Influence of synthetic wastewater on entrapped air on the isotactic and atactic polypropylene microplastic surfaces

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Abstract

The municipal wastewater collection system is recognized as an initial point of interaction between microplastics (MPs) and the urban wastewater matrix. The raw wastewater contains a wide variety of organic and inorganic substances including chemicals and heavy metals. However, the fate of MPs in urban sewer systems is not yet well understood. In this work two types of virgin polypropylene (PP) samples, isotactic (iPP) and atactic (aPP), were exposed to two synthetic wastewater solutions in order to study their effects on the physical properties of the hydrophobic polymer surfaces. Particular attention was paid to the pollution adhesion at the air-liquid-solid interfaces of the surface air pockets entrapped on the polymer surfaces. The first wastewater solution consists of mixed fat, oil and grease (FOG) - surfactant and another which is an exclusively contained wastewater surfactant. The interaction experiment over a period of 10 min between the polymer's air pocket and solutions indicated that the size of the bubble in the mixed FOG-surfactant solution increased more pronouncedly for iPP (%152) in contrast to aPP (%31) and was also compared with the greater surface roughness of the polymers. The size variation of the spherical cap on the immersed polymer surfaces were measured between 17 μm and 85 μm using image processing techniques while the data was analyzed by the Young-Laplace equation. The corresponding technical surface roughness of the polymers, the surface tension of the liquids and their air/water contact angle on the flat polymer surfaces were also measured. The results of this study indicated that surface air pockets influence the adsorption capacity of MPs and thus their buoyancy and contamination potential.

Keywords Polypropylene (PP) · Surface roughness · Air pocket · Surfactants · FOG · Wastewater

Introduction

The emergence of microplastics (MPs) in water, soil and air pose a substantial environmental concern throughout the globe. The lack of a viable strategy between plastic production and particle collection has led to the dispersion of hundreds of millions of microplastic particles found in the receiving water and collected wastewater. On the global scale, the plastic production has grown from 1.5 MT in 1950 to 359 MT in 2018 [1], driven by the world population growth and demand for

commercial goods which have dramatically increased the quantity and variety of the polymer-based products [2, 3, 4, 5]. Plastic debris, byproducts of plastic wastes, is an immense problem for all societies worldwide [6, 7, 8]. The general term for MPs particles includes all polymer-based materials with a size of less than 5 mm [9, 10, 11]. However, this definition varies from *mm* to *nm*, depending on the experimental requirements for the marine pollution research, wastewater treatment or water supply. The MPs are grouped into two types: primary and secondary [12, 13, 14]. The primary type refers to the engineered manufacturing in MPs sizes, while the secondary type within a MPs size range is formed by the act of mechanical or natural forces.

The municipal wastewater collection system is an initial source of contact with MPs and urban wastewater. The MPs in facial scrubber, toothpaste and personal care products or fragments of plastic debris from households, roads, industries and airborne resources enter into the sewer systems where they are mixed with raw wastewater containing oils, surfactants, chemicals, soil particles and nano-/microparticle metals

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that can adsorb onto the MPs surfaces [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. These adsorbed materials onto the hydrophobic surfaces of plastic particles can change their properties in such a way that they are not responding properly during wastewater treatment phases such as membrane filtration or flotation [27, 28]. Moreover, the diverse release of detergents from households and industries into the collecting sewer pipe create different spatial conditions such as level of mixing, chemical exposure, density, viscosity, temperature and surface tension which can influence the fate of microplastics in the sewer pipe. Therefore, we exposed the polymer samples directly to the wastewater surfactants in order to evaluate the physical changes on the MPs surfaces before mixing them with the rest of wastewater constituents.

Two important organic groups in the wastewater can be responsible for the change in the properties of the MPs surfaces; fat, oil, grease (FOG) and surfactants. The FOG deposit with a density less than water is an organic substance produced during the manufacturing processes in the food industry or by household production in urban sewer systems [29, 30]. The majority of FOG about 94–96% are triglyceride molecules with a polar hydrophilic carboxyl group head and a non-polar hydrophobic long hydrocarbon chain of fatty acids [31, 32]. Another group is surfactants that enter the sewage system by detergents from households or industries [33, 34, 35, 36]. Surfactants are grouped as ionic and non-ionic with polar heads and long chain hydrocarbon tails with a particular tendency to locate at the interfaces. The adsorption of surfactants at the interfaces is a time-dependent process and through this adsorption the surface properties or the interfacial tension can be significantly altered. As far as our research has shown, the studies of synergistic impact of the mixed ionic (anionic, cationic and amphoteric) and non-ionic surfactants with the lipids and their influence on the surface properties of MPs requires further investigation. While this particular area is of interest to the researchers, it suffers from complex interactions leading to enormous parameters intervened during the experiments. Therefore, the adhesion of lipids and surfactants from the bulk onto the MPs surfaces can alter their degree of surface hydrophobicity as well as their adsorption capability [37].

There is also a need for data on the dynamics of adsorption of polar wastewater constituents in three phases of gas/liquid/solid interfaces [38]. The surface properties of MPs, such as heterogeneity and roughness play a crucial role in holding air prior to immersion in a liquid, as does their hydrophobicity for the adhesion of the submicron bubbles from a liquid [39, 40]. Regardless of the hydrophobicity of MPs, their wetting properties can be enhanced by the polar components. The molecules of pollutants such as surfactants and lipids are able to adsorb at both the gas-liquid and the liquid-solid interfaces and orient themselves in the interfacial film, allowing the interfacial forces to change the contact angle/wettability of the particle surfaces [41, 42]. Hence, particular attention is paid to

the behavior of the air pockets after the addition of wastewater surfactants and FOG contributors because they play a crucial role both in the adsorption capacity on MPs surfaces [43, 44] and their buoyancy.

In this study, we investigated the effects of two wastewater solutions, namely mixed FOG-surfactants and the exclusive surfactants, on the two types of clean polypropylene (PP) polymer, isotactic (crystalline) and atactic (amorphous). The two types of polypropylene were selected for their different surface properties and their importance with respect to environmental pollution. For the first time, we have also introduced the surface air pockets as an indicator for the quantification of pollution uptake at polymer surfaces using the image processing techniques. The influence of the parameters such as surface tension, contact angles and surface roughness will be discussed. The results compare the influence of urban wastewater constituents on MPs surfaces to the fate of MPs in the wastewater treatment processes and to their contribution in environmental pollution.

Materials and methods

Polymer particles and solutions In order to compare the influence of polar molecules on MPs surfaces, the two wastewater solutions of the mixed FOG- surfactants and surfactants on PP surfaces were tested to quantify the changing size of air pockets in a short-term analysis lasting about 10 min. [45, 46, 39]. By definition, the air pockets are entrapped air inside the nano or micro sized cavities of the plastic surfaces that appear after immersion into the water. They facilitate the adsorption of chemicals and organic compounds of the wastewater matrix onto the solid surfaces [47] and thus changing the density and transport of MPs in the urban sewers [48, 49]. The PP polymer was formed by repeating units of propane monomer. This polymer was first discovered in 1950 and since then has developed into an enormous product on the market, both as a fiber and as a plastic. It is also the most frequently reported microplastic in global freshwater studies and has the highest market demand as a resin, about 19.3% [1, 50, 51, 52].

The pure dry granular polymeric samples with an average size of about 0.5 mm and a density of about 0.9 g/ml as atactic polypropylene (aPP) and isotactic polypropylene (iPP) were purchased from the Sigma Aldrich (Co.). The aPP is an amorphous and rubbery polymer with a random position of the methyl group along the polymer's molecular chain. The iPP is a rigid, crystalline polymer that is resistant to stress and thermal variations, with the methyl group only on one side of the molecular chain of the polymer. Two applied chemical solutions for testing on MPs surfaces were formulated using the components listed in Tables 1 and 2. The wastewater

surfactants (WWSF) solution was prepared according to the components outlined in Table 1 containing anionic sodium dodecylbenzene sulfonate surfactant (SDBS), cationic surfactants hexa-decyl-trimethyl-ammonium bromide (CTAB) and non-ionic surfactants triton X-100. The values of the ingredient were based on the WWSF solution which prepared in accordance with literature [53]. The synthetic wastewater (WW) solution prepared according to the components outlined in Table 2 contains the major contributors to the FOG formation [54] which include stearic acid, palmitic acid, oleic acid as well as fine sands, calcium chloride, iron oxide as $\text{Fe}^{+2}/\text{Fe}^{+3}$ with a size of less than 5 μm in addition to the surfactants listed in Table 1. The solutions were mixed well inside the ultrasound cleaner for about 45 min and then placed into the preheated oven up to a temperature of 70 °C for 5 min. The surface tensions of the applied liquids were measured using the pendant drop method and results are presented in Table 3. The deionized water was used for all cleaning and preparation of various solutions. The measured pH values of the final solutions of the WWSF, WW are neutral as 6.9, 6.0 and their conductivity as an indicator for ionic pollution measured as 5 $\mu\text{S}/\text{cm}$, 180 $\mu\text{S}/\text{cm}$ at a temperature of 22 °C, respectively.

Visualization techniques In the short-term analysis, the surfaces of the PP samples were examined for the air pocket formation. The selected virgin samples of aPP and iPP were separately submerged in deionized water in a laboratory glass plate and inspected by the stereomicroscope Müller GmbH which was mounted with a digital camera DCM310. Then in separate trials, 2 ml of WWSF and WW solutions were added to the plates and images from the growth process of an air pocket were taken. The surface tension of the applied liquids and their static contact angle in the air on the two flat iPP and aPP samples were measured using a Drop Shape Analyzer DSA100 KRÜSS Germany (See Table 3). To detect the contact angle on horizontal surfaces of the flat polymer, a dose of the solution with a volume between 3 μl and 5 μl was manually injected from the syringe onto the polymer surfaces. The drop was detected through a CCD camera and its contact angle analyzed using the device's software. To increase the statistical population, the measurements were repeated at three

Table 2 List of synthetic wastewater constituents, their values and linear structure

Constituents	Linear formula	Value mg/l
Stearic acid	$\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$	33
Palmitic acid	$\text{CH}_3(\text{CH}_2)_{14}\text{COOH}$	34
Oleic acid	$\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$	33
SDBS	$\text{CH}_3(\text{CH}_2)_{11}\text{C}_6\text{H}_4\text{SO}_3\text{Na}$	7.5
CTAB	$\text{CH}_3(\text{CH}_2)_{15}\text{N}(\text{Br})(\text{CH}_3)_3$	1.5
TX100	$t\text{-Oct-C}_6\text{H}_4\text{-(OCH}_2\text{CH}_2)_x\text{OH}$, $x = 9\text{--}10$	10.2
Quartz, 210 to 297 μm	SiO_2	273
Calcium Chloride	CaCl_2	74
Iron Oxides II/ III < 5 μ	$\text{Fe}^{+2}/\text{Fe}^{+3}$	1

positions on each polymer surface with the liquids listed in Table 3.

Image processing To detect the area of trapped air, an image was scaled and the area of the bubble was carefully marked. Next, a mask with the same size of the bubble cap/marked area was created and the corresponding area using the ImageJ plugin for particle analysis measured. Figure 1 shows a graphic sketch of the steps from microscopic detection to final size estimation. The surface roughness was measured using the ImageJ plugin SurfCharJ.

Results and discussion

Air-liquid-solid interfaces of polymer's air pocket The trapped air pockets on the polymer surfaces in the DI water were exposed to the wastewater solutions and exhibited a transformation into a spherical bubble (Fig. 2). As a result of bubble expansion, their size gradually increased and the measured radius of the bubble-cap as a function of time on the iPP and aPP surfaces shown in Fig. 3 varied between 17 μm to 85 μm .

When a bubble interacts with surfactants, the monomers are constantly dispersed from the bulk toward the air-liquid interfaces, forming a monolayer with the head oriented inside the water and the tail towards the air. Formation of a thin layer of surfactants creates a pressure difference between the inside/outside of the bubble which gradually increases the size of air pockets (See Figs. 2 and 3). On the other hand, the adsorption of surfactants at solid-liquid interfaces of the submerged polymer increases the wetting properties of the solid surface at the wedge of three-phase contact line [55, 56]. This process is called de-wetting and leads to a gradual replacing of the solid-liquid phase when the trapped air becomes more

Table 1 List of wastewater surfactants, their values and linear structure

Constituents	Linear formula	Value mg/l
SDBS	$\text{CH}_3(\text{CH}_2)_{11}\text{C}_6\text{H}_4\text{SO}_3\text{Na}$	7.5
CTAB	$\text{CH}_3(\text{CH}_2)_{15}\text{N}(\text{Br})(\text{CH}_3)_3$	1.5
TX100	$t\text{-Oct-C}_6\text{H}_4\text{-(OCH}_2\text{CH}_2)_x\text{OH}$, $x = 9\text{--}10$	10.2

Table 3 The average values of the absolute surface tension measurements for the applied solutions in the tests at room temperature ($20 \pm 3^\circ$). The average value of three tests comprised contact angle measurements of drop/polymer in air on the samples areas of aPP and iPP

Solution	Surface tension (mN/m)	Contact angle θ° aPP	Contact angle θ° iPP
DI water	71.3 ± 0.1	101.9 ± 1.5	99.8 ± 1.3
Wastewater surfactants (WWSF)	57.8 ± 0.1	87.14 ± 1.5	74.5 ± 1.2
Synthetic wastewater (WW)	48.4 ± 0.4	84.3 ± 1.3	73.8 ± 1.4

spherical [57]. The trapped air pockets inside the MPs cavities are highly stable due to the high Laplace pressure and the low contact angle. After the addition of surfactants, adsorption of monomers at the liquid-solid interfaces appears to remarkably change the electrostatic charges of the polymer surface and facilitating bubble growth [58]. The slight decrease in the constant expansion of bubble size over the time seen in Fig. 3 could be attributed to the heterogeneous surface topography of the polymer samples, the gradual increase in surface wettability and the replacement of gas-solid interfacial areas with the liquid-solid interface. By contrast, the sudden increase in the bubble radius can be explained by the adsorption of surfactants at the air-liquid interfaces and their efforts to reduce the surface energy by initiating a spherical shape bubble as well as the sudden increase of the bubble radius due to the de-wetting process.

The WWSF solution contained a mixture of three surfactants. The ionic SDBS and CTAB with opposite charges were mixed with nonionic TX100 and exhibit a concentration lower than the critical micelle concentration (CMC) determined at 0.022 mM, 0.004 mM and 0.017 mM, respectively. In the solution containing cationic (s^+) and anionic (s^-) molecules of surfactants, the electrical balance at the air-liquid interface can be achieved as $s^+ + s^- \approx 0$. The interaction between SDBS and CTAB molecules could reduce the ionic charges of the solution due to the opposing anionic/cationic molecules, thus weakening the repulsion of the electrostatic head group. The result of the measured conductivity of the WWSF $\sim 5 \mu\text{S}/\text{cm}$

shows a weak ionic strength for the solution. This indicates that hydrophobic attraction is the dominate force and air-liquid positioning by the surfactants formed by the pairs of cationic/anionic as well as nonionic monomers [59, 60].

On the contrary, the WW solution with an ionic strength of $\sim 180 \mu\text{S}/\text{cm}$ contains other components, including inorganic salt (CaCl_2), divalent/trivalent magnetite particles (Fe_3O_4) and the macromolecules of lipids. The adsorption of anionic surfactants on the iron oxide particles could alter the electrostatic repulsion between cationic and anionic monomers, suggesting a remarkable decrease in the formation of paired surfactants. In the bulk and before the interaction with air pockets, the free surfactant monomers actively form complexes with lipids and after the interaction they compete for locating at air-liquid interfaces. That means the ionic and hydrophobic forces act simultaneously to neutralize the free energy at the air-liquid interfaces. The presence of divalent Ca^{2+} around the aggregated surfactants leads to their more compact aggregation at the air-liquid interface [61] resulting in a pronounced stability of the bubble film. Hence, the synergistic impact between surfactants and FOG constituents led to a decrease in the surface tension of the solution which is about $10 \text{mN}/\text{m}$ (see Table 3).

The results for the short term analysis represented in Fig. 4 compare the growing rate of the trapped air at the surfaces of the iPP, aPP samples after addition of WWSF and WW solutions. As shown in the normalized graph of Fig. 4a, the initial response of the air bubble size to the contaminants is significantly increased over a measurement period of 600 seconds

Fig. 1 Graphical illustration of the procedure for detecting and measuring of an air pocket

Fig. 2 A series of selected image sequences illustrating the transformation of an air pocket after the addition of the WW solution

(10 min). A much higher values were found for the initiative growth of the bubble after the addition of WW for the two polymer samples. On the other hand, the values of bubble growth are higher for both liquids at the crystalline surfaces of iPP compared to aPP. In the pure DI water, air pockets in different sizes spread over the polymer surfaces within the surface crevices. The Young-Laplace equation shows the relationship between pressure differences inside and outside of a spherical bubble in equilibrium constant as:

$$\Delta P = \frac{2\gamma}{R} \quad (1)$$

Where ΔP is the pressure differences across the bubble film, γ is the surface tension and R is the radius of sphere. By using the Eq. 1, the pressure variations around a growing bubble are calculated and their normalized graph over time is shown in Fig. 4b. The results show a lower Laplace pressure variation for the bubble on the iPP due to the indirect

Fig. 3 The measured radius of the spherical cap including standard error for the WW and WWSF solutions on the iPP and aPP samples

Fig. 4 Normalized graphs of (a) bubble expansion radius and (b) bubble pressure variations over time after the addition of WWSF and WW solutions on the surfaces of iPP and aPP samples

relationship between R and ΔP of Eq. 1. The pressure variation is also lower for the WW as compared with WWSF for the two polymer samples due to the direct relationship between pressure variation and surface tension of the liquids (see Table 3).

Figure 4a shows the variation in the size of the growing cap for iPP and aPP is larger for WW than WWSF due to the lower surface tension of WW (see Table 3) which results in a pronounced increase in the radius of curvature of Eq. 1. As shown in Fig. 4a, the growth of the bubble cap is highest for the iPP sample compared to the aPP. Some initial work in this topic has studied the behavior of hydrophobic surfaces in an aqueous solution and reported variations in the attractive forces in all cases [62, 63, 64] which can be attributed to the heterogeneous surface properties.

Figure 5 illustrates the surface topography of the aPP and iPP polymers as a function of the height variation of the cross line. In aPP, the pore sizes are characterized by randomly distributed rough patterns with some creases of high amplitude and others with low amplitude along the crossed line while the pore sizes of iPP are somewhat identical with periodic wave shape creases. The arithmetic mean Ra value and the root mean square Rq value of the roughness profile over an area size $0.4\text{ mm} \times 0.4\text{ mm}$ for the aPP and iPP samples were measured about $22.6\text{ }\mu\text{m}$, $26.7\text{ }\mu\text{m}$ and $29.4\text{ }\mu\text{m}$, $33.5\text{ }\mu\text{m}$, respectively, which confirms a higher surface roughness for the iPP.

The results of the wettability on the flat polymer samples in Table 3 using the contact angle measurement show that WWSF and WW solutions can wet the iPP surfaces faster than aPP surfaces due to the lower surface energy of the adhering/adhesive molecules. This means that iPP with lower contact angle values achieved the higher wetting properties for the

two solutions. The values of the three phase equilibrium contact angles of the solutions-/surfaces of polymers were calculated according to the Young equation as:

$$\cos\theta_Y = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}} \quad (2)$$

where γ_{lg} , γ_{sg} and γ_{sl} refer to the liquid-gas, solid-gas and solid-liquid interfacial tensions, respectively. In comparison with the values of clean DI water, it is clear that liquids dispersed more rapidly on the iPP surfaces and presumably allow a much faster growth of bubbles due to pollutant adsorption at the air-liquid-solid interfaces (see Table 3; Fig. 4). Whereas the iPP is a low-adhesive polymer due to a low surface energy and hydrophobicity, a greater surface roughness could influence the degree of its surface hydrophobicity/adhesive properties [65]. The influence of methyl group on the reduction of surface tension is considered to be another reason for facilitating the transport of chemicals on the iPP surfaces. Therefore, Eq. 2 which is restricted to the ideal surface properties can be influenced by other physical or chemical factors, such as surface roughness, surface chemical properties, surface chemical heterogeneity, molecular orientation and swelling or partial dissolution of constituents in the material [66, 67].

Figure 6 represents the normalized bubble growth velocity for the two investigated polymers after the addition of WW and WWSF solutions. The average velocity of the growing bubble measured as following:

$$\bar{v} = \frac{\Delta d}{\Delta t} \quad (3)$$

where Δd is the diameter variables of the measured air pocket over the time t sequences of taken images. From Fig. 6a it can

Fig. 5 Microscopic images of the aPP and iPP samples, corresponding plot profile of the crossover line and 3D visualizations of the above original images

be seen that an initial decrease in the normalized velocity of the bubble growth on two PP samples in the first 300 seconds was followed by the stationary lines. Figure 6a and b also shown that the trends behave similarly for the four graphs which can be considered as a mean fit trend line for all measured normalized bubble growth velocity versus time. Comparisons between the best proposed polynomial and exponential curve fit is represented in Fig. 6b. As shown in Fig. 6c, the exponential fit model is the best fit with a determination coefficient $R^2 = 0.994$ and thus the expressed equation in the represented table of Fig. 6 is the closest acceptable for the two applied liquids on the polymer samples. The velocity of the shape variation of bubbles on polymer surfaces contributes to a better understanding of the pollution adsorption at air-liquid-solid interface.

Figure 7 compares the percentage of bubble growth rate with the surface roughness of aPP and iPP after the addition of WW and WWSF. The value of growth rate was calculated from the formula:

$$GR = \frac{g_p - g_i}{g_i} \times 100 \quad (4)$$

where g_p is the maximum measured value of the bubble size and g_i is an initial measured value of the bubble size. The bubble growth rate for the WW and WWSF solutions on the iPP surfaces with a R_a 29.4 μm was calculated as 152% and 63%, respectively. In a similar procedure, bubble growth on the aPP surfaces with a R_a 22.6 μm was found to be 31% and 8% after adding the WW and WWSF solutions.

Fig. 6 (a) Normalized graph of the bubble growth velocity over time and (b) the tested best fit for the average of four lines. (c) The exponential fit gave the best produced fit as the result of several indices e.g. reduced Chi-Sqr and R-square as shown in the corresponding table

Fig. 7 Comparisons of the bubbles radius growth rate at the aPP and iPP surfaces after the addition of WW and WWSF and their relation to the surface roughness

Based on the above results, if the bubble growth is determined by a constant C accounting for adsorption of pollution at the air-liquid interfaces, the time dependent growth of the bubble radius R frequently follows a power-law according to Frank [68]:

$$R_t = Ct^n \quad (5)$$

where $n \neq 1$. According to the results of Fig. 7, a direct relationship was found between air pocket radius and roughness value which can be expressed as:

$$R \propto \frac{1}{r} \text{ when } r = Ra \quad (6)$$

where $1/r$ is the rough surface coefficient of the solid surface and has the value $1/r \leq 1$. To incorporate the effect of surface

roughness of polymer particles, we have to modify Eq. 5 by the particle surface roughness r as follows:

$$R_t = \frac{Ct^n}{r} \quad (7)$$

Hence, the variation of the bubble growth rate in this study is well correlated with Eq. 7 and is also proven by the experimental results represented in Fig. 7.

Conclusion

The present study investigated the interaction of two forms of PP polymers, iPP (crystalline with $R_a \sim 29.4 \mu\text{m}$) and aPP (amorphous with $R_a \sim 22.6 \mu\text{m}$), into two synthetic wastewater solutions, mixed FOG-surfactants and exclusively surfactants, that focused on adsorption of pollutants at air-liquid-solid interfaces of polymer's air pocket.

During the investigation of air pockets it is found that the change in the size of the trapped air after the addition of two wastewater solutions is different and related to the ionic strength of the solutions, to the type of surfactant and the surface properties of the polymers. Based on the results, the initial changes in the size of the trapped air in a periodic time of about 10 min shows an apparently higher growth of the bubble diameter for the iPP. This growth was also higher for the synthetic wastewater solution (iPP 152% and aPP 31%) which contains a greater pollution concentration compared with the surfactants solution (iPP 63% and aPP 8%). From the results it is implied that there is a correlation between an increase in the bubble size and the surface roughness of the polymers. The data also indicated that there is a relationship between the measured normalized velocities of bubble shape variation over the exposure time, which is in agreement with an exponential model.

In summary, the synergistic impact between wastewater constituents and surfactants could intensify the growth rate of surface air-pockets and thus increasing both the pollution uptake at air-liquid-solid interfaces and buoyancy of the MPs inside the fluid. Future studies should address the interaction of various types of MPs with raw wastewater in order to optimize their separation process during treatment procedures.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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