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Removal efficiency of selected micropollutants from municipal wastewater using disc cloth filters – a case study

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Abstract: At the municipal wastewater treatment plant in Międzyzdroje (approximately 6,000 permanent residents; ~370,000 people during the summer season), a tertiary treatment stage based on gravity filtration using disc filters (Mecana SF6/30; PES-13) was implemented between 2021 and 2023. Despite a twofold increase in influent flow during the summer of 2024, the quality parameters of the treated wastewater (TSS, BOD5, COD, TN, and TP) remained well below the limits specified in the water permit. The filtration process effectively stabilized effluent quality under conditions of increased seasonal load. However, only limited removal of selected pharmaceuticals was observed: 7-17% (metoprolol 7%, candesartan 17%, irbesartan 5%, venlafaxine 14%, citalopram 10%, amisulpride 14%) and 33% for clarithromycin. No removal was observed for hydrochlorothiazide, carbamazepine, or diclofenac. Benzotriazole concentrations decreased by only 3%. All 24 PFAS compounds were below the limit of quantification (LOQ), and the ∑16 PAHs concentration was <0.21 Σg/L. These results confirm that effective reduction of micropollutant emissions requires the implementation of a quaternary treatment stage (e.g., advanced oxidation processes, adsorption, or membrane technologies).

Introduction

Increasing requirements for water protection and the implementation of circular economy principles mean that treated municipal wastewater is increasingly perceived not as waste, but as a potential source of water for reuse. Of particular importance is the stability of treated effluent quality, especially in the context of limiting emissions of suspended solids, nutrients, and organic micropollutants to receiving waters and reuse schemes. In response to these challenges, tertiary treatment comprising filtration and disinfection has become increasingly common at European wastewater treatment plants, while, in a longer-term perspective, quaternary technologies targeting micropollutant removal are being implemented (European Parliament and Council of the European Union 2020; Szymański 2024).

The new Directive (EU) 2024/3019 on urban wastewater treatment and Regulation (EU) 2020/741 on minimum requirements for water reuse clearly indicate the need to improve wastewater treatment plant effluent quality, including the reduction in pharmaceutical emissions and perfluoroalkyl and polyfluoroalkyl substances (PFAS) (European Parliament and Council of the European Union 2024; European Parliament and Council of the European Union 2020). These documents also emphasize the monitoring of representative micropollutants in wastewater treatment plant influents and effluents, as well as the gradual implementation of technological solutions tailored to plant size and catchment characteristics.

A particular operational challenge is posed by wastewater treatment plants located in tourist areas, which are characterized by strong inflow seasonality and rapid variations in hydraulic and mass loading. In such facilities, short-term overloads may lead to deterioration of effluent quality after biological treatment, even when activated sludge reactors are properly designed and operated. Full-scale studies have shown that maintaining an appropriate aerobic and anoxic balance is critical for stable nitrogen removal. However, under highly variable inflows, the biological process often requires support from additional polishing steps (Maciołek et al. 2021; Włodarczyk-Makuła and Kamizela 2024).

One tertiary treatment solution is cloth media disc filtration, which is designed for the final filtration of biologically treated wastewater. These filters operate under gravity and use a multi-disc configuration with filtration media of nominal pore size on the order of 10 micrometers, enabling effective reduction of total suspended solids and total phosphorus. A characteristic feature of this technology is automatic media regeneration

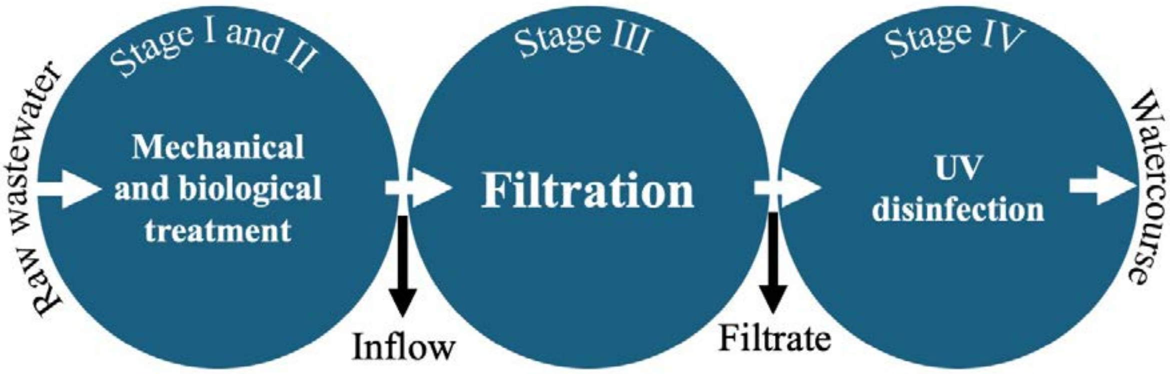

Fig 1. Simplified technological scheme of the municipal WWTP in Międzyzdroje with sampling locations indicated (inflow and filtrate)

achieved by slow disc rotation and localized sludge suction without interrupting filtration, which supports stable hydraulic performance and effluent quality (Operating and maintenance manual for disk filter SF6/30: third-stage filtration; Mecana AG 2024).

Operational experience indicates that disc filters are particularly useful at facilities with variable hydraulic loading, where they act as a quality buffer and reduce short-term deterioration of treated wastewater parameters (Szymański 2024). At the same time, it should be emphasized that disc filtration with cloth media is a mechanical process primarily targeting particulate removal. Its impact on dissolved organic micropollutants, such as pharmaceuticals or benzotriazole, is inherently limited and results mainly from sorption onto solids and indirect retention of fine particulate matter (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020).

The literature extensively documents the effectiveness of quaternary technologies, such as advanced oxidation processes, activated carbon adsorption, and membrane processes in removing pharmaceuticals and PFAS (Evich et al. 2022; Gupta et al. 2024). Considerably less attention has been paid to the actual full-scale impact of disc filtration on the concentrations of selected micropollutants, especially at small and medium-sized municipal wastewater treatment plants with pronounced seasonal variability.

In this context, case studies are valuable for determining to what extent tertiary treatment based on disc filters can not only stabilize basic effluent quality parameters, such as total suspended solids, biochemical oxygen demand, chemical oxygen demand, nitrogen, and phosphorus, but also, to a limited extent, contribute to the reduction of selected pharmaceutical micropollutants and other indicator substances (Łuczkiewicz et al. 2021; Rosik-Dulewska 2023).

The aim of this study was to assess the efficiency of gravity filtration using Mecana SF6/30 disc cloth filters in the removal of selected micropollutants (pharmaceuticals, PFAS, PAHs, and benzotriazole) from municipal wastewater under seasonally variable inflow conditions in 2024. In addition, the study evaluated the limitations of this technology in the context of the need to implement quaternary treatment processes, in accordance with the new requirements of Directive (EU) 2024/3019 of the European Parliament and of the Council.

Materials and methods

The WWTP characteristics

The research was carried out at a WWTP located in the seaside town of Międzyzdroje. Prior to modernization, the plant had an average daily capacity of 4,000 m^3/d and a maximum daily capacity of 7,000 m^3/d, corresponding to 25,160 PE. Following modernization, the facility operates in a conventional municipal configuration, including mechanical and biological treatment based on activated sludge with enhanced biological nutrient removal (EBNR) (Figure 1). The upgraded plant achieves an average daily capacity of 6,000 m^3/d and a maximum daily capacity of 13,800 m^3/d, corresponding to 53,883 PE. As a result of the modernization, stable treated effluent quality has been ensured, as evidenced by consistent values of key operational parameters.

According to data from the Central Statistical Office of Poland, the town has a permanent population of approximately 6,000 inhabitants. However, during the summer season (July-August 2024), the temporary population increases by up to 60-fold, reaching nearly 370,000 tourists. Table 1 presents the conditions of the water permit applicable to the facility, specifying the permissible values of quality indicators for treated municipal wastewater.

The modernized wastewater treatment system was equipped with an advanced final filtration unit forming part of the tertiary treatment stage. The system employs SF6/30-type disc cloth filters manufactured by Mecana AG (Figure 2),

Table 1. Regulatory limits for treated wastewater (WWTP water permit)

Parameter	pH	COD	BOD_5	TN	TP	TSS
Unit	-	mg O_2/L		mg/L		
Permissible Value	6.5-9	125	15	15	2	35

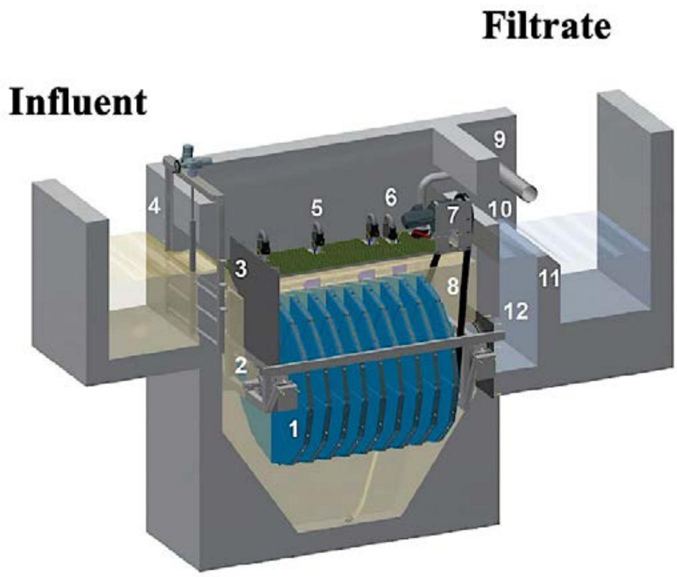

Fig 2. Disc filter type SF (Mecana AG): 1 – disc with filter cloth; 2 – suction head and edge; 3 – partition wall; 4 – wastewater inlet channel; 5 – filter cloth cleaning pump; 6 – sludge pump; 7 – drive motor; 8 – drive chain; 9 – backwash and sludge return pipeline; 10 – safety overflow; 11 – filtrate outlet channel; 12 – rising shaft (Mecana AG, 2024)

consisting of six discs with a diameter of 2.1 m and an individual filtration area of 5 m², providing a total filtration surface of 60 m².

In the gravity filtration process (Piekarski 2019), the solid phase of the suspension is retained on the surface of the filter cloth (1). The resulting filtrate is conveyed through a central conduit into the rising chamber, then toward the overflow weir and the discharge channel (11). As the clogging process progresses, hydraulic resistance increases, leading to a gradual rise in the wastewater level in the tank (4). When the wastewater level reaches a threshold approximately 25 - 35 cm above the minimum level, the control system activates the filter cloth regeneration cycle. The drive motor (7) induces slow rotational movement of the filter discs (1) at a speed of 1 - 2 min^{-1}, while the pump (5), through suction heads positioned adjacent to the cloth surface, removes the deposited sludge layer. The removed sludge is directed to the primary sedimentation tank or another preliminary treatment stage. Upon completion of the backwashing cycle, the hydraulic resistance of the filter cloth decreases, resulting in the reduction of the wastewater level in the tank (4) . Consequently, the filtration flow returns to its maximum value at the minimum wastewater level.

The filters are equipped with a polyester fiber filter cloth (OptiFiber® Pile Cloth Media Filter) of the PES-13 type, with fiber lengths ranging from approximately 3 mm in the dry state to approximately 5 mm when wet. The applied material belongs to the group of standard PES-13 filter fabrics with a nominal pore size of approximately 10 µm, enabling the reduction of total suspended solids (TSS) to the level of 5 - 10 mg/L and total phosphorus (TP) concentration to below 0.5 mg/L. The manufacturer also offers specialized filter media designed for advanced tertiary polishing of wastewater, enabling the removal of microplastics, activated carbon, and microorganisms (Disc Filter Operation and Maintenance Manual, 2022). According to the manufacturer's data, energy consumption of the filtration process is below 5 Wh/m³ of treated wastewater. For comparison, the total energy demand of modern WWTPs typically ranges from 0.3 to 0.8 kWh/m³, with more than half attributed to aerobic processes associated with activated sludge aeration.

Laboratory Analyses

Analyses of basic physicochemical parameters, including pH, total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP), were carried out in 2024 by the accredited research laboratory of J.S. Hamilton Ltd. in Gdynia.

Micropollutant analysis was based on a single sampling campaign conducted on 19 August 2024, primarily due to the high analytical costs. Wastewater samples were collected as grab samples at the inlet to the disc filter, following primary and secondary treatment, and at the corresponding outlet. Sampling was performed during the peak tourist season, when the wastewater treatment plant operated near its maximum seasonal hydraulic load of 5,189 m³/d, corresponding to approximately 96 % of the maximum average daily flow recorded in 2024. The collected samples therefore represent peak-load operating conditions. However, it should be noted that a single grab sample does not capture daily or seasonal variability in micropollutant concentrations. Therefore, future studies should include repeated seasonal sampling campaigns and 24-hour flow-proportional composite sampling in order to improve representativeness and support uncertainty analysis.

The analyses were carried out by the accredited laboratory of Eurofins OBiKŚ Polska Ltd. in Katowice, which subcontracted part of the determinations to Eurofins Analytical Services Hungary Kft, Eurofins Umwelt West GmbH (Wesseling), and other laboratories within the Eurofins Group. In accordance with the Directive's guidelines, concentrations of ten pharmaceuticals were determined: carbamazepine (CBZ), clarithromycin CLA), diclofenac (DIC), hydrochlorothiazide (HCTZ), metoprolol (MET), venlafaxine (VEN), irbesartan (IRB), amisulpride (AMI), citalopram (CIT), and candesartan (CAN), as well as benzotriazole (BTA). Pharmaceutical compounds were quantified using standardized methods DIN EN ISO 21676:2022-01 and DIN 38407-F36:2014-09 by high-performance liquid chromatography coupled with tandem mass spectrometry (HPLC-MS/MS) following direct injection (LOQ values are provided in Table 2).

Among the compounds classified as PFAS, twelve perfluoroalkyl carboxylic acids (PFCAs) were analyzed. These substances possess fully fluorinated carbon chains terminated with a carboxyl group (-COOH). Short-chain compounds (C4-C6) included perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), and perfluorohexanoic acid (PFHxA). Medium-chain compounds (C7-C9) comprised perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), and perfluorononanoic acid (PFNA). Long-chain compounds (C10 and above) included perfluorodecanoic acid (PFDeA), perfluoroundecanoic acid (PFUnA), perfluorododecanoic acid (PFDoA), perfluorotridecanoic acid

(PFTrA), perfluorotetradecanoic acid (PFTA), and perfluoro-3,7-dimethyloctanoic acid (PF-3,7-DMOA).

Six perfluoroalkyl sulfonic acids (PFSAs), characterized by fully fluorinated carbon chains terminated with a sulfonic group (-SO_3H) were also determined. Short-chain compounds included perfluorobutanesulfonic acid (PFBS), perfluoropentanesulfonic acid (PFPeS), and perfluorohexanesulfonic acid (PFHxS). Longer-chain compounds comprised perfluoroheptanesulfonic acid (PFHpS), perfluorooctanesulfonic acid (PFOS), and perfluorodecanesulfonic acid (PFDS).

Additionally, three fluorotelomer sulfonic acids (FTS) were analyzed. These are partially fluorinated compounds containing a characteristic -CH_2CH_2- segment. This group included 4:2 fluorotelomer sulfonic acid (4:2 FTS), 6:2 fluorotelomer sulfonic acid (6:2 FTS), and 8:2 fluorotelomer sulfonic acid (8:2 FTS). PFAS concentrations were measured using standardized method DIN 38407-42 (F42):2011-03 by HPLC-MS/MS following solid-phase extraction (SPE) (LOQ <0.01 µg/L) (Baabish et al. 2021).

In addition, sixteen polycyclic aromatic hydrocarbons (PAHs) were analyzed, including naphthalene (NAP), acenaphthylene (ACY), acenaphthene (ACE), fluorene (FLU), phenanthrene (PHE), anthracene (ANT), fluoranthene (FLA), pyrene (PYR), benzo(a)anthracene (BaA), chrysene (CHR), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), benzo(a)pyrene (BaP), indeno(1,2,3-cd)pyrene (IcdP), dibenzo(a,h)anthracene (DahA), and benzo(g,h,i)perylene (BghiP). PAHs were determined by gas chromatography–mass spectrometry (GC-MS) (LOQ >0.21 µg/L).

Results and Discussion

Figure 3 and Figure 4 present the variation of the daily average hydraulic load and selected pollutant indicators in treated municipal wastewater in Międzyzdroje during 2024.

The study demonstrated that despite a more than twofold increase in the average daily hydraulic load from 2,625 m^3/d in January to 5,385 m^3/d in August, followed by a decrease to 2,400 m^3/d in December (Figure 3), the WWTP in Międzyzdroje maintained stable and highly efficient operation (Figure 4). This performance was attributed to modernization works carried out in recent years. The average daily hydraulic load on the sampling days remained within the standard deviation range.

Based on the obtained results (Figure 4), it can be concluded that, despite considerable variation in hydraulic loading throughout the year, the pH of the treated wastewater did not exceed the permissible limits (6.5-9.0) and remained

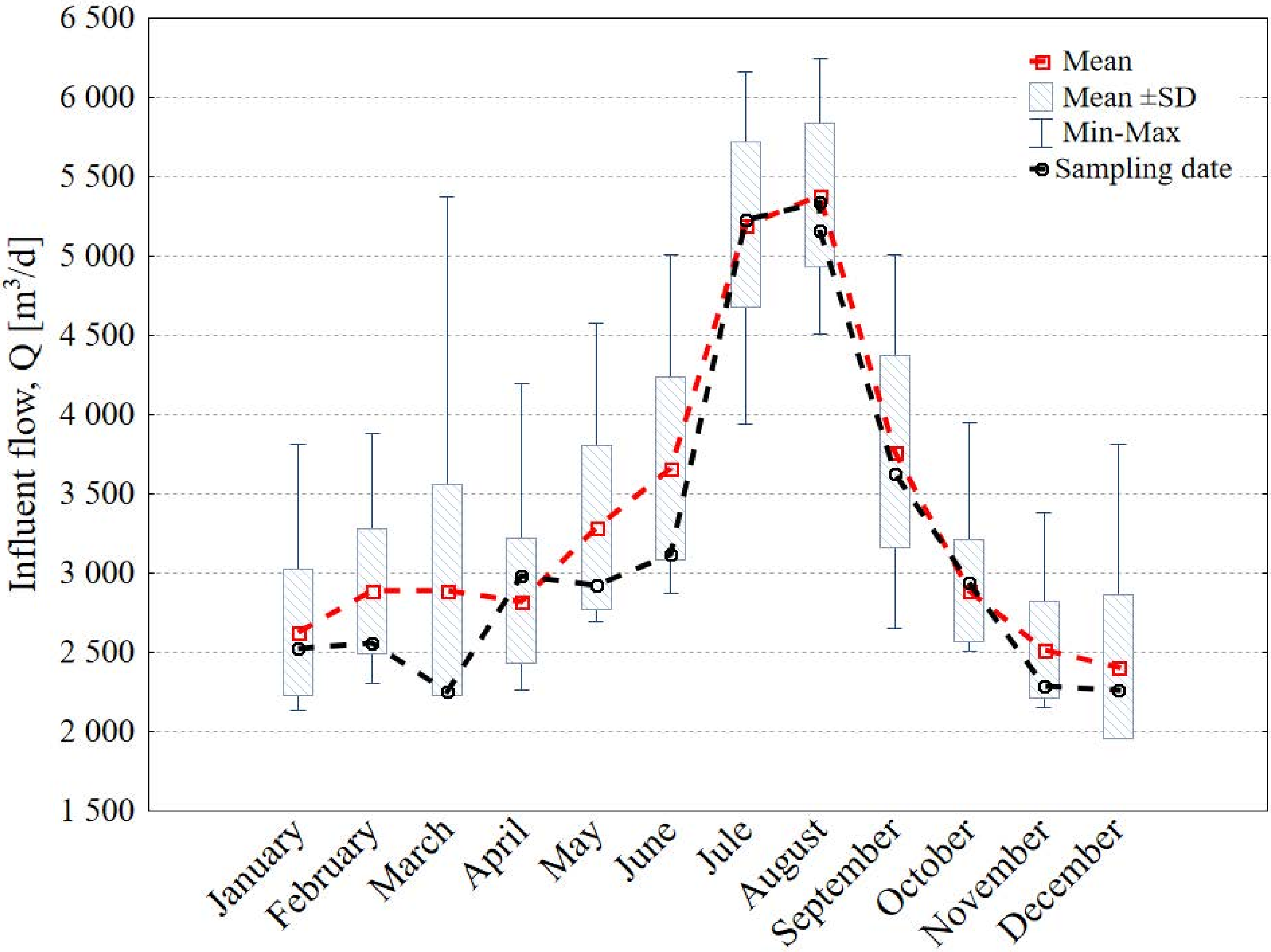

Fig 3. Average daily influent flow at the WWTP in 2024

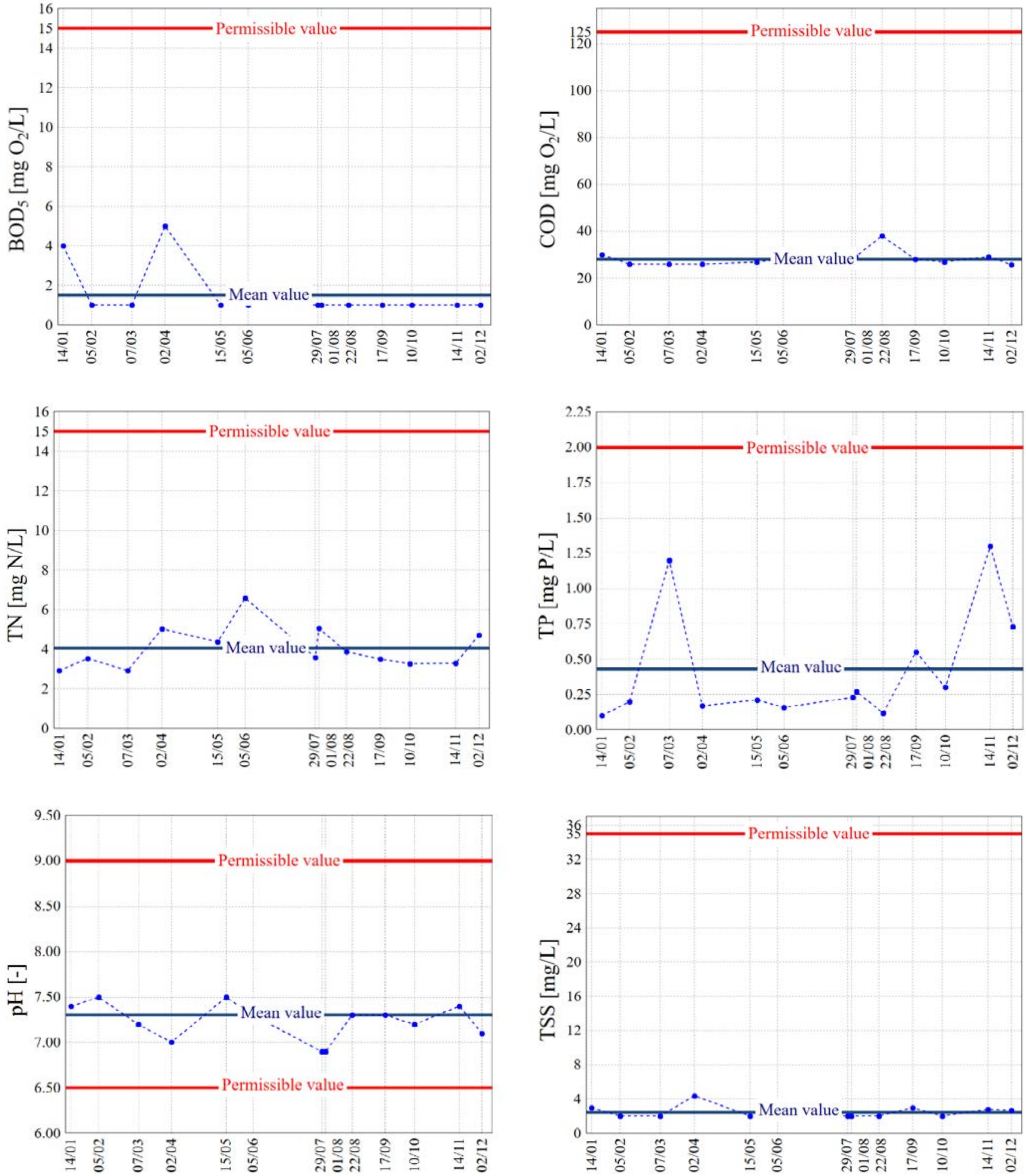

Fig 4. Annual variation in selected municipal wastewater quality indicators in Międzyzdroje (2024)

within a safe range of 6.9–7.5, thereby ensuring stable conditions for biological processes. The total suspended solids (TSS) concentration varied between 2.0 and 4.4 mg/L (mean 2.45 mg/L), representing only 7% of the permissible value. A minor increase observed in May may have resulted from temporary flow fluctuations or filter backwashing, but it did not affect the overall effluent quality. The biochemical oxygen demand (BOD_5) remained very low (1–5 mg O_2/L, mean 1.5 mg O_2/L), approximately 90% below the permissible limit of 15 mg O_2/L (Table 1). A single, slight increase in May had no effect on the stability of the biological treatment process. The chemical oxygen demand (COD) ranged between 26

Table 2. Concentrations of pharmaceuticals and benzotriazole in wastewater prior to the SF6/30 filter

Pharmaceutical Group	Active Compound	Influent Wastewater	LOQ
		mg/L	
Cardiovascular drugs	MET	1.40	0.010
	CAN	1.20	0.025
	IRB	0.19	0.050
	HCTZ	3.00	0.100
Neuroactive (psychotropic) drugs	CBZ	1.50	0.010
	VEN	1.40	0.010
	AMI	0.50	0.025
	CIT	0.10	0.025
Anti-inflammatory and analgesic drugs	DIC	3.50	0.100
Antibiotic	CLA	0.09	0.010
Other micropollutants	BTA	0.32	0.050

and 38 mg O_2/L, with a mean of 28 mg O_2/L, corresponding to about 22% of the allowable value. A small rise noted in June-July was likely related to a higher organic load during the tourist season. For total phosphorus (TP), concentrations ranged from 0.1 to 1.3 mg P/L (mean 0.43 mg P/L), representing approximately 22% of the permissible threshold. Two local peaks (in May and December) may have been caused by changes in coagulant dosing or temporary fluctuations in influent composition. The total nitrogen (TN) concentration ranged from 2.92 to 6.59 mg N/L (mean 4.05 mg N/L), accounting for approximately 27% of the permissible value. Minor variations during the summer months were likely due to temperature differences and increased ammonium nitrogen load in the influent. Consistent with Maciołek et al. (2021), maintaining an appropriate aerobic and anoxic balance proved critical for effective nitrogen removal. Comparable stability of nitrogen removal under variable hydraulic loading was also reported by Włodarczyk-Makuła and Kamizela (2024), who emphasized the role of process configuration and temperature conditions. Similar conclusions were drawn by Szymański et al. (2022), who demonstrated that maintaining appropriate redox conditions significantly improves nitrification and denitrification efficiency in municipal wastewater treatment plants.

Pharmaceutical Micropollutants

On the day of sampling for micropollutant analysis (19 August 2024), the WWTP received 5,189 m^3 of influent, which falls within the standard deviation range (Figure 3) and represents approximately 96% of the maximum average daily hydraulic load. Therefore, the collected sample can be considered representative of conditions typical for the peak summer season with the highest wastewater inflow.

Table 2 presents the concentrations of selected pharmaceutical compounds in municipal wastewater after the primary and secondary treatment stages. The dataset includes commonly used pharmaceuticals not only drugs acting on the cardiovascular system, anti-inflammatory and analgesic agents, and an antibiotic, but also a widely used stabilizing compound frequently applied in pharmacotherapy.

Cardiovascular drugs are among the most frequently detected micropollutants in effluents from municipal wastewater treatment plants, due to their widespread use and limited removal in conventional biological treatment processes (Verlicchi and Zambello 2020; Łuczkiewicz et al. 2021). Numerous studies have shown that β-blockers, including metoprolol (MET), exhibit low biodegradability and poor removal efficiency in activated sludge systems. Verlicchi and Zambello (2020) reported that average metoprolol removal in full-scale European wastewater treatment plants was only 10 to 20%, which is consistent with results from Poland, where Łuczkiewicz et al. (2021) reported elimination efficiencies of 12 to 16% even under advanced biological configurations. Monitoring studies conducted by the U.S. Environmental Protection Agency demonstrated the presence of metoprolol in more than 90 percent of treated wastewater samples collected from 50 large wastewater treatment plants in the United States, with concentrations ranging from 0.66 ng/L to 8.04 µg/L (U.S. EPA 2023). Comparable effluent concentrations have been reported in southern Europe; for example, municipal wastewater treatment plants in Almería, Spain, recorded effluent levels of up to 1.3 µg/L, while facilities in Poland showed concentrations in the range of 0.67 to 1.21 µg/L (Verlicchi and Zambello 2020; Łuczkiewicz et al. 2021).

The limited removal of metoprolol is attributed to its high polarity, low sorption affinity for activated sludge, and resistance to microbial degradation (Verlicchi and Zambello 2020). Some authors further indicate that the presence of β-blockers in wastewater may adversely affect nitrifying bacteria by inducing oxidative stress and disrupting nitrogen metabolism, which may lead to reduced nitrification efficiency under elevated pharmaceutical loads (Gupta et al. 2024; Piaskowski 2024).

The present results confirm that conventional and tertiary treatment steps, including filtration-based polishing, are

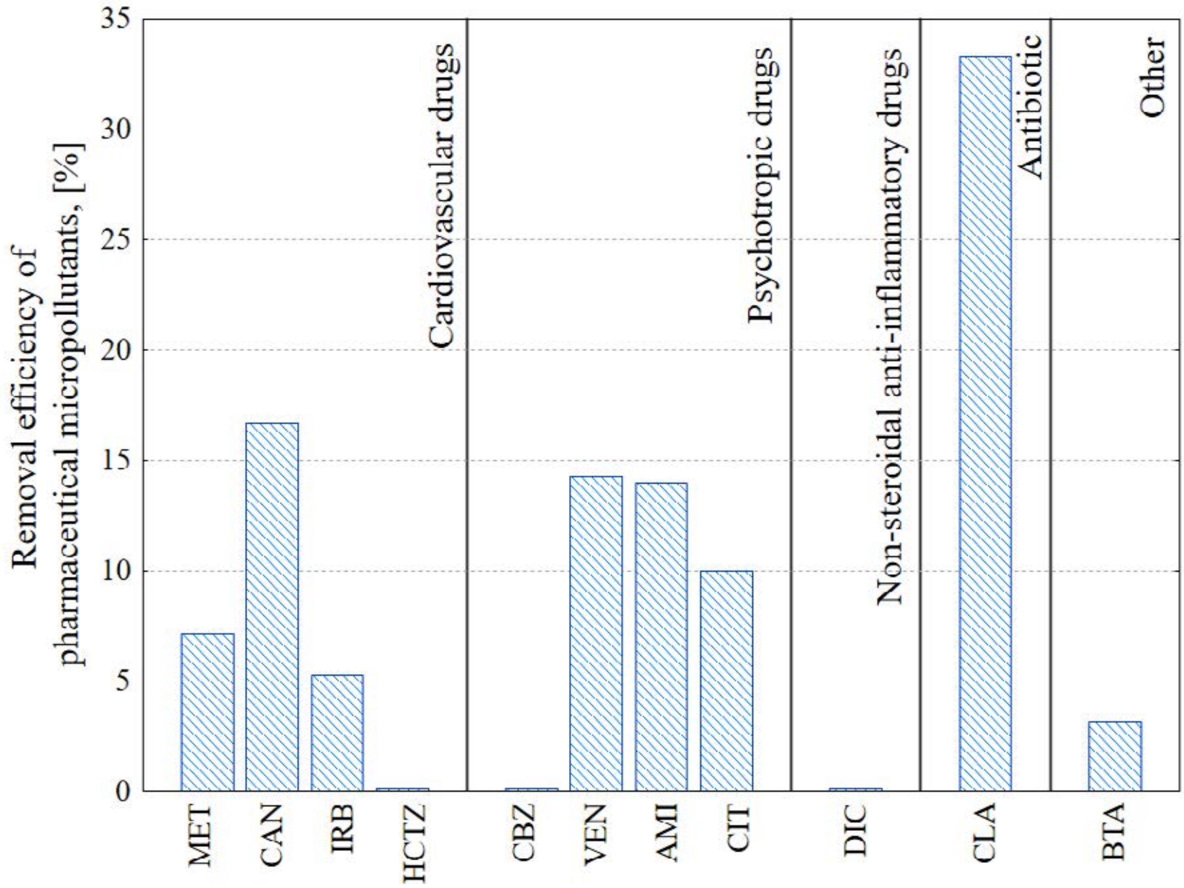

Fig 5. Removal of selected pharmaceutical micropollutants during gravity filtration using an SF6/30 disc filter

insufficient for effective metoprolol removal. Significant reduction can only be achieved through the application of quaternary treatment technologies, such as advanced oxidation processes, activated carbon adsorption, or membrane separation (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020). Furthermore, the application of gravity filtration as a tertiary treatment stage resulted in only a minor reduction (approximately 7%) in metoprolol concentration, reaching a final level of 1.3 µg/L in the effluent (Figure 5).

Angiotensin II receptor blockers, including candesartan (CAN) and irbesartan (IRB), are widely used antihypertensive drugs and are frequently detected in municipal wastewater due to their high consumption and limited metabolism in the human body. Available studies indicate that ARBs are excreted largely unchanged and exhibit low to moderate biodegradability under conventional activated sludge conditions. Monitoring studies conducted in Germany and Denmark reported effluent concentrations of up to 1.7 µg/L for candesartan and 0.6 µg/L for irbesartan, with removal efficiencies typically not exceeding 30 percent (Verlicchi and Zambello 2020). Similar results have been reported in Poland, where ARBs were identified in municipal wastewater effluents at concentrations ranging from several hundred nanograms per liter to more than 1 µg/L (Łuczkiewicz et al. 2021). The limited removal of ARBs is attributed to their hydrophilic character, low sorption affinity for activated sludge flocs, and resistance to microbial degradation (Kasprzyk-Hordern et al. 2009). Consequently, effective reduction of ARBs generally requires the application of quaternary treatment technologies such as ozonation, activated carbon adsorption, or membrane processes (Verlicchi and Zambello 2020). Results of the present study demonstrated that the application of gravity filtration as a tertiary treatment stage enabled a reduction of candesartan concentration by 17% (to 1.0 µg/L) and irbesartan concentration by 5% (to 0.18 µg/L) (Figure 5).

Among antihypertensive drugs, diuretics, particularly thiazide diuretics such as hydrochlorothiazide (HCTZ), are the most frequently used. This compound is poorly biodegradable and is only partially removed from municipal wastewater through adsorption onto activated sludge. Effective degradation of HCTZ can be achieved primarily through advanced oxidation processes (AOPs); however, some of the resulting degradation by-products are also toxic to aquatic organisms. In studies conducted by the U.S. Environmental Protection Agency (EPA) across 50 large WWTPs, HCTZ was detected in 100% of treated wastewater samples, with an average concentration of 1.1 µg/L (U.S. EPA 2023). In Ireland, during annual monitoring of two WWTPs, mean effluent concentrations of 0.44 ±0.25 µg/L and 0.55 ±0.10 µg/L were reported. In the Netherlands, the average effluent concentration of HCTZ reached 1.27 ±0.26 µg/L (Verlicchi and Zambello, 2020). In the present study conducted at the Międzyzdroje WWTP, the HCTZ concentration after gravity filtration was 3.0 µg/L. The use of the Mecana SF6/30 disc filter with OptiFiber® PES-13 fabric medium did not result in any measurable reduction of this compound.

Another group of four indicator pharmaceuticals includes drugs affecting the nervous system, particularly antiepileptic agents whose active compound is carbamazepine (CBZ), commercially available under trade names such as *Tegretol*, *Amizepin*, *Neurotop*, and *Finlepsin*. CBZ exhibits anticonvulsant and mood-stabilizing properties, being commonly prescribed for epilepsy and bipolar disorder. It is characterized by hydrophobicity, low biodegradability, and high environmental persistence, and is therefore classified as a persistent pharmaceutical pollutant. CBZ enters the environment mainly through municipal and hospital effluents as well as leachates from landfills. It is toxic to aquatic organisms, affecting hormonal and enzymatic functions, and can disrupt the biological balance of activated sludge. Its removal typically requires advanced oxidation processes (AOPs), adsorption on activated carbon, or membrane separation techniques such as nanofiltration and reverse osmosis. In studies conducted in the United Kingdom, CBZ was detected in effluents from three WWTPs at concentrations up to 1.6 µg/L (Zhou et al., 2009). CBZ is also widely detected across Europe in treated wastewater, with reported mean concentrations in the range of 0.1 to 1.0 µg/L (Zhou et al. 2009; Verlicchi and Zambello 2020). In Poland, studies conducted at wastewater treatment plants in Kraków reported CBZ concentrations in effluents of up to 1.0 µg/L, with removal efficiencies ranging from 17 to 79%, depending on operating conditions (Łuczkiewicz et al. 2021). The present study demonstrated that gravity filtration using OptiFiber® PES-13 fabric was ineffective in CBZ removal (Figure 5). The CBZ concentration in the treated effluent reached 1.5 µg/L.

Neuroactive pharmaceuticals, particularly selective serotonin reuptake inhibitors (SSRIs) such as citalopram (CIT) and serotonin–norepinephrine reuptake inhibitors (SNRIs) such as venlafaxine (VEN), are persistent micropollutants commonly detected in treated municipal wastewater (Verlicchi and Zambello 2020). Studies conducted in Europe and North America have demonstrated limited removal of these compounds in conventional wastewater treatment processes, with reported elimination efficiencies typically below 20% (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020). Effluent concentrations of venlafaxine and citalopram of up to 1.2 µg/L and 0.4 µg/L, respectively, have been reported in Spain, Canada, and Scandinavian countries (Vieno et al. 2007; Verlicchi and Zambello 2020). Studies carried out in Poland have also confirmed the presence of these substances in effluents from large urban agglomerations, with concentrations ranging from several tens to several hundreds of nanograms per liter (Łuczkiewicz et al. 2021). SSRIs and SNRIs may inhibit the activity of activated sludge microorganisms and adversely affect nitrification processes by inducing oxidative stress in nitrifying bacteria (Gupta et al. 2024). Consequently, advanced treatment technologies are required for their effective removal (Kasprzyk-Hordern et al. 2009). In the present study, gravity filtration reduced the VEN concentration by approximately 14% (to 1.2 µg/L) and CIT concentration by 10% (to 0.09 µg/L) (Figure 5).

A representative compound among persistent pharmaceutical contaminants is amisulpride (AMI), a benzamide-based atypical antipsychotic drug (commercially available as *Solian*, *Amizepin A*, and *Amisulpirid Teva*), prescribed for the treatment of schizophrenia and psychotic disorders. AMI is excreted from the human body largely unchanged (80–90%). In aquatic environments, it may interfere with the dopaminergic system and adversely affect microbial activity in activated sludge by inhibiting the growth of nitrifying and denitrifying bacteria. Due to its high solubility and low biodegradability, AMI is poorly removed in conventional WWTPs. Effective degradation can only be achieved through advanced oxidation processes (AOPs). Studies conducted in France and Germany detected AMI in treated wastewater at concentrations up to 0.8 µg/L, with its presence confirmed in over 70% of analyzed samples (Vieno, Tuhkanen & Kronberg, 2007). Studies conducted in Spain reported lower AMI concentrations in treated wastewater, ranging from 0.05 to 0.3 µg/L, depending on location and the applied treatment technology (Kasprzyk-Hordern et al. 2009). In Poland, AMI has been identified in municipal wastewater effluents in multiple monitoring studies at concentrations on the order of several hundred nanograms per liter, confirming its persistence and limited removal in biological treatment processes (Kasprzyk-Hordern et al. 2009; Łuczkiewicz et al. 2021; Rosińska 2022; Piaskowski 2024). In the present study, gravity filtration achieved a 14% reduction in AMI concentration, lowering it to 0.43 µg/L (Figure 5), confirming its persistence and limited removability by conventional treatment processes.

Among indicator pharmaceuticals, diclofenac (DIC) is a widely used nonsteroidal anti-inflammatory drug (NSAID) with analgesic and antipyretic effects. Since 2013, diclofenac has been included on the European Union list of priority substances requiring environmental monitoring in aquatic ecosystems (Verlicchi and Zambello 2020). DIC is excreted both unchanged and in the form of metabolites and exhibits high resistance to removal in conventional primary and secondary wastewater treatment processes (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020). Effective degradation of diclofenac generally requires advanced treatment methods such as ozonation or other oxidation processes, adsorption, or membrane filtration. However, the resulting transformation products may also be persistent and toxic to aquatic organisms (Kasprzyk-Hordern et al. 2009). As noted by Piaskowski (2024), even low pharmaceutical concentrations in wastewater can alter the structure and settling properties of activated sludge, resulting in a deterioration of its technological performance. DIC inhibits enzymatic activity of microorganisms in activated sludge and exhibits toxicity toward fish and aquatic invertebrates, causing hormonal disruptions, oxidative stress, and damage to cellular membranes and DNA. In avian species, diclofenac exposure has been linked to renal failure (gout). A well-documented case occurred in India, where widespread mortality of vultures was observed following scavenging of livestock carcasses treated with DIC. In Germany and Spain, DIC concentrations in wastewater treatment plant effluents have been reported to reach up to 1.2 µg/L, with detection frequencies exceeding 90% (Verlicchi and Zambello 2020). Similar concentration ranges, from 0.2 to 1.0 µg/L, have been reported in Finland and Sweden (Zhou et al. 2009; Verlicchi and Zambello 2020). In Poland, DIC is among the most frequently identified pharmaceuticals in treated municipal wastewater, with reported concentrations reaching up to 3.7 µg/L (Łuczkiewicz et al. 2021; Rosińska 2022; Piaskowski 2024). In the present study, gravity filtration was found to be ineffective for diclofenac removal, as the concentration in the filtrate remained 3.5 µg/L.

Among the indicator pharmaceuticals, clarithromycin (CLA) is one of the most widely used antibiotics and is a macrolide derived from erythromycin (Verlicchi and Zambello 2020). It is frequently detected in wastewater and surface waters (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020). CLA is excreted partly unchanged, in the range of 40 to 70%, and partly as an active metabolite, and it is persistent and poorly biodegradable in aquatic environments (Kasprzyk-Hordern et al. 2009). In aquatic organisms, CLA induces oxidative stress and disrupts developmental and metabolic processes, contributes to the development of antibiotic resistance, and may reduce nitrification and denitrification efficiency at wastewater treatment plants (Kasprzyk-Hordern et al. 2009; Gupta et al. 2024). Studies conducted in Spain and Italy reported CLA concentrations in municipal wastewater effluents of up to 1.4 μg/L, with detection frequencies exceeding 80% (Verlicchi and Zambello 2020). Similar concentration ranges, from 0.1 to 1.0 μg/L, were reported in Scandinavian countries and Germany (Vieno et al. 2007; Verlicchi and Zambello 2020). In Poland, clarithromycin concentrations in treated municipal wastewater typically range from several tens to several hundreds of nanograms per liter, occasionally exceeding 1 μg/L (Łuczkiewicz et al. 2021). In the present study, gravity filtration reduced the concentration of clarithromycin by 33%, reaching a final concentration of 0.06 μg/L in the filtrate (Figure 5).

It should be noted that comparing pharmaceutical concentrations reported by different authors is challenging, as wastewater composition strongly depends on local conditions, the share of industrial inputs, and the applied treatment technologies (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020). Additional variability in micropollutant concentrations arises from factors such as wastewater treatment plant location, land use characteristics within the catchment, and the presence of inflows from hospitals, healthcare facilities, or veterinary units (Gupta et al. 2024; Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020).

The final indicator substance in this group is benzotriazole (BTA), which has a very broad range of applications. It is commonly used as a corrosion inhibitor in cooling systems, industrial installations, and the automotive sector, for example in coolants, windshield washer fluids, brake fluids, oils, and lubricants. Benzotriazole also serves as a UV stabilizer in plastics, cosmetics, and detergents, and it occurs in household products such as cleaning agents and cosmetics containing UV filters (Verlicchi and Zambello 2020). Due to its high water solubility and resistance to biodegradation, BTA readily enters wastewater and surface waters. It exhibits toxicity to aquatic organisms and is poorly removed in conventional biological treatment processes (Kasprzyk-Hordern et al. 2009).

During wastewater treatment, BTA can inhibit the enzymatic activity of nitrifying and denitrifying bacteria, thereby reducing biological treatment efficiency. It may also accumulate in sludge and biomass, and some of its degradation products can be toxic (Kasprzyk-Hordern et al. 2009). In addition, BTA can disrupt photosynthesis and algal growth, limiting oxygen production in aquatic ecosystems (Siebielska and Sidełko 2003). Benzotriazole can be effectively removed by ozonation, photocatalysis, or adsorption; however, some transformation products formed during these processes may exhibit mutagenic and cytotoxic effects on aquatic microorganisms (Kasprzyk-Hordern et al. 2009; Verlicchi and Zambello 2020).

Studies conducted in Berlin reported benzotriazole concentrations in treated wastewater of up to 18 μg/L. Its derivatives, such as 4-methylbenzotriazole and 5-methylbenzotriazole, were detected at concentrations of up to 5 μg/L and 1.2 μg/L, respectively (Kasprzyk-Hordern et al. 2009). Similar concentration ranges, from 1 to 10 μg/L, were reported in Switzerland and the Netherlands (Verlicchi and Zambello 2020). In Poland, benzotriazole has been detected in treated wastewater at concentrations of approximately 0.8 to 1.1 μg/L and in surface waters in urbanized and industrialized areas (Łuczkiewicz et al. 2021; Siebielska and Sidełko 2003). In the present study, gravity filtration did not result in any statistically significant change in BTA concentration, showing a variation of approximately 3%, with a final concentration of 0.31 μg/L (Figure 5).

PFAS and PAH Micropollutants

The analyzed PFAS compounds can be classified according to their resistance to biological and chemical degradation. The first group includes short-chain and short-lived PFAS (C4-C6), which are less likely to bioaccumulate but easily migrate in the aquatic environment, such as PFCAs (PFBA, PFPeA, PFHxA) and PFSAs (PFBS, PFPeS, PFHxS). The second group consists of medium-chain PFAS (C7-C9), which exhibit toxic and bioaccumulative properties. This group includes PFCAs (PFHpA, PFOA, PFNA), PFSAs (PFHpS, PFOS), partially fluorinated compounds (HPFHpA), and fluorotelomers (4:2 FTS, H4PFOS). The so-called "forever chemicals" group includes the most persistent, toxic, and bioaccumulative long-chain PFAS (C10+), which are resistant even to thermal degradation. This category comprises PFCAs (PFDeA, PFUnA, PFDoA, PFTrA, PFTA, PF-3,7-DMOA), PFSAs (PFDS, H2PFDA, H4PFUnA), and the fluorotelomer 8:2 FTS. The final group consists of precursors such as PFOSA, Capstone Product A, and Capstone Product B, which show variable stability depending on environmental conditions and may transform into persistent PFOA/PFOS compounds.

Standard primary and secondary wastewater treatment processes do not effectively degrade PFAS. Only tertiary (quaternary) treatment enables their removal through advanced oxidation processes (AOPs), adsorption, and membrane filtration (Evich et al., 2022). In general, PFAS removal efficiency increases with chain length, whereas short and ultra-short PFAS tend to remain in wastewater. These compounds accumulate in sewage sludge, which, when applied to agricultural land, may subsequently contaminate soil and groundwater.

Based on the conducted analyses, it was found that in municipal wastewater directed to gravity filtration (following primary and secondary treatment), the aforementioned PFAS compounds were not detected or were present below the lower quantification limit, which was 0.010 μg/L (0.3 μg/L for PFOSA and 0.015 μg/L for Capstone Products A and B). Therefore, the results did not allow for a quantitative assessment of PFAS removal efficiency in the gravity filtration process employing OptiFiber PES-13 filter cloth.

European studies have shown that higher PFAS concentrations occur in urban areas and in the vicinity of chemical and electroplating plants, where fluoropolymers, hydrophobic coatings, and firefighting foams are commonly used (Evich et al., 2022). In comparison, the results obtained for the investigated facility confirm the low environmental PFAS load and the high overall efficiency of municipal wastewater treatment processes under conditions of no industrial inflow.

Although, as indicated by Siebielska and Sidełko (2003), compounds from the PAH group are characterized by high persistence and the ability to migrate within the environment, the present study showed that the sum of PAH concentrations (NAP, ACY, ACE, FLU, PHE, ANT, FLA, PYR, BaA, CHR, BbF, BkF, BaP, IcdP, DahA, BghiP) in municipal wastewater after treatment was below the quantification limit of 0.21 µg/L. This result indicates that the concentrations of individual PAHs were below the instrumental detection threshold, suggesting either a very low occurrence of these compounds in the wastewater catchment area or their effective removal during biological treatment processes and the tertiary treatment stage. From an environmental assessment perspective, the obtained results meet the requirements specified in Directive 2008/105/EC (European Parliament and Council of the European Union, 2008), confirming that the treated wastewater does not contain measurable amounts of carcinogenic and mutagenic substances characteristic of the PAH group. Comparable findings have been reported in studies conducted in Germany and other Western European countries, where PAH concentrations in treated effluents from typical WWTPs did not exceed 0.01 µg/L (Vierke et al., 2021).

Considering the coastal location of the facility and the highly seasonal nature of the wastewater inflow, the obtained results provide valuable reference data for the design and modernization of municipal wastewater treatment systems in tourist regions. The findings confirm the potential of gravity filtration as an effective technical solution supporting circular economy principles and compliance with the EU water reuse policy.

Although micropollutant determinations were based on a single sampling event, the results can be considered representative and reliable for the investigated wastewater treatment plant and the analyzed operating conditions. Sampling was performed during peak hydraulic and mass loading typical of the summer season, when inflow approaches the upper range of annual variability. On the sampling day, the influent flow fell within the annual standard deviation range, supporting the representativeness of the samples for maximum-load operation.

Available literature indicates that concentrations of many pharmaceuticals in treated wastewater exhibit relatively low short-term variability compared with basic physicochemical parameters, particularly under stable biological operation. At the investigated wastewater treatment plant, no process disturbances were observed during sampling, and both the biological stage and the tertiary filtration stage operated under steady-state conditions, further supporting the reliability of the obtained results.

Analytical determinations were performed by accredited laboratories using validated analytical methods and clearly defined limits of quantification. Where low removal efficiencies below 20 % were observed, the concentration differences between influent and effluent were consistent with ranges reported in the literature for full-scale facilities, indicating that the results reflect real technological limitations rather than measurement uncertainty. Conversely, the absence of detection above the limit of quantification for some compounds should be attributed to low influent loading or effective removal at earlier treatment stages, which is typical for municipal wastewater without significant industrial contributions.

Nevertheless, a single sampling campaign does not allow a comprehensive assessment of seasonal variability or short-term fluctuations in micropollutant concentrations. Therefore, the presented results should be regarded as indicative and as valuable reference data for evaluating the performance of gravity filtration under maximum-load conditions. For a more comprehensive characterization of micropollutant removal efficiency, further measurement campaigns covering different seasons and hydraulic regimes are recommended.

Conclusions

The study demonstrated that the gravity filtration system using disc cloth filters applied at the Międzyzdroje WWTP effectively stabilizes effluent quality, even under conditions of strong seasonal fluctuations and temporary hydraulic overloads. This process mitigates short-term deterioration of biologically treated wastewater, maintaining effluent parameters well below the permissible limits.

Final gravity filtration provided highly efficient removal of total suspended solids and phosphorus (below 5 mg/L and 0.5 mg/L, respectively) and partial elimination of selected indicator pharmaceuticals. A measurable reduction was observed for more polar compounds (e.g., metoprolol, candesartan, venlafaxine, amisulpride, clarithromycin), while persistent compounds such as carbamazepine and diclofenac remained largely unaffected.

The results confirm that gravity filtration alone (tertiary treatment) cannot ensure complete removal of pharmaceutical micropollutants. Nevertheless, it serves as an important pre-treatment stage facilitating the application of advanced technologies in the fourth treatment stage, including advanced oxidation processes (AOPs), adsorption, and nanofiltration. PFAS and PAHs were not detected above the quantification limits, indicating the absence of local sources of these pollutants and the typical municipal character of the influent. However, this does not necessarily imply their complete absence, as the results may reflect the detection limits of the analytical methods used. Therefore, trace concentrations below the limit of quantification (LOQ) may still occur and could be confirmed only using more sensitive analytical techniques.

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Skuteczność dyskowych filtrów tkaninowych w usuwaniu wybranych mikrozanieczyszczeń ze ścieków komunalnych – studium przypadku

Streszczenie. Celem badań była ocena skuteczności filtracji grawitacyjnej na dyskowych filtrach tkaninowych typu Mecana SF6/30 w redukcji wybranych mikrozanieczyszczeń (farmaceutyki, PFAS, WWA, benzotriazol) ze ścieków komunalnych w warunkach sezonowo zmiennego dopływu w 2024 roku. W komunalnej oczyszczalni ścieków w Międzyzdrojach (ok. 6 tys. mieszkańców; w sezonie letnim ~370 tys. osób) w latach 2021-2023 wdrożono trzeci stopień: grawitacyjną filtrację na filtrach dyskowych (Mecana SF6/30; PES-13). Pomimo 2-krotnie większego dopływu w sezonie letnim 2024 roku, parametry ścieków oczyszczonych (TSS, BZT_5, ChZT, N, P) pozostawały wyraźnie poniżej wymogów pozwolenia. Proces filtracji skutecznie stabilizował jakość ścieków przy wzroście obciążenia sezonowego. Jednocześnie wykazano ograniczoną redukcję wybranych farmaceutyków: 7-17% (metoprolol 7%, candesartan 17%, irbesartan 5%, wenlafaksyna 14%, citalopram 10%, amisulpryd 14%) oraz 33% dla klarytromycyny; brak redukcji dla hydrochlorotiazydu, karbamazepiny i diklofenaku. Benzotriazol spadł o 3%. Wszystkie 24 PFAS były <LOQ, a ∑16 WWA <0,21 µg/L. Wyniki potwierdzają, że pełne ograniczanie emisji mikrozanieczyszczeń wymaga IV stopnia (AOP/adsorpcja/membrany).