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Efficiency of microplastics removal in selected wastewater treatment plants – preliminary studies

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ABSTRACT

Recently more and more attention is being paid to pollution of the environment by microplastics. The problem is well recognized in marine and surface water in Western Europe. There are also well-documented studies on removal of microplastics during wastewater treatment in Germany, Finland, Denmark, Canada and Norway. So far the problem has not been identified in Eastern European countries, including Poland. Because of this, it is of high importance to evaluate the scale of problem also in these countries. The paper presents the results of preliminary studies on microplastics content in influents, effluents and sewage sludge of selected wastewater treatment plants in southern Poland. It was stated that content of microplastics in influents was in the range from $19.4 \cdot 10^3$ to $552.2 \cdot 10^3$ particles per 1 m^3, in effluents from 28 to 960 particles per 1 m^3. Microlitter particles removed from raw wastewater were accumulated in sewage sludge. Total concentration of microplastic particles in the sludge was in the range from $6.7 \cdot 10^3$ to $62.6 \cdot 10^3$ particles per 1 kg d.m. In liquid phase, finer fractions of microplastics were dominant. In sewage sludge larger particles, especially fibers, were effectively cumulated. About 95%–99% removal efficiency of microplastics from influents was stated. No correlation has been found between the wastewater flow rate and the content of microplastics in influent, these problems require, however, more detailed analysis of microplastics chemical composition and mass.

Keywords: Microplastics; Wastewater; Sewage sludge; Influent; Effluent

1. Introduction

Microplastics, most frequently, are defined as small particles (of various shapes) and fibers of plastics with sizes within the range 1 nm to <5 mm [1]. Until now, there is no official definition of microplastics. It should be emphasized that in practice the size ranges of microplastics particles are constrained by sampling techniques. Till now, there is no normalized method of microplastics sampling. It concerns both water and wastewater samples. In many research works, especially before 2016, plankton nets were used for sampling of microplastics from liquid phase. When we consider wastewater, this sampling technique can be eventually effective in case of effluent, but it does not usually work in case of influent (raw wastewater). It is because of the fact that raw wastewater contains not only microplastics but also high quantities of other solids which quickly make the net clogged [1]. In practice of wastewater treatment usually special nets (e.g., Estahbanati and Fahrenfeld [2] have used 153 μm nets – diameter 0.2 m; 0.51 m long) or various filtration equipments are used. Talvitie [3], the researcher experienced in microplastics analysis in wastewater samples has, for example, used filtering device for in-situ fractionation

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of 300 μm – <5 mm, 100–300 μm and 20–100 μm fractions. Also other special samplers, such as, for example, VanDorn, Niskin or Kramer or extraction pumps can be used to collect the samples [4,5]. Sampled wastewater is next filtered under pressure in the laboratory through the set of filters to obtain proper fractions of microplastics [4]. This procedure allows for identifying number of particles and their sizes. These parameters are strongly linked to the behavior of the particles. These data are, however, not enough adequate if we would like to estimate microplastics mass loads [6]. As Simon et al. [6] indicated, fragmentation of microplastic particles during treatment processes can affect the results of these micropollutants quantification in wastewater. Fragmentation of microplastics during wastewater treatment can potentially result in overestimation of microplastics in effluents. Also Talvitie et al. [7] indicate that sampling procedure significantly affects the results obtained in various studies and makes them difficult to compare.

Because of this sampling method should be adapted to the kind of matrix from which we would like to separate microplastics' particles. Quantification of microplastic (MP) by identifying particle numbers and shapes is enough during preliminary studies which should answer if the pollution of wastewater by microplastics is a problem in specific area and specific installations. When we would like to make more detailed studies we should also take into consideration the mass of microplastics opposed to number of particles [6].

More detailed surveys also include qualification of microplastics to various classes of plastics. Six classes of microplastics are dominant in the world market: polyethylene (PE) of low or high density polyethylene (HDPE), polypropylene, polyvinyl chloride, polystyrene, polyurethane and polyethylene terephthalate [1]. They are used as materials for bottles, bottle caps, pipes, textiles, films, bags, etc. [1]. The important properties which influence the behavior of microplastics in the water environment are the density and sizes of scraps [1]. It is believed that because of low density microplastics particles float and concentrate mainly in the surface layers of flowing water.

There are various opinions among researchers on the necessity of using more advanced identification techniques for analysis of microplastics in wastewater and sludge. Some researchers [5,7] think that using only light microscope counting technique is enough to analyse the real content of MPs in samples if the wastewater or sludge is adequately prepared. Preparation of sample removes most degradable organic matter from sample but not microplastics or inorganic solids. Methods the most frequently used for sample preparation are enzymatic degradation or oxidation of with strong oxidants, such as e.g. H_2O_2, Fenton's reagent. Whereas others, for example, Gies et al. [8] suggest that even well-prepared "microplastics" samples analysed using Fourier transform infrared spectroscopy (FT-IR) show that really only about 30% of suspected MPs were plastic polymers. Also, for example, Ziajahrmomi et al. [9] suggest that visual analysis should be completed by other methods, such as FT-IR, mentioned above, or Raman spectroscopy. Definitive decision on the analytical procedure should be undertaken based on the aim of the research study.

Microplastics can be divided into "primary" and "secondary". Primary microplastics are the ones originally manufactured. They are mainly industrial "scrubbers", plastic powders, microbeads used in cosmetics, and other nanoplastic particles used in industry [1]. The secondary ones are the effect of defragmentation of plastic debris such as plastic bags, textiles, paints, tyres [1]. Rate of defragmentation is connected with various environmental factors, such as temperature, kind of plastic, time, water flow, etc. [10]. Secondary microplastics are more differentiated in respect of sizes and shapes. The shapes could be fragments of foil, fibers, granules, etc. [1]. It means that abundance of microplastics of various shapes in the samples is informative when we consider sources of pollution of water environment by microplastics.

Wastewater treatment plants (WWTPs) are one of the sources of microplastics in the water environment. However, as indicates Simon et al. [6] by example of Denmark WWTPs emissions of microplastics to the surface water in the whole country is about 3 tonnes per year. About 60 times higher loads are discharged to the environment with sewage sludge. This means that more attention should be paid to this waste material. Researchers also emphasize that high particle numbers in raw wastewater do not mean that microplastics are a significant contributor to total mass of suspended solids in wastewater [6].

Both primary and secondary microplastics are discharged into sewage systems, however, the main sources of these pollutants in influents are cosmetics and washing of clothes, for example, in 2012 about 6% of peelings contained microbeads of sizes within the range 450–800 μm [11]. The number of countries which have banned producing of non-degradable microplastics has recently increased. The first country which introduced a ban on microbeads in cosmetics was the Netherlands (in 2014) [11]. Earlier, in 2010, Standard Australia Committee prepared AS5810 Standard on biodegradable plastics, followed by AS 4736 Australian Standard for biodegradable plastics. The standards set the quality standards for plastic products entering Australian market [11]. At present in Australia, sell of cosmetics containing non-degradable microplastics is banned [11]. In the United States, production of cosmetics which contain non-degradable microplastics has been banned in July 2017 by Microbead-Free Waters Act of 2015 [12]. This legal act also forbids the sale of this kind of cosmetics since July 2018. Also in Canada and Great Britain similar law regulations have been introduced. Ban on the sale of cosmetics containing non-degradable microplastics has also been announced in New Zealand, Ireland and Italy since 2018/2019 [11]. From washing of clothes mainly synthetic fibers are discharged into sewer systems. That is the reason why fibers are one of the main forms of microplastics in influents. In combined sewer systems microplastics are also a component of runoff waters, and content and kind of particles is connected with composition of surface and degree of industrialisation in the catchment. Concentrations of microplastics in influents can be in the range from several to even several hundred thousand in 1 m^3 [8,13–17]. According to various studies during wastewater treatment in WWTPs from 50 to more than 99% of microplastics present in influent is removed from wastewater [13]. 90% of microplastics are removed during mechanical treatment, mainly in primary sedimentation tanks [16]. Microfibers of microplastics are, for example, effectively removed in primary settlement tanks because of

Table 1
Retention of microplastics in selected WWTPs according to the results obtained by other researchers

Removal of microplastics from liquid phase	Retention of microplastics in solid phase	Sampling place	References
99% (only about 1% of influent MP was released with treated wastewater)	98% (70% were fibers)	WWTP near Vancouver, Canada	[9]
99% retention of microplastics in WWTPs	79% stored in sewage sludge, about 20% recirculated with reject water	WWTP in Finland	[4,20]
97% (about 97% of microplastics present in influent were removed)	No data	12 WWTP s in the north-western Germany including municipal and municipal/industrial ones	[21]
98.3% removal during conventional treatment of wastewater; use of MBRs allowed for increase the removal efficiency of MPs from 1.0 to 0.4 MPL/L)	No data	Pilot scale MBR reactor in Mikkeli WWTP, Finland	[22]

the affinity to mix with cellulose fibers of toilet paper and plant debris [16]. Sedimentation is believe to be efficient in removal of particles of sizes in the range of at least >20 µm, and the removal efficiency increases as sizes of particles increases [17]. Greater particles (100 µm and higher) can be also separated from wastewater on micro-sieves, while coarse screens are not effective in microplastics removal [18,19]. On fine screens, part of microplastics can also be removed [11]. Microplastic particles of low density can be also effectively removed in aerated grit removal chambers or in flotators [17]. Part of microplastics also accumulates in the foam or sludge in aerated activated sludge chambers. After whole treatment process, only about 1%–3% of initial microplastics content is present in effluents (Table 1).

These micropollutants are not degradable, so they accumulate in sewage sludge and other waste materials after treatment. Because of ability to adsorb other organic and inorganic micropollutants present in wastewater (e.g., polycyclic aromatic hydrocarbons – PAHs, polychlorinated biphenyls – PCBs, pesticides, heavy metals) microplastics can contribute to pollution of sludge and soils by these compounds. Research works on levels of microplastics in influents and effluents to WWTPs were conducted in several countries worldwide, including Finland, Denmark and the United States [8,16,18]. This problem has not been recognized in Poland. The aim of the present study was preliminary evaluation of the levels and removal efficiencies of microplastics in several WWTPs located in southern Poland.

2. Materials and methods

2.1. Research object and sampling points

Samples were taken from six wastewater treatment plants situated in southern Poland. All of them were mechanical–biological wastewater treatment plants. Three of them were the big ones (with wastewater flow rate over 10,000 m^3/d), three were the small and medium ones (wastewater flow rate in the range of 350–3,000 m^3/d). Short characteristics of WWTPs are presented in Table 2.

All WWTPs were mechanical–biological ones with biogen removal (with simultaneous chemical precipitation of phosphorus if it was necessary). Part of them uses anaerobic digestion as a method of raw and excess sludge stabilization (WWTP1, WWTP4, WWTP6), the remaining ones aerobic stabilization processes (WWTP2, WWTP3, WWTP5).

2.2. Sampling procedure

From each WWTPs random samples of influent, outflow from preliminary sedimentation tank, effluent, reject water and sewage sludge were taken. The samples have been taken three times from each WWTP from spring to summer 2017.

Influent and reject waters were sampled using 20 L plastic canisters because use of plankton net for this purpose was difficult. Influent samples contained a lot of organic material which clogged net meshes. In case of influents, the containers were placed in the stream of wastewater and filled with liquid sample. A funnel with wide neck was placed on the input to the container. Larger scraps were removed from the funnel in order to facilitate sampling of finer wastes such as microplastics. In case of reject waters, there were not much scraps visible with the naked eye in the samples. Because of this sampling procedure was easier. The containers were filled with the reject water obtained after dewatering of the biologically stabilized sludge. Because of relatively high content of microplastics, 20 L of sample was enough to obtain reliable results. Effluent water was also collected into 20 L plastic containers; however, it was necessary to use at least five containers to catch enough volume of the wastewater because the content of microplastics in effluent was significantly lower than in influent water. The container was put at the outflow from the secondary sedimentation tank.

Sewage sludge (random samples) was collected to 10 L plastic containers from methane digester chambers or aerobic stabilization chambers.

It should be emphasized that taken samples were random and because of this they were useful only as a background for preliminary, not detailed, studies on microplastics content in wastewater and sludge.

Table 2
Characteristics of wastewater treatment plants from which samples of microplastics were taken for analysis

WWTPs symbol	Flow rate, m^3/d	Technology	Sampling points[1)]/(replicates)
WWTP1	60,000	Mechanical–biological, without tertiary treatment, classical activated sludge with BNR, methane digestion of sludge	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)
WWTP2	12,500	Mechanical–biological, without tertiary treatment, classical activated sludge, aerobic stabilization of the sludge	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)
WWTP3	10,000	Mechanical–biological, without tertiary treatment, classical activated sludge, aerobic simultaneous stabilization of the sludge	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)
WWTP4	3,000	Mechanical–biological, without tertiary treatment, classical activated sludge with BNR, anaerobic stabilization of sludge	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)
WWTP5	900	Mechanical–biological, without tertiary treatment, classical activated sludge with BNR, aerobic stabilization of sludge	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)
WWTP6	350	Mechanical–biological, without tertiary treatment, classical activated sludge with BNR, anaerobic stabilization of the sludge with sludge lagoons	Influent, preliminary sedimentation tank outflow, effluent, sewage sludge, reject water/ (3)

BNR, Biological nutrient removal.

Collected samples of wastewater, reject water and sludge were then processed to separate microplastics particles from the matrix.

2.3. Analytical procedure and statistical analysis

Analytical procedure of microplastics in wastewater and sewage sludge was developed based on the ones presented by other researchers [8,16,18,20,23], including our previous experiences. It was as follows. Liquid samples (influent, effluent and reject water) were taken to a laboratory and sieved through a 5-mm mesh. Next the fraction of <5 mm was vacuum filtered through the filters of meshes 300 and 109 µm. Organic material was then prepared to remove the natural organic matter which was present in the sample probe. The collected fractions were placed in laboratory 1 L beakers filled with distilled water. Fenton's reagent was added (25 mL H_2O_2, 30% and 1 g of $FeSO_4 \cdot 7H_2O$). The probe was heated to accelerate and support the decomposition of natural organic substances contained in the suspended solids. Each sample was evaporated to a volume of 20 mL. Remaining organic material was separated by separation process in $ZnCl_2$. Some remaining not synthetic material still present in the sample after sedimentation was carefully distinguished from the microplastics particles during the microscopic observation. The same sample volumes (1 mL) were then taken by automatic pipette and fed into the Sedgewick-Rafter's Chamber and analysed under optical microscope (magnification 40 µ 100 x). The microplastics particles were counted directly. At least 10 samples of microplastics were counted under microscope from each sample. Statistical analysis of the obtained results was made using STATISTICA software. Because of the limitations of sampling procedure, only standard deviations were calculated and included in the results.

Collected material was studied under microscope and detected microplastics samples were counted and classified to one of the following categories: fibers, granules, flakes and unidentified. In the case of fibers, based on the morphology it was no easy to differentiate synthetic ones from other (e.g., cotton fibers). In case of doubt, it was possible to distinguish them using the test proposed in Science for Environmental Policy [24]. They were placed on an object glass and heated over the flame of a candle. Fibers made of plastics melted, whereas the remaining ones did not melt.

Sewage sludge was also passed through a sieves 5 mm. Fraction below 5 mm was next placed on the filters of meshes 300 and 109 µm and washed repeatedly with distilled water by using vacuum filtration system. The washed material was treated as the liquid samples.

To minimize and control the potential plastic contamination during sample processing in laboratory, laboratory glass was used (not made from, e.g., HDPE) and cotton coats which do not contain synthetic fibers were worn. Because of the rather high concentrations of microplastics particles in wastewater and sludge samples, the effect of potential plastic contamination during analytical procedure was not high and also not statistically important. The analytical procedure was enough for preliminary evaluation of the abundance of microplastics particles in the samples as well for evaluation of removal efficiency.

3. Results and discussion

Total amounts of microplastics of sizes >300 µm and 109–300 µm in raw and treated wastewater are listed in Table 3. Total amounts of microplastics in influents are

Table 3
Size fractions of microplastics in influent and effluent of six examined WWTPs

Sampling point	Raw wastewater (number of particles per 1 m^3)		Treated wastewater (number of particles per 1 m^3)	
	>300 μm fraction	109–300 μm fraction	>300 μm fraction	109–300 μm fraction
WWTP1	$252.2 \cdot 10^3 \pm 70.2 \cdot 10^3$	$300.3 \cdot 10^3 \pm 45.2 \cdot 10^3$	32.2 ± 13.7	105.5 ± 30.8
WWTP2	$78.2 \cdot 10^3 \pm 12.3 \cdot 10^3$	$72.3 \cdot 10^3 \pm 20.5 \cdot 10^3$	5.5 ± 1.2	75.2 ± 41.7
WWTP3	$124.1 \cdot 10^3 \pm 32.4 \cdot 10^3$	$217.2 \cdot 10^3 \pm 78.4 \cdot 10^3$	13.2 ± 3.7	225.5 ± 100.5
WWTP4	$12.3 \cdot 10^3 \pm 1.6 \cdot 10^3$	$8.9 \cdot 10^3 \pm 2.8 \cdot 10^3$	65.2 ± 38.4	895.2 ± 203.6
WWTP5	$32.4 \cdot 10^3 \pm 24.1 \cdot 10^3$	$57.2 \cdot 10^3 \pm 18.7 \cdot 10^3$	105.2 ± 10.7	65.3 ± 8.9
WWTP6	$7.2 \cdot 10^3 \pm 5.5 \cdot 10^3$	$12.2 \cdot 10^3 \pm 3.5 \cdot 10^3$	225.4 ± 10.5	215.4 ± 6.7

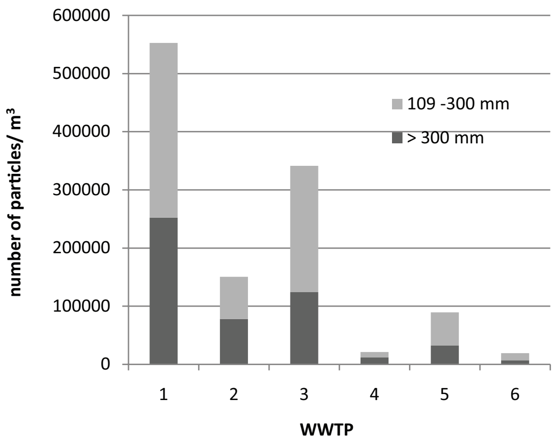

Fig. 1. Shares of >300 μm and 109–300 μm in influents of the WWTPs.

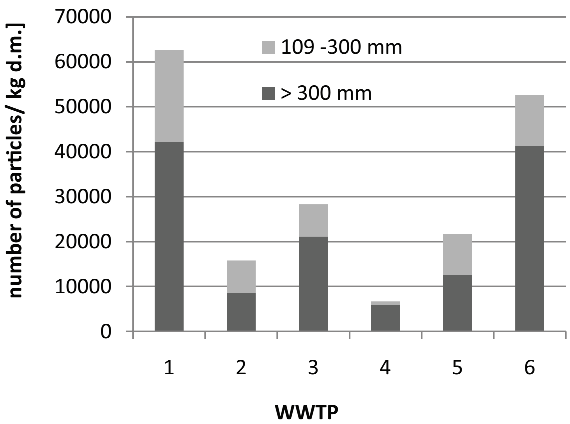

Fig. 3. Total amount of microplastics in sewage sludge from selected WWTPs in southern Poland.

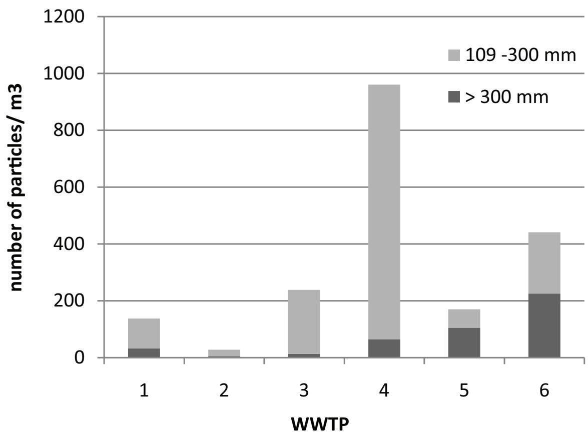

Fig. 2. Shares of >300 μm and 109–300 μm in effluents of the WWTPs.

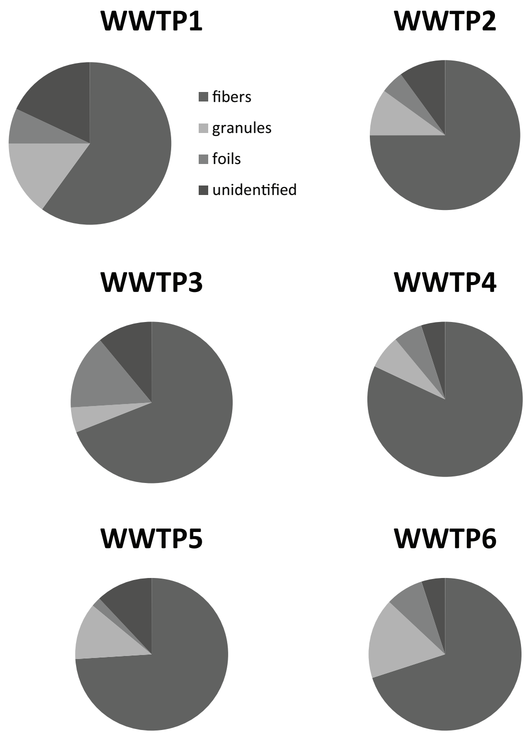

Fig. 4. Abundance of microplastic particles of various shapes in influents from various WWTPs in southern Poland.

presented in Fig. 1, in effluents in Fig. 2. Amounts of MPs in sewage sludge are presented in Fig. 3. Distribution of shape fractions of microplastics in sewage sludge is presented in Fig. 4, and content of microplastics fractions in reject water and sewage sludge are included in Table 4.

Based on the data presented in Table 3 and Fig. 1, it can be stated that fraction 109–300 μm is in influents of many WWTPs (WWTP1, WWTP3, WWTP5, WWTP6) more

Table 4
Size fractions of microplastics in reject water and sewage sludge of six examined WWTPs, data in particles number/m³ and number of particles/kg d.m.

Sampling point	Reject water		Sewage sludge	
	>300 μm fraction	109–300 μm fraction	>300 μm fraction	109–300 μm fraction
WWTP1	$19.3 \cdot 10^3 \pm 70.2 \cdot 10^3$	$7.5 \cdot 10^3 \pm 5.3 \cdot 10^3$	$42.2 \cdot 10^3 \pm 0.2 \cdot 10^3$	$20.4 \cdot 10^3 \pm 5.5 \cdot 10^3$
WWTP2	$3.2 \cdot 10^3 \pm 2.6 \cdot 10^3$	$3.3 \cdot 10^3 \pm 2.1 \cdot 10^3$	$8.5 \cdot 10^3 \pm 6.4 \cdot 10^3$	$7.3 \cdot 10^3 \pm 2.8 \cdot 10^3$
WWTP3	$14.1 \cdot 10^3 \pm 3.6 \cdot 10^3$	$6.2 \cdot 10^3 \pm 1.4 \cdot 10^3$	$21.1 \cdot 10^3 \pm 12.6 \cdot 10^3$	$7.2 \cdot 10^3 \pm 5.7 \cdot 10^3$
WWTP4	$2.4 \cdot 10^3 \pm 1.6 \cdot 10^3$	$1.9 \cdot 10^3 \pm 1.5 \cdot 10^3$	$5.8 \cdot 10^3 \pm 1.3 \cdot 10^3$	$0.9 \cdot 10^3 \pm 0.5 \cdot 10^3$
WWTP5	$12.4 \cdot 10^3 \pm 5.2 \cdot 10^3$	$5.2 \cdot 10^3 \pm 4.2 \cdot 10^3$	$12.5 \cdot 10^3 \pm 4.3 \cdot 10^3$	$9.2 \cdot 10^3 \pm 8.4 \cdot 10^3$
WWTP6	$2.3 \cdot 10^3 \pm 1.5 \cdot 10^3$	$2.2 \cdot 10^3 \pm 1.8 \cdot 10^3$	$41.2 \cdot 10^3 \pm 3.8 \cdot 10^3$	$11.4 \cdot 10^3 \pm 10.6 \cdot 10^3$

Table 5
Content of microplastics in raw wastewater according to the results obtained by various researchers

Number of microplastics particles/m³	Other data concerning microplastic particles	Reference
$15.1 \cdot 10^3$	Fibers 71%, fragments 18%, foils 11%	[22]
$631–100 \cdot 10^3$	Fibers 33%–80%, flakes 5%–20%, foils 5%–50%	[14]
$127 \cdot 10^3$	No data	[15]
$380 \cdot 10^3–900 \cdot 10^3$	Fibers 68%, fragments 9%, flakes 14%, foil 7%, granules 2%	[19]
$200 \cdot 10^3$	No data	[23]

abundant than >300 μm. What was characteristic – total content of microplastics (fraction >109 μm) in influents of six examined WWTPs – was very variable, from $19.4 \cdot 10^3$ (WWTP6) to $552.5 \cdot 10^3$ particles per 1 m³ (WWTP1). No correlation can be found between the wastewater flow rate and microplastics content in influents, however the highest content of microplastics was found in the biggest WWTP (wastewater flow rate 60,000 m³/d). Values of standard deviations indicate that microplastics content vary a lot not only between WWTPs but also for the individual installations. Because of this, it is difficult to predict possible concentrations of microplastics in influents.

Compared with the results obtained by other researchers (Table 5), it can be stated that the results were in the range of other installations. The data collected in Table 5 confirm also that fibers are the dominant fraction in influents. The similar results were obtained in the present study (Fig. 4). Fibers percent shares (60%–82%) in influents were followed by granules (5%–17%) and foils (2%–15%). Shapes of microplastics allow for the identification of sources of microplastics. Fibers and granules present in influents origin among others from laundries, washing of clothes, cosmetics. In influent entering large WWTP1 which cooperate with combined sewerage also fraction of unidentified microlitter was highest of the all examined influents.

In effluents (Fig. 2) percent share of the finest fraction in total amount of microplastics in most cases is higher than in effluents. It was probably due to the fact that very fine particles of microplastics are worse removed from wastewater compared with the larger ones [11].

Concentrations of the microplastics particles in effluents of WWTPs of various wastewater flow rate were in the range 28–960 particles per 1 m³. They were comparable with the ones obtained by other researchers (Table 6). Percent removals of total microplastics amount were as follows:

Table 6
Total content of microplastics in effluent water according to the results obtained by various researchers

Number of microplastics particles/m³	Fractions	Reference
8–43	300 μm–5 mm	[23]
8,600 including 4,900 fibers/m³	300 μm–5 mm	[14]
8–23	No data	[9]
29–43	No data	[9]
1,378	No data	[9]

WWTP1 – 99%, WWTP2 – 99%, WWTP3 – 99%, WWTP4 – 95%, WWTP5 – 99%, WWTP6 – 98%. Relatively higher removal efficiencies were obtained in larger WWTPs, in the smaller ones, the difference between the microplastics content in raw and treated wastewater was lower.

Wastewater treatment removed efficiently fibers from wastewater (Fig. 5). They were efficiently cumulated in sewage sludge (Table 4). Contents of MPS in sewage sludge obtained in our study are compatible with the results obtained by other authors (Table 7). Part of microplastics was, however, recirculated with the reject waters. Reject waters separated from sewage sludge contained from $4.3 \cdot 10^3$ to $26.8 \cdot 10^3$ microplastics particles/m³ (Table 4). It represented not much than 20% of influent content of microplastics; however, the percent share is difficult to set because of the fact that reject waters are separated from sludge which is processed for a dozed days, and accumulation of microplastics in sludge occurs. Contrary to the liquid phase in sewage sludge the dominant fraction was the one >300 μm. It mainly consisted of fibers (Fig. 6). It fits well with the results obtained by Remy et al. [16] who indicate that fibers present in raw wastewater are catched by other kinds of fibers such as cellulose and as a result they are retained in solid phase. After dewatering in reject water, fraction of finer particles (109–300 μm) was most abundant than in sewage sludge, which indicates that in solid phase larger particles and fibers were retained.

When we compare total amounts of microplastics in samples from wastewater treatment plants, it can be stated that effluent concentrations of microplastics are at level 1%–10% of the ones present in raw wastewater. In any WWTPs tertiary treatment was applied. However taking into account the loads of microplastics which can be discharged into the environment with treated wastewater, the scale of pollution is visible and can affect the environment.

Compared with the results obtained by other researchers (Table 5), total amounts of microplastics observed in effluents were within the "typical" range. The dominant fractions in effluents (Fig. 5) were fibers and fragments. Foils were less visible, which fits well with the results obtained by [15].

As indicated by the results of studies obtained by Talvitie et al. [25] the pollution of environment by microplastics can be reduced by using tertiary treatment step in WWTPs. According to the results obtained by these researchers, rapid sand filtration allows for removal of more than 97% of microplastics present in effluents. This method is especially effective when we would like to remove the particles and fibers of >300 μm sizes [26]. According to the literature [18,19], filtration of wastewater through two media filter allows to remove more than 90% of very fine microplastics in effluent water and practically completely the larger ones (>109 μm) such as considered in present study. Very good effects of microplastics removal from wastewater can be obtained by using MBR (membrane biological reactors) [8].

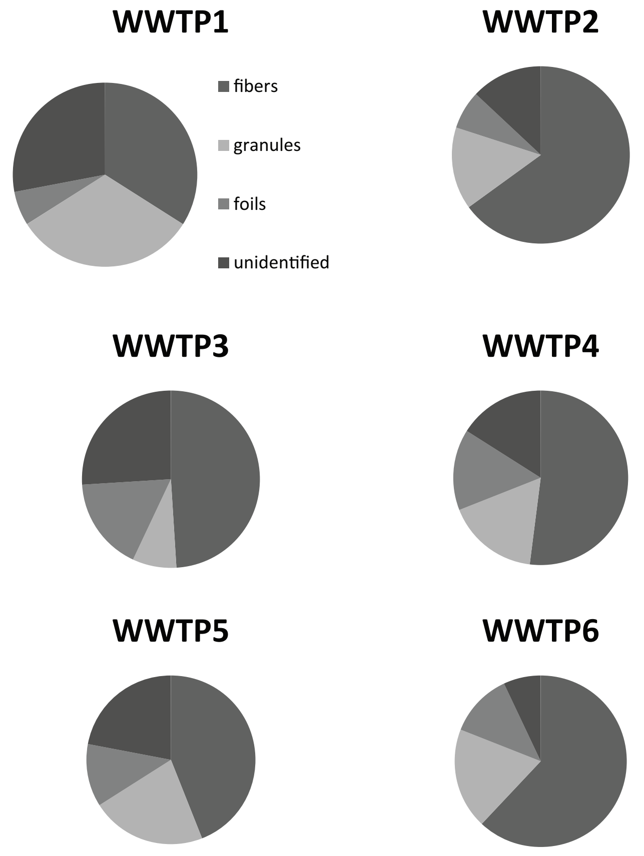

Fig. 5. Abundance of microplastic particles of various shapes in effluent water from various WWTPs in southern Poland.

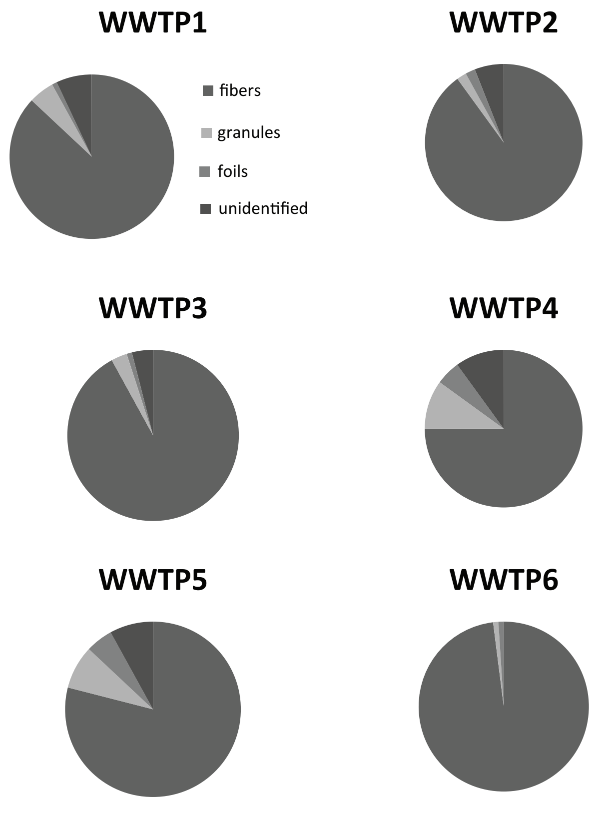

Fig. 6. Abundance of microplastics particles of various shapes in sewage sludge from various WWTPs in southern Poland.

Table 7
Content of microplastics in sewage sludge

Number of microplastics particles/kg d.m.	Other remarks	Reference
$16.7 \cdot 10^3$	Fibers 72%, fragments 20 %, foil fragments 8%, digested sludge	[13]
$2.743 \cdot 10^3$–$5.156 \cdot 10^3$	Digested sludge	[24]
$10.012 \cdot 10^3$–$14.064 \cdot 10^3$	Sludge stabilised with lime	[24]
$169 \cdot 10^3$	Digested sludge	[15]
$4.9 \cdot 10^3$	No data	[25]

However, it should be emphasized that during removal of microplastics in MBRs they are cumulated in sludge. Technologies of microplastics removal from sewage sludge have been not developed yet. At present in the market one membrane technology, dedicated microplastics removal from effluents is offered, it is called VeSave [28].

4. Conclusions

Results obtained in the study permit to formulate the following conclusions:

- During wastewater treatment, main part of microplastics present in influents is cumulated in sewage sludge.
- In liquid media (effluents, influents, reject water), finer fractions of microplastics are more abundant.
- In sewage sludge, larger particles are especially effectively retained, including first of all, fibers.
- Contents of microplastics in influents were at the level of several thousand particles per 1 m^3. About 95%–99% of these pollutants were removed during treatment.

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