassy strips isolated from the native subsoil with the characteristics of eutrophic mountain marshlands (wetlands), designed for tertiary wastewater treatment, i.e. removal of residual biogenic pollutants, especially N and P. They are made in the form of shallow longitudinal earthen basins (channels) with the soil cover removed, along the slopes, in the form of strips 2.0 m wide and at least 15 m long. Their bottoms are divided into sections in the form of cascades (steps) with a 1% slope of the surface of each element of the cascade. These form the basis for the formation of a sequence of mini filtration beds with horizontal flow. The number and length of these cascades depend on the slope of the terrain at the site. The longitudinal earthen basins shaped in this way are isolated (at the bottom and sides) from the native soil by an impermeable polyvinyl chloride (PVC) membrane, and are then filled with appropriately selected filter materials. A characteristic feature of slope biofilter beds, which distinguishes them from classic horizontal flow wetland-type beds, is the much smaller thickness (0.2–0.25 m) of the filter media layer. For filling slope biofilter beds, native materials from the immediate vicinity or from the site are recommended, suitably selected for the required hydraulic permeability. In practice, the predominant material for filling slope biofilter beds is a mixture of screened native soil and coarse sand of 1–4 mm, at an approximate volume ratio of 2:1. The surface of the slope biofilter beds should be protected from storm scour by re-planting the turf elements removed during the construction of the earth basins. Seedlings of hydrophilic grasses from local wetland habitats, primarily water manna (*Glyceria aquatica*), reed canary grass (*Phalaris arundinacea*), and bulrush (*Scirpus sylvaticus* L.) are then introduced to the surface of the deposits. The vegetation cover, which is (besides the snow cover) an additional thermal insulator in winter, should be removed from the surface of the strips in spring, replenishing the plants as necessary. The specificity of filtration conditions in soil-grass slope beds makes it difficult to apply empirical formulas useful for dimensioning of classical constructed wetlands, given, among others, by Gajewska, Obarska-Pempkowiak and Wojciechowska (2010) and Dotro

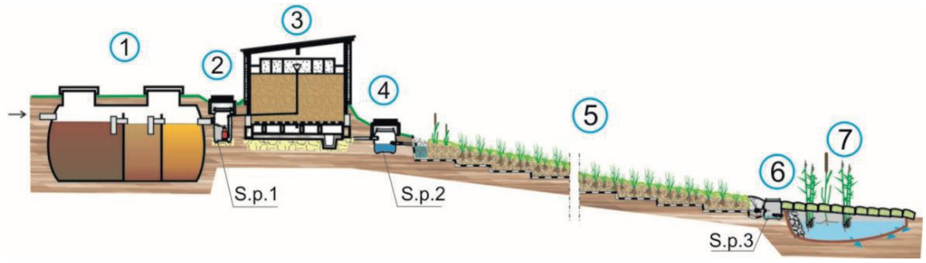

Fig. 1. Innovative installation proposed by the Mountain Research and Education Centre in Tylicz; *1* = multi-chamber flow-through septic tank of concrete or synthetic plastic, unit volume 800–1000 $dm^3 \cdot PE^{-1}$, *2* = pumping well: sampling point S.p.1, *3* = biological reactor with a sprayed filter bed filled with granular calcined clay materials (LECA), *4* = inspection and distribution well: sampling point S.p.2, *5* = slope biofilter with soil and grass bed, *6* = inspection well: sampling point S.p.3, *7* = infiltration pond; source: own elaboration

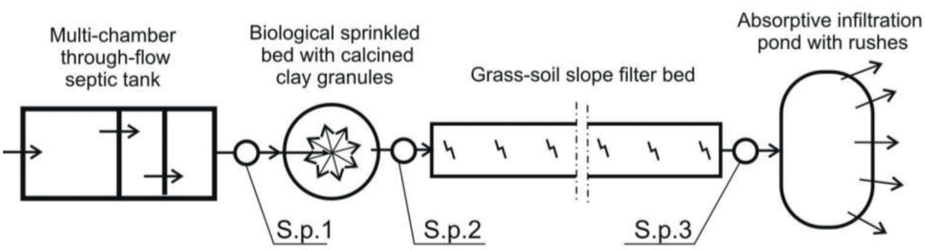

Fig. 2. Block diagram of the analysed installations No. 1 and No. 2; source: own elaboration

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

et al. (2017). Therefore, in these solutions, it is preferable to use a rate of overall hydraulic loading of the bed surface in the range of 10–15 mm·d^{-1}. At the end of this installation, there is a pond with a permeable bottom, covered with a variety of rush vegetation, which serves to receive the treated wastewater and further infiltrate it into the soil complex. The reuse of treated wastewater for farm (non-consumptive) purposes or the infiltration of surplus treated wastewater into the soil sorption complex is fully in line with the principles of water-efficient closed-loop management. The year-round process stability of plants with the proposed treatment technology, as well as their resistance to the impact of the lower year-round ambient temperature prevailing in the foothill region of the study, in the practical context of the main objective of the study was to assess their potential to protect the valuable natural and water resources in mountain areas.

The structural differences between the installations No. 1 and No. 2 are:

- different design of the septic tank (monolithic concrete tank with classic three-chamber division vs combined multi-chamber),
- active volume of the septic tank (7.0 vs 4.7 m^3),
- shape and material of the housing of the sprayed bioreactor (cylindrical plastic vs rectangular concrete slabs),
- the length of the slope biofilter beds (32 vs 20 m) and the dominant plant species covering the slope filter beds.

In both cases, the installations were originally planted with native turf elements and hydrophilic plants: water manna, reed canary grass and bulrush. The dominance of these plants has changed naturally over the years of operation, through their gradual displacement by the aggressive self-introduction of nitrophilous plants (nettle (*Urtica dioica*), water mint (*Mentha aquatica* L.) and butterbur (*Petasites*)), which have spontaneously colonised the area from the surrounding habitat.

Facility No. 1 served between 5 and periodically 15 (during tourist seasons) PEs, and facility No. 2 served between 4 and 6 PEs. The average daily wastewater inflow to the analysed facilities was 514.6 and 586.7 dm^3·d^{-1}, respectively. Wastewater samples were collected at the sampling points marked on the drawings of the analysed facilities, respectively. A series of $n = 33$ samples was collected from both sites. These samples were taken at a frequency of approximately once a month during three full one-year study periods, completed between 2013 and 2018 at facility No. 1, and between 2010 and 2015 at facility No. 2. On the basis of the measured data of the pollutant components, the values of their mean, maximum, minimum and median concentrations were calculated, as well as the standard deviations and coefficients of variation at each treatment stage. The results are tabulated for comparison of the facilities No. 1 and No. 2. The difference in pollutant concentrations in wastewater after the septic tank results from the specific characteristics of wastewater originating from a tourist facility compared to that from a typical household, as confirmed by the research results presented by Bugajski, Chmielowski and Kaczor (2016).

The efficiency of wastewater treatment at each stage (η, %) was calculated from the formula:

$$\eta = 100 \cdot (1 - C_o/C_i) \tag{1}$$

where: C_i = concentration of the analysed pollutant component in the influent effluent, C_o = concentration in the effluent.

The biochemical oxygen demand over five days (BOD_5) was determined using WTW's OxiTop respirometric measurement kit. The chemical oxygen demand (COD) and total nitrogen (TN) were determined using Merck SQ118 and Merck Prove 100 photometers, after prior mineralisation of the samples in a Merck TR-200 thermoreactor. In the analysis, the PO_4-P levels were determined. This is justified by the results of long-term measurements of phosphorus concentrations ($n = 150$) in effluent flowing away from rural septic tanks. In this study, the authors found that the dominant form of phosphorus in domestic wastewater after septic tanks is its phosphate form, PO_4-P. It is strongly correlated with total phosphorus (P_{tot}) at a level only 11.8% lower. Determination of this complex in wastewater is much quicker and cheaper. The ammonium and nitrate forms of nitrogen, NH_4-N and NO_3-N, were determined using a photometric method. The total suspended solids (TSS) content was determined by the weight method, in accordance with PN-72/C-04559/02 (Polski Komitet Normalizacyjny, 1972). The WTW pH-METR 320 universal meter was used to measure the temperature and pH of the wastewater. Wastewater flow rates were determined on the basis of water consumption read from domestic water meters.

Pearson's linear correlation analysis was used to assess the relationship between effluent temperature and the removal efficiency of individual pollutant components. The strength of the relationship between the two variables was determined using the (−1; 1) scale proposed by Stanisz (2006). The graphical form of the correlation is presented in the correlation charts. The significance of the analysed correlations was determined using the Student's *t*-test at a confidence level of $\alpha = 0.05$. Statistical analyses of the test results were performed using Statistica 10. The probability of exceeding the permissible concentrations of pollutants in treated wastewater (according to the parameters defined in the aforementioned national regulation for PE < 2000) was determined using empirical functions of cumulative distributions determined from the size of the class intervals of the relative frequency of distribution of these parameters (Bugajski *et al.*, 2022).

RESULTS AND DISCUSSION

EFFLUENT CHARACTERISTICS AT SUCCESSIVE TREATMENT STAGES

Both facilities treated wastewater coming exclusively from rural farms, and it must therefore be assumed that their physical and chemical properties resulted from the accepted living standards of their inhabitants. In the testing procedure for quasi-technical installations adopted at the Institute, the reference basis for assessing the quality of their subsequent treatment is wastewater pre-treated in septic tanks. Raw wastewater discharged from the internal installations of buildings is characterised by particularly high variability of flow rates and pollutant loads and concentrations over the course of a day. Under the conditions of a typical rural farm, it is practically impossible to collect them correctly and make a meaningful assessment of their composition. The results of national studies on septic tanks are scarce and, in addition, the results of assessments of their functionality are highly variable in terms of individual pollutant components

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

depending on the design of the device under study (Pawęska *et al.*, 2011). This makes it difficult to make a meaningful prediction of the characteristics of the wastewater discharged directly from the building. In practice, a number of different septic tank designs are used, which was confirmed by the different solutions used in the analysed installations No. 1 and No. 2. The significant differences that were found in the composition of the wastewater discharged from the septic tanks used in installations No. 1 and No. 2 are due both to the different specific nature of the way of life of the residents and to the difference in their design, resulting in different efficiency of the initial wastewater treatment processes. The physical and chemical characteristics of the influent and effluent from the individual process units of the two plants are statistically presented in Table S1.

Assessing the septic tanks in terms of fulfilling their primary function, i.e. the sedimentation of suspended solids, the average TSS concentration of 58.0 $mg \cdot dm^{-3}$ in the effluent flowing out of the septic tank of facility No. 1 is significantly lower compared to the average TSS concentration of 142.4 $mg \cdot dm^{-3}$ in the effluent flowing out of the septic tank of facility No. 2. Analysing the magnitudes of the other pollutant indicators in the effluent discharged from the septic tank at facility No. 2, it can easily be concluded that its efficiency is significantly worse than at facility No. 1, despite the comparable unit active volume in both septic tanks (dm^3 per person). In general, the higher values of pollutant indicators in the effluent discharged from the septic tank at facility No. 2 may be due to the smaller volume of the first chamber (1.5 m^3 at facility No. 2 vs 3.5 m^3 at facility No. 1). The use of three-chamber tanks in both installations has had a positive effect on the volumetric stabilisation of the wastewater outflow from these facilities.

The average daily volumes of wastewater discharged from the septic tank at facility No. 2 had a low variability (coefficient of variation < 25%), and at facility No. 1, a medium variability (coefficient of variation: 25–45%), which was due to the much higher periodic volume of wastewater generated in the building (tourists). Analysis of the coefficients of variation for individual pollutant constituents in the effluent discharged from the septic tank at facility No. 2 showed generally low (<25%) or medium (25–45%) variability, and at facility No. 1, medium and occasionally above-average (>45%) variability.

The wastewater treated at successive stages of the overall process at both treatment plants was characterised by a strong variation in the magnitude of individual pollutant components (variability in the middle of the range: 45–100%), and in several cases, the variability range of 100% was slightly exceeded. It should be emphasised, however, that these variations were already found at the final stages of the treatment process, with very low levels of pollutant concentrations characterising the effluent that has already been thoroughly treated, thus minimising the risk of adverse environmental impact on its receivers.

ASSESSMENT OF THE BIODEGRADABILITY OF WASTEWATER

Measures of the potential susceptibility of wastewater to organic matter decomposition and nitrogen and phosphorus removal by biological processes are the quotients of organic matter readily available to bacteria and these constituents, expressed by biochemical oxygen demand over five days (BOD_5)/chemical oxygen demand (COD), BOD_5/total nitrogen (TN) and BOD_5/P (PO_4-P). The values of $BOD_5/COD \geq 0.5$–0.6, $BOD_5/TN \geq 4$, $BOD_5/TP \geq 20$ are accepted as the limiting indicators of good biodegradability of wastewater (Heidrich and Witkowski, 2005; Młyński *et al.*, 2020). The analysis of the indicators characterising the biodegradability of the basic pollutants in the effluents flowing out of the septic tanks of the analysed installations (Fig. 3) leads to the conclusion that the lower quotient of BOD_5/COD = 0.46 in the effluents flowing into the sprayed bed of facility No. 1 compared to the value of the quotient of BOD_5/COD = 0.71 in the effluents flowing into the sprayed bed of facility No. 2 may indicate a much more effective retention of organic matter in the septic tank of facility No. 1.

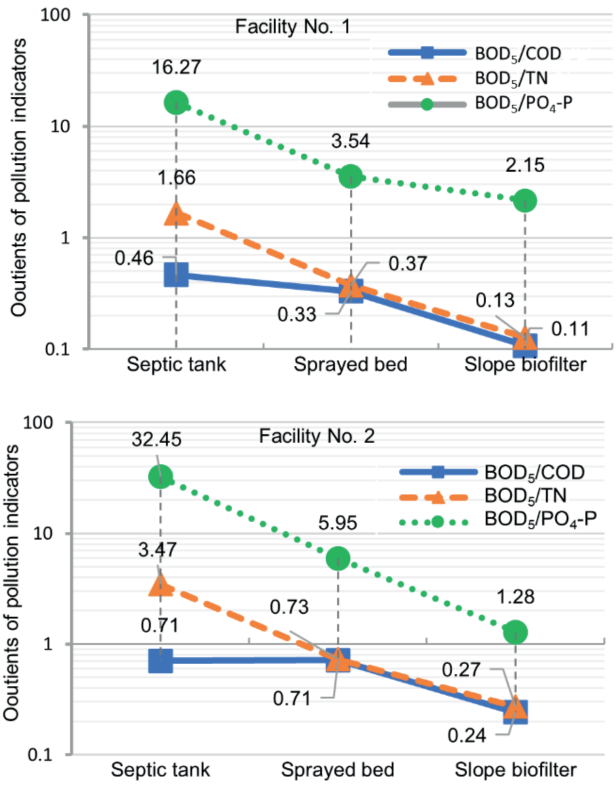

Fig. 3. Changes in effluent biodegradation rates (in average values) after successive treatment stages at facilities No. 1 and No. 2; source: own study

This results in a slightly lower BOD_5 reduction efficiency in the sprayed bed at facility No. 1 (80%) than at facility No. 2 (85%). The lower supply of organic carbon in the effluent treated in the sprayed bed at facility No. 1, with the additionally low BOD_5/TN = 1.66, results in lower denitrification efficiency and consequently lower total nitrogen removal efficiency (11.6%) compared to the effluent treated in the sprayed bed at facility No. 2 (BOD_5/TN = 3.47), where the total denitrification efficiency reaches 31.8%. The significantly different BOD_5/PO_4-P ratios of 16.27 at facility No. 1 and 32.45 at facility No. 2 are reflected in the different efficiencies of the sprayed beds in biological phosphate removal from wastewater: 8.6% and 22.3%, respectively.

It should be noted that the characteristics of the infill material and the resulting specificity of the wastewater filtration processes in these beds do not favour biological phosphate removal mechanisms.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

ANALYSIS OF WASTEWATER TREATMENT EFFICIENCY IN THE CONTEXT OF TEMPERATURE

Both installations were tested on rural farms located in the specific conditions of the cool foothill climate zone in the Krynica-Zdrój municipality in the Beskid Sądecki region. Facility No. 1 is located at an altitude of 690 m a.s.l., and facility No. 2 at an altitude of 645 m a.s.l. According to publicly available meteorological data, the average annual air temperature in the study area is +4°C (−4.5°C in January, +15°C in July). The average number of days with temperatures <+10°C ranges from 235 to 245 days per year, and the growing season lasts only 195–200 days.

From the graph in Figure 4, it can be estimated that an air temperature of ≥+12°C occurs on only 109 days per year. This figure defines the specific thermal conditions in the wastewater treatment processes at both research facilities. The temperature distribution in the treated wastewater is strongly related to the ambient temperature distribution of the research facilities. The effluent in the septic tank of facility No. 1 (with a larger volume) is less sensitive to cooling than the effluent in the septic tank of facility No. 2, which translates into the number of days with temperatures ≥+12°C of 177 and 158, respectively. The temperature distribution during wastewater filtration in both slope biofilters (Fig. 5) is more uniform throughout the year (111 and 110 days with temperatures ≥+12°C) and directly corresponds to the thermal conditions in the surroundings of the facilities.

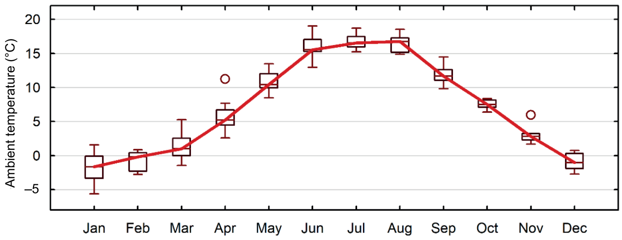

Fig. 4. Multi-year monthly air temperature distribution in the study area; source: own study

Temperature is one of the primary physical determinants of animate and inanimate matter activity (Klimiuk and Łebkowska, 2003; Ferrier and Chlubek, 2018; Rodziewicz *et al.*, 2020). In the context of wastewater treatment, higher temperatures intensify the processes of dissolution, aerobic and anaerobic biodegradation, nitrification and denitrification, chemical and physical adsorption and precipitation, as well as evaporation and evapotranspiration. Operacz *et al.* (2023) showed that the pollutant removal efficiency of the treatment plant was significantly higher in the growing season than outside the growing season and that temperature determined the efficiency of the wastewater treatment. Particularly noteworthy in this study are the high removal efficiency values of total nitrogen from the treated wastewater in the facilities analysed, in the context of a regulation by the national legislator, which states that efficiency tests for this component shall not be carried out when the temperature of the treated wastewater is below 12°C. This means that nitrogen discharged with effluent from the various domestic wastewater treatment plants into the environment may be uncontrolled most days of the year, which is dangerous and contrary to the requirements for its protection. However, in the

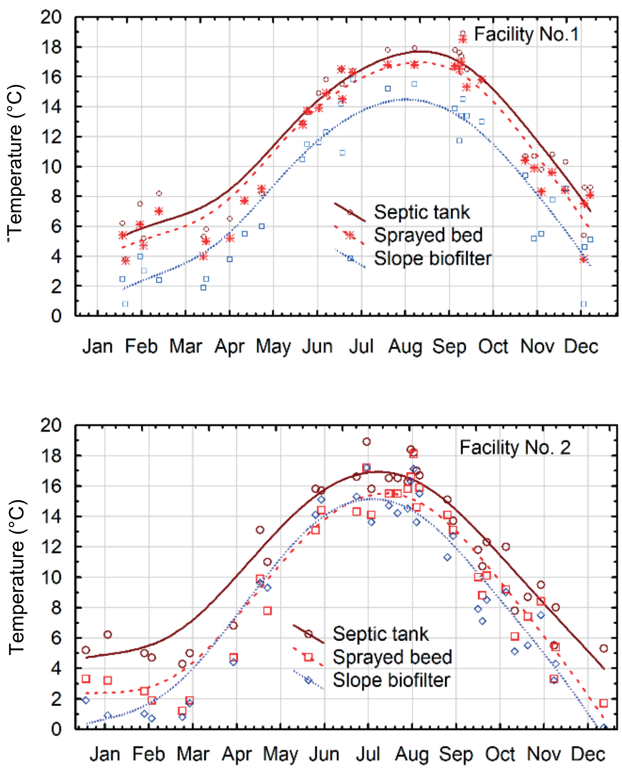

Fig. 5. Annual distribution of the effluent temperature measured during the study period at the outflows from successive process units at both facilities; source: own study

specific case of the facilities analysed, such a limitation of nitrogen testing is unjustified, given the high capacity of these facilities in this respect.

According to well-established knowledge in the literature, the efficiency of total nitrogen removal from wastewater in nitrification processes reaches a maximum at 25–28°C (Bhaskar and Charyulu, 2005; Paredes *et al.*, 2007), and denitrification has a maximum at 20°C (Chen *et al.*, 2017). However, Rostron, Stuckey and Young (2001) found that lowering the temperature in a biofiltration reactor from 25 to 16°C resulted in only a 10% decrease in nitrification efficiency. It has also been found that nitrifying bacteria in sequencing batch reactor (SBR) and moving bed biofilm reactor (MMBR) processes still remain active at temperatures of 1–0.5°C (McCartney and Oleszkiewicz, 1990; Young *et al.*, 2017). Furthermore, denitrification intensity decreases rapidly at temperatures below 10°C, but the process continues at temperatures between 10 and 8°C (Carrera, Vicent and Lafuente, 2004; Vacková *et al.*, 2011). The activity of heterotrophic denitrifying bacteria is less temperature-dependent than that of nitrifying bacteria, and their activity has been confirmed at temperatures between 1 and 5°C (Elgood *et al.*, 2010). A recent study by Rodziewicz *et al.* (2020) showed that removal of total nitrogen from wastewater in a biofilter by nitrification and denitrification is possible even at 0°C.

In the light of the above reports, it can be concluded that the unfavourable thermal properties of the wastewater treated in the innovative quasi-technical test facilities – officially considered "sub-optimal" – were not a significant obstacle to achieving high removal efficiencies for all analysed pollutants (Tab. 1), especially total nitrogen, as confirmed previously by Kuczewski and Paluch (1997) and Jucherski (2000).

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

Table 1. Average removal efficiency (%) of pollutants from wastewater after treatment in sprayed beds and slope biofilters at facilities No. 1 and No. 2

Parameter	Facility No. 1		Facility No. 2	
	sprayed bed	slope biofilter	sprayed bed	slope biofilter
BOD_5	80.1	98.4	85.8	98.8
COD	72.1	93.2	85.9	96.4
NH_4-N	64.2	98.7	71.5	92.1
TN	11.6	79.4	31.8	84.3
PO_4-P	8.6	88.0	22.3	69.1
TSS	44.9	86.2	60.9	93.9

Explanations: BOD_5 = biochemical oxygen demand over five days, COD = chemical oxygen demand, TSS = total suspended solids, TN = total nitrogen.

The unfavourable values of the coefficients characterising the biodegradability of pollutants in the effluents flowing into the two slope soil-grass deposits did not significantly affect the final high quality of the treated effluents. The specific diversity of biogeochemical conditions in the biotopes of the slope soil-grass beds, where biochemical processes of mineralisation of residual organic matter, nitrification, denitrification, filtration of suspended solids, as well as processes of adsorption and chemical precipitation and immobilisation of phosphates in the soil complex take place in the rhizosphere, are conducive to achieving high final quality of wastewater treatment (Jucherski and Walczowski, 2012).

Both innovative treatment plants with sprayed and slope beds provided virtually constant high levels of treatment throughout the year of operation. The graphs show comparatively the wastewater treatment efficiency rates for the analysed pollutant components during the summer and winter seasons for both treatment plants (Fig. 6). The lack of seasonal variability in the efficiency of organic matter removal from wastewater in the

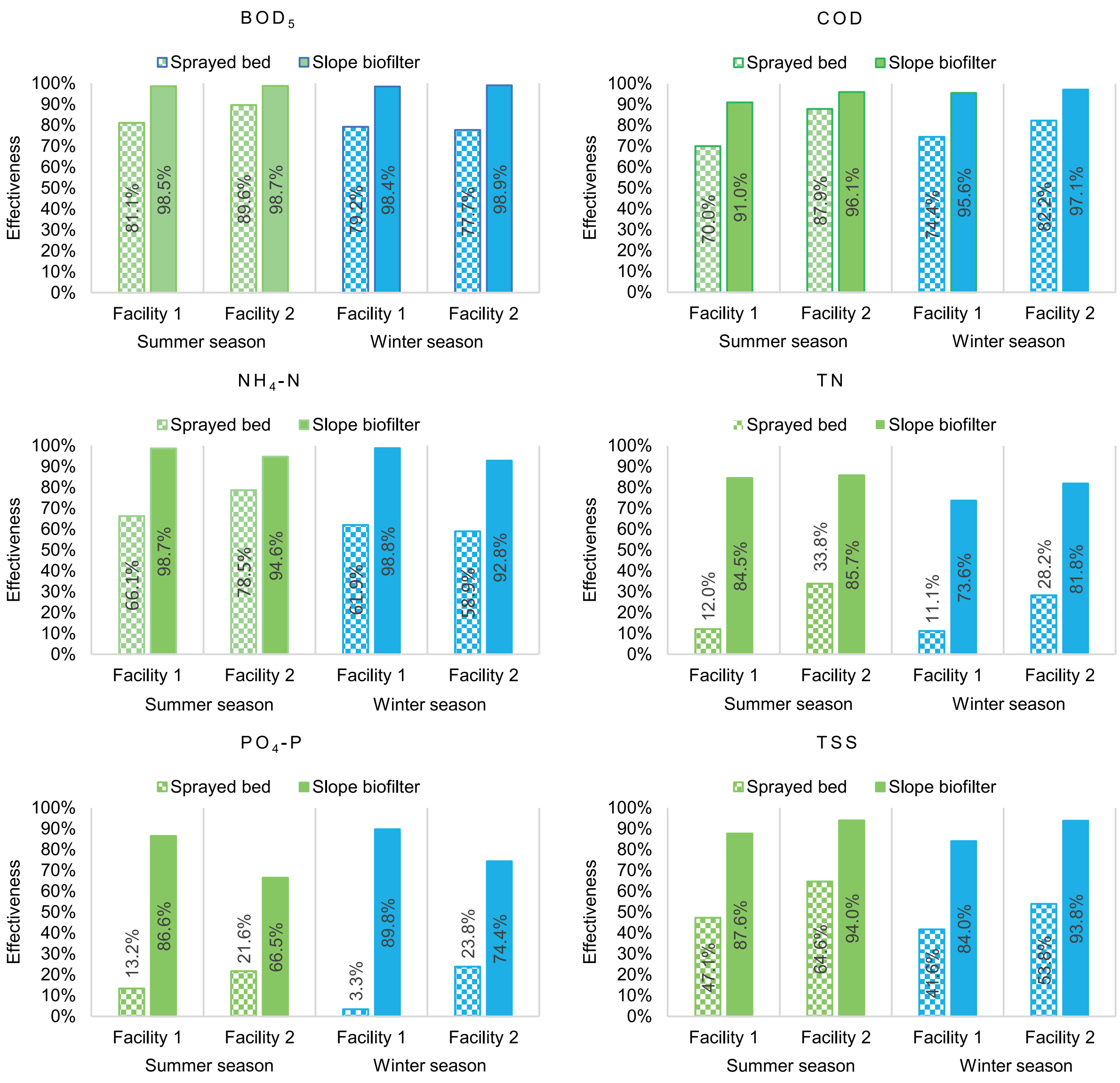

Fig. 6. Comparison of effluent treatment efficiency rates in sprayed and slope soil and grass beds at the two analysed sites during the summer and winter seasons; source: own study

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

analysed facilities is also confirmed by a study by Rodziewicz *et al.* (2020), which shows that the efficiency of carbon index reduction is highest at 25°C, while lowering the temperature to 0°C results in only a 9–16% decrease in this efficiency. Against the background of the generally very high treatment efficiency, the slight decrease in total nitrogen removal efficiency during the winter periods (by 10.9 and 3.9% at facilities No. 1 and No. 2, respectively) may have been due to a decrease in the denitrification rate in the slope-type biofilters as a result of the low organic carbon available to the denitrifying bacteria in the previously treated effluent, as well as to the higher oxygen saturation of the effluent at lower temperatures during the winter periods. To a lesser extent, this decrease in efficiency is due to the winter decrease in effluent temperature, which justifies the average level of correlation in the scatter plots between effluent temperature and total nitrogen removal efficiency in both slope-type beds (p < 0.005, r = 0.47). Together, these factors may have had a negative impact on the efficiency of simultaneous nitrification–denitrification occurring in the filtration media of slope grass-soil beds (Pochana and Keller, 1999; Jucherski, 2000). The lower overall and seasonal efficiency of phosphate removal from wastewater in the soil-grass biofilter at facility No. 2 can be explained by both the higher concentration of this constituent in the effluent flowing into this bed and by its shorter length, which results in a smaller volume of the filter filling. This is important because of the sorption and precipitation processes dominating the removal of this component from the wastewater in these beds.

In Figure S1, the probabilities of exceeding the limit values of the analysed pollutant components are shown, which were estimated on the basis of the cumulative empirical distribution curves determined using the determined sizes of the class intervals for the relative frequencies of the analysed parameters.

The graphs for BOD_5, COD and TSS (Fig. S1) show that there is no danger of exceeding the limits for these constituents (40 mg O_2·dm^{-3}, 150 mg O_2·dm^{-3} and 50 mg·dm^{-3}, respectively). There is also no risk of phosphate concentrations (4.4 mg·dm^{-3}) being exceeded at facility No. 1, while at facility No. 2, this risk is 35%. In the case of TN, the probability of exceeding the limit values of 30 mg·dm^{-3} is only 19% for facility No. 1 and 20% for facility No. 2, with practically similar very high annual average efficiencies of both sites in removing this component. It should be noted that the possible risk of exceeding the specified pollution limits at both facilities relates to wastewater with an already very high degree of treatment, which should not pose a significant risk to the receiving environment of the treated wastewater. A comparison of the seasonal (summer–winter) wastewater treatment efficiency rates in sprayed beds and slope biofilters with soil-grass beds at the two facilities analysed (Fig. 6) showed that the effect of wastewater temperature on seasonal changes in the reduction (removal) efficiency of the pollutants analysed is small or negligible, with the efficiency of these processes being very high. This can also be seen by considering the correlations between the efficiency of removal of the analysed pollutants from wastewater and the temperature of wastewater being treated (Fig. S2).

On the basis of this analysis, it can be concluded that either some of the variables being compared are not correlated at all, or the strength of some of the correlations is average, or that existing relationships, even if statistically significant, are nevertheless illogical in terms of the process. For example, with a comparably high average annual BOD_5 reduction efficiency in both sprayed beds, bed No. 1 showed no statistically significant relationship between the analysed variables, while bed No. 2 of the same type showed a statistically significant relationship (p = 0.0003, r = 0.59). Similar relationships in both sprayed beds were found for COD. In the case of the slope biofilters, the relationship between the temperature of the treated effluent and the effectiveness of BOD_5 reduction was not confirmed at either site. In contrast, when considering the highly effective reduction in COD in both slope biofilters, at facility No. 1, there was a lack of process logic in the relationship between the variables, with the conclusion that, with a statistically significant relationship, an increase in temperature causes a reduction in COD, which is difficult to explain in process terms. In contrast, no statistically significant relationship was found between the variables in the slope biofilter at facility No. 2. Similar contradictions were found in the case of NH_4-N conversion, where an inherently reasonable increase in process efficiency with increasing temperature was found in the sprayed bed of facility No. 2, while no such relationship was found in the similar sprayed bed of facility No. 1. In contrast, a complete lack of correlation between these variables was found in the slope biofilters at the two sites analysed.

Analysing the correlations between the efficiency of total nitrogen removal, TN and the temperature of the treated wastewater in the sprayed beds, a correlation was found in the sprayed bed of facility No. 2 at a medium level, while no such correlation was found in the sprayed bed of facility No. 1, with an overall equally low efficiency of these processes in both facilities. Statistically significant correlations were, however, found in the slope biofilters equally in both study sites. However, this was a correlation determined at an average level (p = 0.005, r = 0.42, after Stanisz, 2006). This indicates that the generally high level of efficiency of nitrogen removal processes in these beds is also influenced (at a fixed wastewater inflow) by other non-thermal factors, e.g. adsorption of ammonium ions in the bed matrix, uptake of nitrogenous components by plants, seasonally variable activity of bacteria involved in the removal of this nutrient (Cooper *et al.*, 1996; Jucherski, 2000).

In the case of PO_4-P removal in sprayed beds, it was found that there was practically no significant relationship between the removal efficiency of this component and temperature. The specificity of filtration in a granular filter fill in this type of bed does not favour phosphorus removal in this process. The lack of significant relationships between these variables in soil-grass biofilters can be explained by the specificity of the removal processes of these components in soil media, which include ion exchange, precipitation, sedimentation and deposition. Similar conclusions can be drawn by analysing the correlation relationships between TSS and wastewater temperature at the two analysed sites.

CONCLUSIONS

The analysed facilities, with similar configuration and specification of technological equipment, but differing in the design of the septic tanks and in the physicochemical characteristics of the treated wastewater, showed similarly very high average annual removal efficiency of all analysed pollutants, despite unfavourable biodegradability indicators and operation under specifically difficult foothill climatic conditions.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

The average annual efficiency of reduction in effluent biochemical oxygen demand over five days (BOD_5) and chemical oxygen demand (COD) indicators at both sites exceeded 90%, and total suspended solids (TSS) removal efficiency was in the range of 86.2–93.9%.

There was no risk of exceeding the limit values for BOD_5 (30 mg $O_2 \cdot dm^{-3}$), COD (150 mg $O_2 \cdot dm^{-3}$) and TSS (50 $mg \cdot dm^{-3}$).

The removal efficiencies for total nitrogen TN at the sites were 79.4% and 84.3%, respectively, and 88.0% and 69.1% for PO_4-P, respectively, with the probability of exceeding the TN limit values (30 $mg \cdot dm^{-3}$) falling within the range of 19% to 20%, and the probability of exceeding the limit values (PO_4-P = 4.4 $mg \cdot dm^{-3}$) was no greater than 35%.

The removal efficiencies of BOD_5, COD, NH_4-N and TSS were almost as high in winter periods as in summer periods. At the same time, no statistically significant relationship was found between the removal efficiency of these constituents and the temperature of the treated wastewater.

The facilities investigated are only slightly more effective in removing carbonaceous pollutants than the prefabricated activated sludge micro-treatment plant solutions known to the authors, but already significantly outperform them in terms of removal efficiency for total nitrogen, phosphate and suspended solids.

They are significantly more energy efficient. Their energy consumption does not exceed 0.25 $kWh \cdot d^{-1}$ and is almost four times lower than the energy requirements of facilities operating using activated sludge technology.

Specific slope biofilters with soil-grass beds play a key role in these processes, and only in these were statistically significant correlations found between TN removal efficiency and effluent temperature.

However, these were of moderate strength, implying that the overall high removal rates of this component in these deposits are more strongly influenced by non-thermal factors.

However, taking into account commercial considerations (reproducibility of assembly) and the ever-increasing scientific and technical development of containerised micro-treatment plants – as the authors can confirm in ongoing studies of new solutions – prefabricated small-scale sewage treatment plants may soon dominate the basic equipment of individual programmes to provide wastewater treatment capacity in rural areas.

The innovative, high-efficiency quasi-technical installations outlined here should also play an important and complementary role in this challenge, as they are particularly useful in rural areas with high natural values, especially mountainous areas, which require special protection but lack access to collective sewage systems.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_66_Jucherski.pdf.

CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

REFERENCES

Bhaskar, K.V. and Charyulu, P.B.B.N (2005) "Effect of environmental factors on nitrifying bacteria isolated from the rhizosphere of *Setaria italica* (L.) Beauv," *African Journal of Biotechnology*, 4(10), pp. 1145–1146.

Bugajski, P. *et al.* (2022) "Reliability and probability of organic and biogenic pollutants removal in a constructed wetland wastewater treatment plant in the aspect of its long-term operation," *Desalination and Water Treatment*, 278, pp. 13–22. Available at: https://doi.org/10.5004/dwt.2022.29051.

Bugajski, P., Chmielowski, K. and Kaczor, G. (2016) "Optimizing the percentage of sewage from septic tanks for stable operation of a wastewater treatment plant," *Polish Journal of Environmental Studies*, 25(4), pp. 1421–1425. Available at: https://doi.org/10.15244/pjoes/62299.

Bugajski, P., Kurek, K. and Jóźwiakowski, K. (2019) "Effect of wastewater temperature and concentration of organic compounds on the efficiency of ammonium nitrogen removal in a household treatment plant servicing a school building," *Archives of Environmental Protection*, 45(3), pp. 31–37. Available at: https://doi.org/10.24425/aep.2019.128638.

Carrera, J., Vicent, T. and Lafuente, F. (2004) "Influence of temperature on denitrification of an industrial high-strength nitrogen wastewater in a two-sludge system," *Water SA*, 29(1), pp. 11–16. Available at: https://doi.org/10.4314/wsa.v29i1.4939.

Chen, X. *et al.* (2017) "Controlling denitrification accompanied with nitrite accumulation at the sediment-water interface," *Ecological Engineering*, 100, pp. 194–198. Available at: https://doi.org/10.1016/J.ECOLENG.2016.12.019.

Cooper, P.F. *et al.* (1996) *Reed beds and constructed wetlands for wastewater treatment*. Swindon: WRc Publication.

Directive (2024) "Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment," *Official Journal*, L. http://data.europa.eu/eli/dir/2024/3019/oj (Accessed: May 11, 2025).

Dotro, G. *et al.* (2017) *Treatment Wetlands. Vol. 7. Biological Wastewater Treatment Series*. London: IWA Publishing. Available at: https://doi.org/10.2166/9781780408774.

Elgood, Z. *et al.* (2010) "Nitrate removal and greenhouse gas production in a stream-bed denitrifying bioreactor," *Ecological Engineering*, 36, pp. 1575–1580. Available at: https://doi.org/10.1016/j.ecoleng.2010.03.011.

Ferrier, D.R. and Chlubek, D. (2018) *Biochemia [Biochemistry]*, 7 edn. Wrocław: Edra Urban & Partner.

Gajewska, M., Obarska-Pempkowiak, H. and Wojciechowska, E. (2010) Hydrofitowe *oczyszczanie wód i ścieków [Hydrophyte treatment of water and sewage]*. Warszawa: Wydawnictwo Naukowe PWN.

GUS (2022) *Ochrona środowiska 2022 [Environment 2022]*. Warszawa: Główny Urząd Statystyczny. Available at: https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2022,1,23.html (Accessed: May 10, 2025).

Heidrich, Z. and Witkowski, A. (2005) *Urządzenia do oczyszczania ścieków [Sewage treatment equipment]*. Warszawa: Seidel-Przywecki.

Istenič, D. *et al.* (2023) "Challenges and perspectives of nature-based wastewater treatment and reuse in rural areas of central and Eastern Europe," *Sustainability*, 15(10), 8145. Available at: https://doi.org/10.3390/su15108145.

Jóźwiakowski, K. *et al.* (2018) "The efficiency and technological reliability of biogenic compounds removal during long-term operation of a one-stage subsurface horizontal flow constructed

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

wetland," *Separation and Purification Technology*, 202, pp. 216–226. Available at: https://doi.org/10.1016/j.seppur.2018.03.058.

Jucherski, A. (2000) "*Wpływ wybranych czynników technicznych na skuteczność oczyszczania ścieków bytowo-gospodarczych w oczyszczalniach roślinno-gruntowo-glebowych w rejonach górzystych [Influence of selected technical factors on the effectiveness of domestic wastewater treatment in vegetable-and soil type treatment plants in mountainous regions]*," *Prace Naukowe IBMER*, pp. 38–84.

Jucherski, A. and Walczowski, A. (2012) "Quasi-techniczne oczyszczalnie ścieków w ochronie zasobów wody na wiejskich terenach górzystych [Quasi-technical wastewater treatment plants in the protection of water resources in mountainous areas]," *Problemy Inżynierii Rolniczej*, 3(77), pp. 151–158.

Jucherski, A. and Walczowski, A. (2020) "Ocena funkcjonalna współczesnych rozwiązań technologicznych stosowanych w przydomowych oczyszczalniach ścieków – POŚ do 50 RLM (5 m^3/d) [Functional assessment of modern technological solutions used in household wastewater treatment plants up to 50 PE]," in M. Strzelczyk (ed.) *Przydomowe oczyszczalnie ścieków w sanitacji terenów wiejskich w Polsce. Rozwiązania techniczne, ocena funkcjonalna, oddziaływanie na środowiska [Household wastewater treatment plants in sanitation of rural areas in Poland. Technical solutions, functional assessment, environmental impact]*. Warszawa–Wrocław–Tylicz: Wydawnictwo ITP, pp. 40–84.

Jucherski, A. *et al.* (2019) "Technological reliability of domestic wastewater purification in a small sequencing batch biofilm reactor (SBBR)," *Separation and Purification Technology*, 224, pp. 340–347. Available at: https://doi.org/10.1016/j.seppur.2019.05.024.

Jucherski, A. *et al.* (2024) "Reliability of organic and biogenic pollutant removal in selected technologies used in domestic wastewater treatment plants: A comparative analysis," *Journal of Environmental Management*, 354, 120381. Available at: https://doi.org/10.1016/j.jenvman.2024.120381.

Klimiuk, E. and Łebkowska, M. (2003) Biotechnologia w *ochronie środowiska [Biotechnology in environmental protection]*. Warszawa: Wydawnictwo Naukowe PWN.

Kuczewski, K. and Paluch, J. (1997) *Oczyszczanie ścieków bytowo-gospodarczych na terenach wiejskich w oczyszczalniach roślinno-glebowych [Treatment of domestic wastewater in rural areas in plant-soil treatment plants].* Wrocław: Wydawnictwo Akademii Rolniczej we Wrocławiu.

McCartney, D.M. and Oleszkiewicz, J.A. (1990) "Carbon and nutrient removal in a sequencing batch reactor at low temperatures," *Environmental Technology*, 11(2), pp. 99–112. Available at: https://doi.org/10.1080/09593339009384844.

Młyński, D. *et al.* (2020) "Investigation of the wastewater treatment plant processes efficiency using statistical tools," *Sustainability*, 12(24), 10522. Available at: https://doi.org/10.3390/su122410522.

Operacz, A. *et al.* (2023) "Impact of climate conditions on pollutant concentrations in the effluent from a one-stage constructed wetland: A case study," *Sustainability*, 15(17), 13173. Available at: https://doi.org/10.3390/su151713173.

Paredes, D. *et al.* (2007) "New aspects of microbial nitrogen transformations in the context of wastewater treatment – A review," *Engineering in Life Sciences*, 7(1), pp. 13–25.

Pawęska, K. *et al.* (2011) "Osadnik gnilny – podstawowy element przydomowej oczyszczalni ścieków [Septic tank – basic element of household treatment plant]," *Infrastruktura i Ekologia Terenów Wiejskich*, 10, pp. 43–53.

Philip, H. *et al.* (1993) "Septic tank sludges: Accumulation rate and biochemical characteristics," *Water Science & Technology*, 28(10), pp. 57–64. Available at: https://doi.org/10.2166/wst.1993.0205.

PN-72/C-04559/02. *Woda i ścieki – Badania zawartości zawiesin – Oznaczanie zawiesin ogólnych, mineralnych i lotnych metodą wagową [Suspension content testing – Determination of total, mineral and volatile suspensions by gravimetric method].* Warszawa: Polski Komitet Normalizacyjny.

Pochana, K. and Keller, J. (1999) "Study of factors affecting simultaneous nitrification and denitrification (SND)," *Water Science & Technology*, 39(6) pp. 61–68. Available at: https://doi.org/10.1016/S0273-1223(99)00123-7.

Rodziewicz, J. *et al.* (2020) "Biofilter with innovative filling for low-temperature treatment of sewage from de-icing airport runways," *Separation and Purification Technology*, 242, 116761, pp. 1575–1580. Available at: https://doi.org/10.1016/j.seppur.2020.116761.

Rostron, W.M., Stuckey, D.C. and Young, A.A. (2001) "Nitrification of high strength ammonia wastewaters: Comparative study of immobilisation media," *Water Research*, 35(5), pp. 1169–1178. Available at: https://doi.org/10.1016/S0043-1354(00)00365-1.

Rozporządzenie (2019) "Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 12 lipca 2019 r. w sprawie substancji szczególnie szkodliwych dla środowiska wodnego oraz warunków, jakie należy spełnić przy wprowadzaniu do wód lub do ziemi ścieków, a także przy odprowadzaniu wód opadowych lub roztopowych do wód lub urządzeń wodnych [Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging sewage into waters or soil, as well as when discharging rainwater or meltwater into waters or into water devices]," *Dz. U.* 2019 poz. 1311. Available at: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20190001311 (Accessed: May 11, 2025).

Stanisz, A. (2006) *Przystępny kurs statystyki z zastosowaniem STATISTICA PL na przykładach z medycyny [An accessible course in statistics using STATISTICA PL with medical examples]*. Kraków: StatSoft Publishing.

Steinhoff-Wrześniewska, A. *et al.* (2020) "Charakterystyka technologiczno-lokalizacyjna obiektów badawczych [Technological and location characteristics of research facilities]," in M. Strzelczyk (ed.) *Przydomowe oczyszczalnie ścieków w sanitacji terenów wiejskich w Polsce. Rozwiązania techniczne, ocena funkcjonalna, oddziaływanie na środowiska [Household wastewater treatment plants in sanitation of rural areas in Poland. Technical solutions, functional assessment, environmental impact]*. Warszawa–Wrocław–Tylicz: Wydawnictwo ITP, pp. 127–134.

Vacková, L. *et al.* (2011) "Comparison of denitrification at low temperature using encapsulated Paracoccus denitrificans, Pseudomonas fluorescens and mixed culture," *Bioresource Technology*, 102(7), pp. 4661–4666. Available at: https://doi.org/10.1016/j.biortech.2011.01.024.

Young, B. *et al.* (2017) "Low temperature MBBR nitrification: microbiome analysis," *Water Research*, 111. pp. 224–233. Available at: https://doi.org/10.1016/j.watres.2016.12.050.

© 2025. The Authors. Published by Polish Academy of Sciences (PAN) and Institute of Technology and Life Sciences – National Research Institute (ITP – PIB).
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)