International Journal of Environmental Science and Technology (2019) 16:8663–8670
https://doi.org/10.1007/s13762-019-02496-z

SHORT COMMUNICATION

Nano- and microparticles-induced effect on activated sludge properties

E. Liwarska-Bizukojc[1]

Received: 9 January 2019 / Revised: 29 July 2019 / Accepted: 30 July 2019 / Published online: 5 August 2019

Abstract
Nanomaterials have been usually perceived as a potential contamination of wastewater and thus tested in this context. On the contrary to this approach, here the possibility of the application of mineral microparticles or nanoparticles to improve the operation of activated sludge systems was studied for the first time. This work was aimed at checking the influence of aluminum oxide micro- and nanoparticles on morphology and settling properties of activated sludge. It was found that aluminum oxide micro- and nanoparticles changed the morphology of activated sludge flocs making them more circular. Moreover, the addition of aluminum oxide microparticles at the concentration up to 0.5 g l^{-1} or aluminum oxide nanoparticles at the concentration up to 0.25 g l^{-1} to activated sludge system caused the increase in flocs size. The changes in flocs morphology induced by aluminum oxide micro- or nanoparticles improved the separation processes in wastewater treatment systems and simultaneously did not deteriorate the efficiency of organic pollutants removal. It indicates the possibility to use aluminum oxide micro- or nanoparticles at the appropriate concentrations in wastewater treatment plants as a new solution to struggle against the bulking events.

Keywords Activated sludge · Aluminum oxide · Microparticles · Morphology · Nanoparticles · Separation

Introduction

Nanomaterials due to their beneficial physical and chemical properties, particularly small size and large specific surface area, have many applications in different areas of industry. The wide range of applications increased the risks of their potential release into the environment (Qu et al. 2013; Santhosh et al. 2016). Thus, many types of nanomaterials, including zinc oxide (ZnO), aluminum oxide (Al_2O_3), cerium (IV) oxide (CeO_2), silicon (IV) oxide (SiO_2) and silver (Ag), were tested toward their fate in wastewater treatment plants and/or their effect on biological treatment processes. It was found that the presence of mineral nanoparticles (NPs) in wastewater usually did not significantly influence organic matter removal, nitrification and denitrification (Chen et al. 2012, 2014; Qiu et al. 2016; Wang et al. 2012) although in some conditions the decrease in nitrogen removal was observed (Chen et al. 2012; Cervantes-Avilés and Cuevas-Rodríguez 2017; Wang et al. 2012). Generally, the degrees of nitrogen and phosphorus removal decreased with the increase in NPs concentration (Chen et al. 2012; Wang et al. 2016; Li et al. 2017). Xiao et al. (2017) proposed the application of the magnetic mineral particles to remove and recover phosphorus from the secondary effluent of the wastewater treatment plant.

Regarding the fate of NPs in the conventional activated sludge systems, it was found that nanoparticles usually adsorbed onto activated sludge flocs and then they entered the interior of the microbial cells (Chen et al. 2012; Qiu et al. 2016; Cervantes-Avilés and Cuevas-Rodríguez 2017; Wang et al. 2016; Xiao et al. 2017). In this context, the question raised is whether the presence of nanomaterials in wastewater positively or negatively influenced the flocs morphology and settling properties. The studies performed so far have not answered this question. Limited data published in this

Editorial responsibility: M. Abbaspour.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13762-019-02496-z) contains supplementary material, which is available to authorized users.

✉ E. Liwarska-Bizukojc
ewa.liwarska-bizukojc@p.lodz.pl

[1] Institute of Environmental Engineering and Building Installations, Lodz University of Technology, Al. Politechniki 6, 90-924 Lodz, Poland

field are contradictory. In the case of microparticles (MPs), hardly any data concerning their effect on activated sludge system have not been published yet. Regarding nanoparticles, Cervantes-Avilés and Cuevas-Rodríguez (2017) found that ZnO–NP improved the settling properties of activated sludge; however, the flocs size decreased or increased depending on the composition of wastewater (filtered or not-filtered) used in the experiments. At the same time, Qiu et al. (2016) observed that sludge volume index (SVI) increased due to the presence of silver nanoparticles. Ag NPs contributed to the overproduction of extracellular polymeric substances (EPS) and soluble microbial products (SMP) (Qiu et al. 2016), which deteriorated the sedimentation of suspended solids and induced turbidity in treated wastewater.

Taking into account that nanomaterials adsorb onto surface of activated sludge flocs and subsequently penetrate into the internal regions of these microbiological aggregates, it is highly probable that they change the morphology of flocs and exert the effect on their settleability.

Therefore, in this work the influence of mineral micro- and nanoparticles on morphology of activated sludge flocs and sludge settling properties was studied. It is the first attempt, in which effect of mineral (Al_2O_3) MPs and NPs on activated sludge was compared. It was made with regard to the possible application of MPs and/or NPs for the enhancement of sedimentation processes. Al_2O_3 MPs and NPs were selected due to their inert behavior, i.e., no changes of pH, no leachate products and no toxic effect toward microorganisms, in the cultivation of pure cultures of microorganisms (Etschmann et al. 2015). Some other mineral compounds, e.g., SiO_2, iron (II, III) oxide, were not as inert as Al_2O_3 (Etschmann et al. 2015). All experimental works were made at Lodz University of Technology (Poland) from June to August 2018.

Materials and methods

Size of nano- and microparticles tested

In this work, aluminum oxide nanoparticles (Al_2O_3 NPs) and microparticles (Al_2O_3 MPs) were selected to the tests. Al_2O_3 NPs were purchased from Sigma-Aldrich (Sigma-Aldrich, Germany), while Al_2O_3 MPs were obtained from Fluka (Fluka, USA). According to the manufacturers' data, the particle size of Al_2O_3 NPs was less than 50 nm, whereas the particle size of Al_2O_3 MPs was on average ≤ 10 µm. The purity was 99.5%.

Characterization of activated sludge and synthetic wastewater

Activated sludge was from the aeration part of the bioreactor operating in the Combined Wastewater Treatment Plant (WWTP) in Lodz (Poland). The properties of activated sludge were as follows: The total suspended solids (TSS) were from 3.6 to 4.2 g l^{-1}, and volatile suspended solids (VSS) were from 2.7 to 3.4 g l^{-1}. Sludge volume index (SVI) ranged from 116 to 142 ml g TSS^{-1}. Flocs can be classified as small on average (mean diameter from 77 to 88 µm) and irregular (circularity ranged from 0.317 to 0.379). The average number of filamentous bacteria corresponded to category 2 of the classification formulated by Eikelboom (2000).

The detailed composition of synthetic wastewater used in the tests was presented elsewhere (Gendaszewska and Liwarska-Bizukojc 2013).

Activated sludge tests

The tests were aerobically carried out in shake flasks in the batch mode. First, the appropriate amount of NPs or MPs was weighted and carefully transferred into Erlenmeyer flask of the total volume of 350 ml. Then, 160 ml of fresh synthetic wastewater was added and finally 60 ml of activated sludge biomass was introduced to each Erlenmeyer flask. Activated sludge biomass concentration at the beginning of the tests was 990 ± 85 mg VSS l^{-1}. At the same time, the following concentrations of NPs or MPs were tested: 0.25, 0.50, 1.00 and 2.00 g l^{-1}.

Each of the experiments lasted for 24 h. They were performed at 20 ± 0.5 °C in a rotary shaker Certomat® IS at speed of 130 min^{-1}. Also the control tests (without addition of NPs or MPs) were performed according to the same procedure. All tests were made in triplicate.

Analytical methods

At the start and at the end of each test, chemical oxygen demand (COD), TSS, VSS, SVI and turbidity were determined (APHA-AWWA-WEF 2012).

TSS and VSS were determined gravimetrically and expressed in mg l^{-1}. In order to determine TSS, a well-mixed sample of known volume was filtered and then the filter was dried at 105 °C, cooled, desiccated and weighted until a constant weight was obtained. Next, the filter was placed into a porcelain crucible and combusted at 550 °C, and then again cooled, desiccated, weighed until a constant weight of ash was obtained. VSS was calculated as the difference between TSS and ash.

Apart from the above-mentioned methods, digital image analysis of images was used for the purpose of the determination of the basic morphological descriptors of activated sludge flocs. The activated sludge suspension was mixed properly in the Erlenmeyer flask, and sampling was made with the use of polypropylene Pasteur pipette possessing a tip of diameter equal to 3 mm that was ideal for the preparation of slides from inhomogeneous suspension. As a result, four vital unstained slides of activated sludge sample were prepared. A light microscope Nikon Eclipse N*i* was used for bright-field observations. The magnification of the objective lens was 4×. From each sample, not less than 40 RGB images were snapped, processed and analyzed by the automated procedure elaborated in NIS-Elements AR software (Nikon, Japan). The following morphological parameters of the flocs were measured: projected area, perimeter, equivalent diameter, convexity and circularity. The definitions of these parameters and image analysis procedure were presented elsewhere (Gendaszewska and Liwarska-Bizukojc 2013).

Calculation and statistical elaboration of the results

The statistical elaboration of image analysis data was performed using MS Excel. It comprised the calculation of mean values, standard deviation (σ) and the tests of goodness of fit for different models of distribution (e.g., normal, log-normal Lorentz and Voigt) of activated sludge flocs diameters.

The relative change in flocs area (A_C) was calculated to quantify the increase or decrease in flocs size. It was calculated according to the following equation:

$$A_C = \frac{\left(A_{24} - A_0\right)}{A_0} \cdot 100\% \qquad (1)$$

where A_{24} is the mean projected area of the flocs after 24 h of the test and A_0 is the mean projected area of the flocs at the beginning of the tests.

Results and discussion

Generally, the size of activated sludge flocs increased for the duration of the experiments. It was confirmed by all morphological parameters measured, particularly by the mean projected area of flocs. The relative change in flocs area was 122% in the control run, whereas the addition of Al_2O_3 MPs or Al_2O_3 NPs contributed to the higher increase in activated sludge flocs (from 155 to 197%) than it was observed in the control run. However, it was found only at lower concentrations of micro- or nanoparticles added (Fig. 1a). In the case of Al_2O_3 MPs, it was observed at 0.25 g l^{-1} and 0.5 g l^{-1}, while in the case of Al_2O_3 NPs, only at 0.25 g l^{-1}. At higher concentrations of Al_2O_3 MPs or Al_2O_3 NPs tested (above 0.5 g l^{-1}), the relative change in flocs area was lower than in the control (Fig. 1a). It is consistent with the observations made by Cervantes-Avilés and Cuevas-Rodríguez (2017). They showed that the size of activated sludge flocs was gradually decreasing when the concentration of ZnO NPs increased from 450 to 2000 mg l^{-1} in the experiments with raw (not-filtered) wastewater.

The mean equivalent diameters of flocs also increased in the course of the test, excluding the run with the highest concentration of Al_2O_3 NPs (2 g l^{-1}) (Fig. 1b). The value of mean equivalent diameter of flocs in the control was equal or higher compared to the values of mean equivalent diameter of flocs in the runs with Al_2O_3 MPs or NPs. The effect of Al_2O_3 MPs and Al_2O_3 NPs on the diameter of activated sludge flocs was different. The addition of Al_2O_3 MPs contributed to the increase in the equivalent diameter of flocs to the higher extent than it was observed for Al_2O_3 NPs. As a result, the mean equivalent diameters of flocs in the runs with Al_2O_3 MPs were higher than those in the runs with Al_2O_3 NPs. For example, at the lowest of concentrations studied (0.25 g l^{-1}), the mean floc equivalent diameter was 115 µm in the runs with Al_2O_3 MPs, while in the runs with Al_2O_3 NPs, it was 95 µm. Moreover, the mean equivalent diameter of flocs decreased with the increase in Al_2O_3 MPs or NPs concentrations. Similar phenomenon was also observed for the mean projected area, particularly in the case of Al_2O_3 NPs (Fig. 1a). The values of mean equivalent diameters and mean projected areas measured in this study indicated that the addition of Al_2O_3 MPs at the concentrations above 0.5 g l^{-1} or the addition of Al_2O_3 NPs at the concentration above 0.25 g l^{-1} contributed to the domination of smaller flocs than it was observed in the activated sludge system without the addition of Al_2O_3 MPs or NPs (Fig. 1). The decrease in flocs size caused by the addition of Al_2O_3 MPs or NPs was most probably the result of the destruction of microbial agglomerates, namely activated sludge flocs. Cervantes-Avilés and Cuevas-Rodríguez (2017) also observed this phenomenon in the case of raw wastewater and explained it similarly as Hou et al. (2015) by lower flocculation ability caused by the overproduction of loosely bound EPS. In the case of pure cultures of filamentous fungi, it was proved that the mineral MPs usually contributed to the decrease in agglomerates diameter. They also loosened their structure (Krull et al. 2013). However, mineral MPs as well NPs may also enhance the agglomeration processes. It was shown by Cervantes-Avilés and Cuevas-Rodríguez (2017) in the tests with filtered wastewater, when the presence of ZnO NPs favored the formation of larger flocs than those in the control test. Kowalska et al. (2018) observed that Al_2O_3 MPs can accelerate the agglomeration of spores and small mycelial objects. The results reported in literature as well as these obtained in this work indicated that the effect of mineral MPs or NPs on the morphology of microbial agglomerates may be different and depends on the concentration, type and the size of particles (MPs or NPs) added, the initial morphology and physiological state of the microbial agglomerates and composition of substrate.

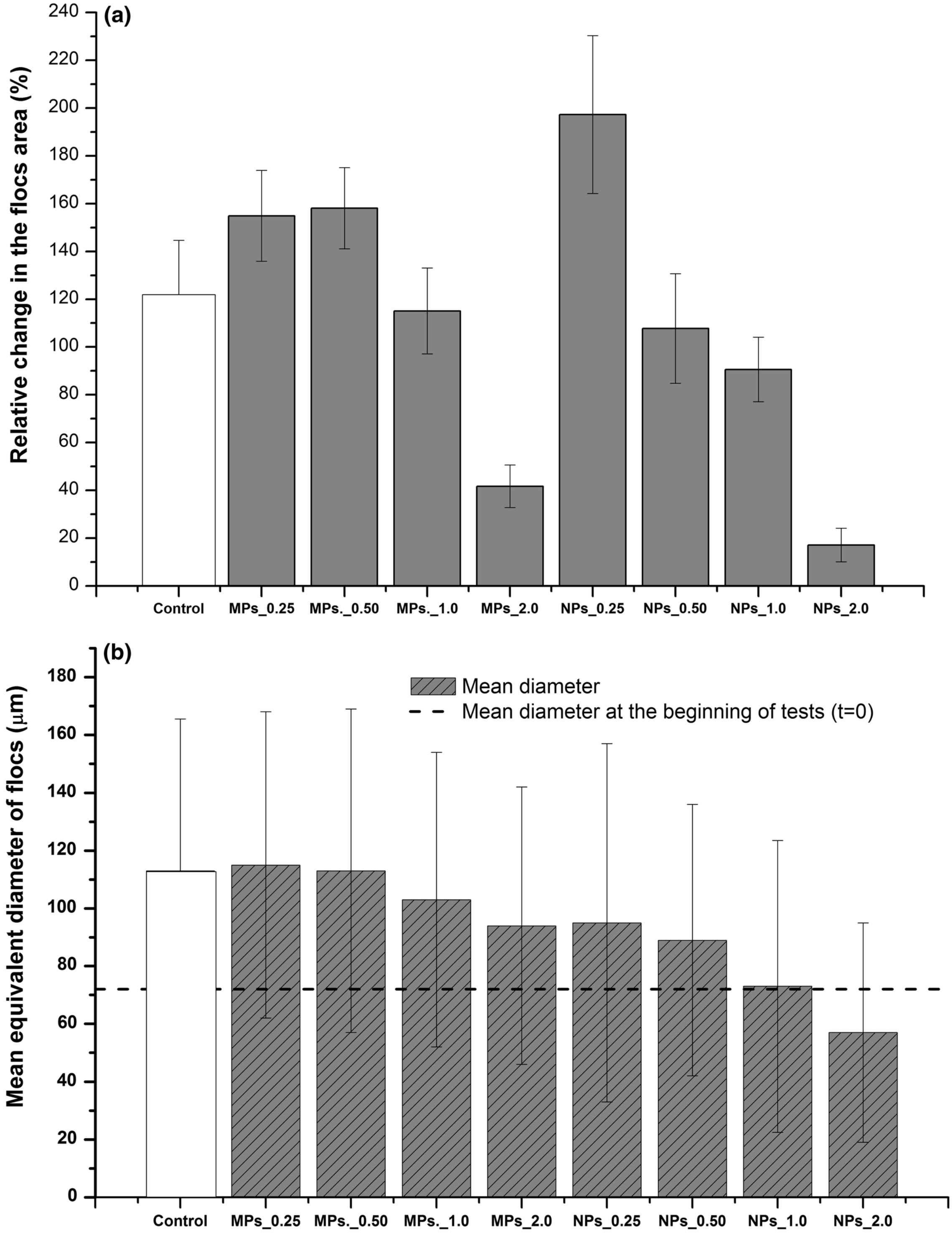

Fig. 1 Effect of Al_2O_3 MPs and NPs on the size of activated sludge flocs: **a** the relative change in the flocs area with the standard deviations; **b** the mean equivalent diameter of flocs with the standard deviations

The distributions of equivalent diameters of flocs corresponded to the log-normal distribution in the case of each test, i.e., with and without Al_2O_3 MPs or NPs (Fig. S1). In order to describe them, the following equation was applied:

$$y = y_o + \frac{A}{\sqrt{2 \cdot \pi} \cdot \sigma \cdot x} \cdot \exp \frac{-\left(\ln \frac{x}{\mu}\right)^2}{2 \cdot \sigma^2} \quad (2)$$

where x is flocs equivalent diameter, μ is the mean value of flocs equivalent diameter, σ is the standard deviation, y_0 is the offset frequency and A is the area under the curve within limits $\pm\sigma$.

The correlation coefficients R^2 ranged from 0.717 to 0.929. The log-normal distribution is frequently observed in various biological systems including activated sludge systems as it was previously shown (Wilén and Balmér 1999). In each test, irrespective of the presence and concentration of Al_2O_3 micro- and nanoparticles, the most frequent were flocs of diameter from 20 to 30 µm.

The addition of Al_2O_3 MPs or NPs also influenced the circularity of the activated sludge flocs. The higher the concentration of Al_2O_3 MPs or NPs was, the more circular the formed flocs were. The Al_2O_3 NPs acted stronger on the circularity of flocs than Al_2O_3 MPs. As a result, the flocs were more circular in the runs with Al_2O_3 NPs than with Al_2O_3 MPs (Fig. 2). In any run, the mean circularity did not exceed 0.560, indicating that the shape of flocs was relatively far from the ideal circle (circularity equal to 1). Simultaneously, the values of mean circularity obtained in the runs with Al_2O_3 NPs (at concentration not lower than 0.5 g l^{-1}) were higher than the values of mean circularity observed during 1-year monitoring of flocs from two wastewater treatment plants (Liwarska-Bizukojc et al. 2015), which usually were below 0.410. The stronger impact of Al_2O_3 NPs than Al_2O_3 MPs on flocs circularity was most probably connected with the size of particles added. Smaller particles changed the morphology of activated sludge flocs to the higher extent contributing to the destruction of agglomerates and, as a result, to the decrease in the diameters of flocs. Thus, the flocs were lower in the experiments with Al_2O_3 NPs than those in the experiments with Al_2O_3 MPs (Fig. 1b). The formation of smaller flocs is often accompanied by their higher circularity in activated sludge systems (Amaral and Ferreira 2005; Bitton 2005). The effect of micro- and nanoparticles on the activated sludge flocs, particularly on their shape, is also seen in the microscopic images shown in Fig. 3.

The changes in flocs morphology induced by the addition of Al_2O_3 MPs or NPs to the activated sludge system influenced the settling properties of sludge. The presence of micro- or nanoparticles of Al_2O_3 improved the settling ability of activated sludge. It was confirmed by the values of SVI, which were lower in the processes with Al_2O_3 MPs or NPs compared to the control runs (Fig. 4). SVI decreased with the increase in the concentration of Al_2O_3 MPs or NPs. It was most probably connected with the increase in flocs density due to the adsorption of mineral particles onto activated sludge flocs, and it was previously observed by Cervantes-Avilés and Cuevas-Rodríguez (2017) too. Additionally, the increase in flocs circularity favored the improvement in flocs settling properties as it could have been expected on the basis of literature data (Eikelboom 2000).The settling velocity of the flocs is reduced if they are irregularly shaped (Eikelboom 2000). The flow resistance is higher for the settling objects of irregular shape than for the circular objects. What is interesting, the decrease in flocs size at higher concentrations (1 and 2 g l^{-1}) of Al_2O_3 MPs or NPs contributed neither to the deterioration of the sedimentation processes, nor to the appearance of turbidity of treated wastewater. It was most probably due to two reasons. First, the decrease in flocs size was not significant,

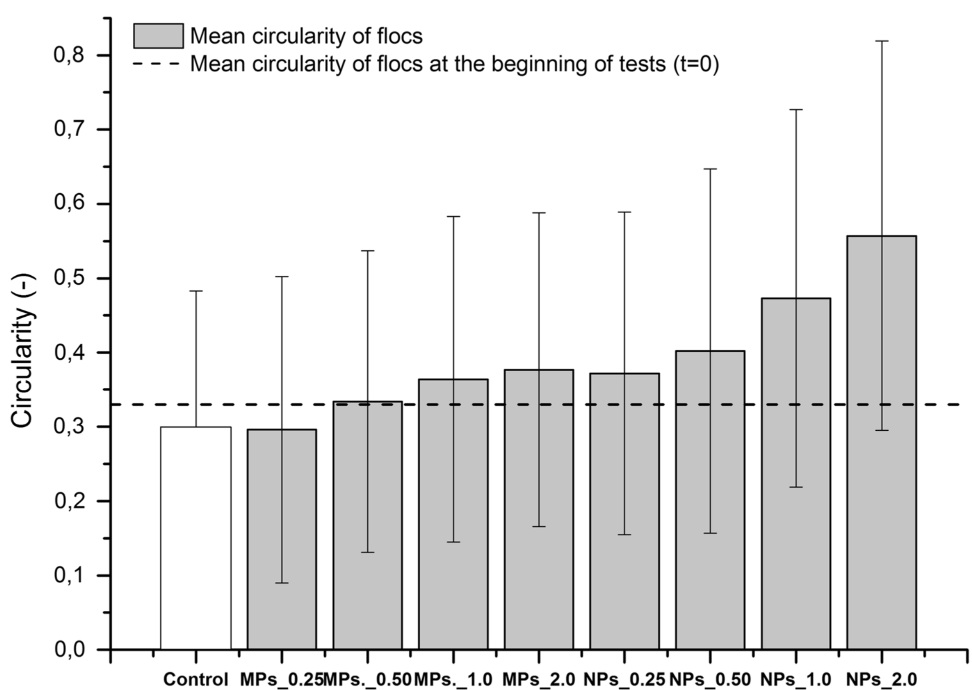

Fig. 2 Effect of Al_2O_3 MPs and NPs on the circularity of activated sludge flocs; the bars reflect the standard deviation of the circularity

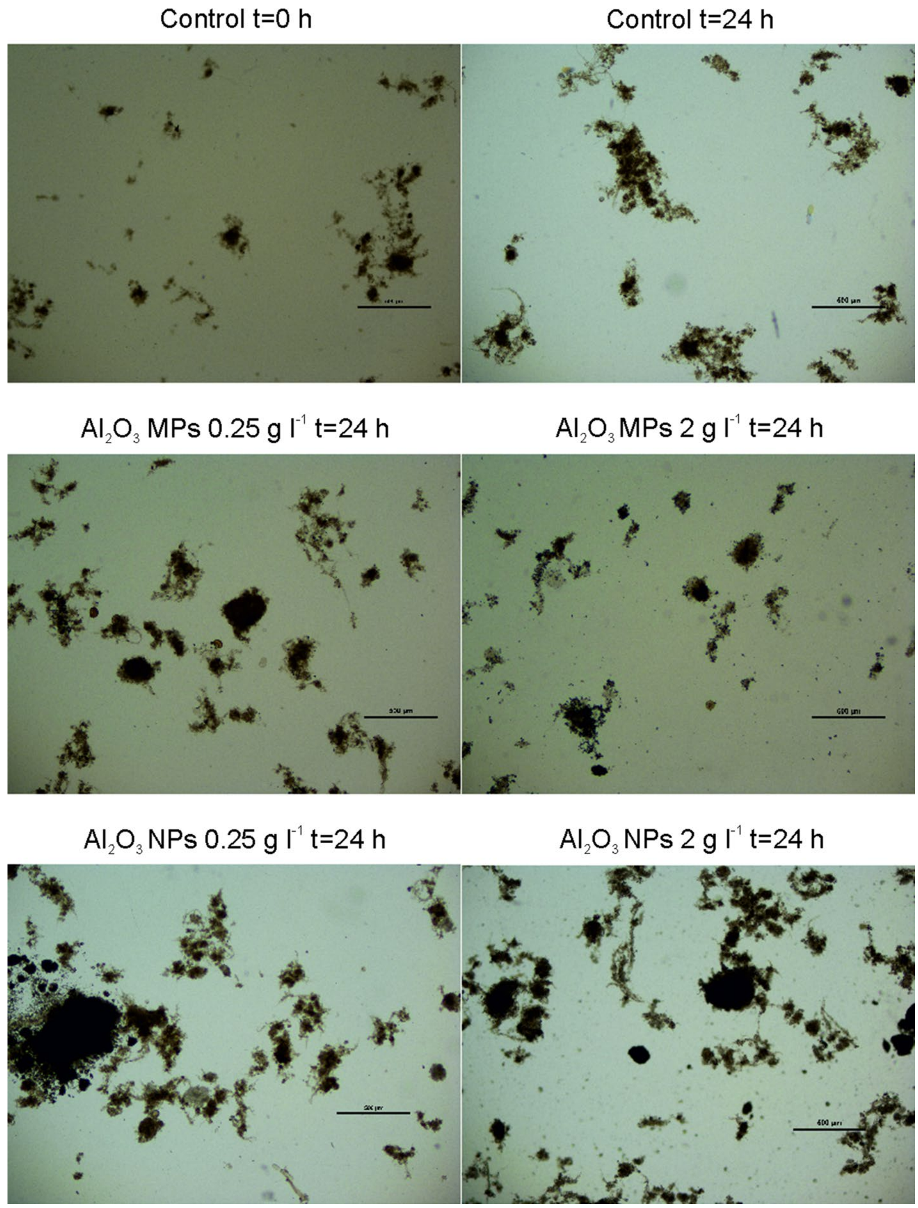

Fig. 3 Comparison of morphology of activated sludge flocs exposed and not exposed (control) to Al_2O_3 micro- and nanoparticles

particularly in comparison with the beginning of the experiment. Second, as it was proved by microscopic observations, Al_2O_3 micro- or nanoparticles were incorporated into sludge flocs increasing their specific gravity. Similar phenomenon was found earlier in the case of other nanomaterials such as SiO_2 NPs, ZnO NPs, Ag NPs or TiO_2 NPs (Qiu et al. 2016; Cervantes-Avilés and Cuevas-Rodríguez 2017; Wang et al. 2016; Li et al. 2017).

The presence of Al_2O_3 MPs or NPs in wastewater at the concentrations up to 2 g l^{-1} did not deteriorate the efficiency of biological treatment processes. The degree of COD removal was at the level from 74 to 80%. It was similar as in the control run, in which its mean value was 78% ± 2.

The application of mineral particles in activated sludge systems has benefits and drawbacks. It depends on chemical composition and concentration of the MPs or NPs used. Upon the own experiments presented in this work and literature data, the advantages and disadvantages of the use of mineral micro- or nanomaterials in activated sludge processes are listed down in Table 1.

Conclusion

1. Al_2O_3 MPs or Al_2O_3 NPs change the shape of flocs into more circular form. Effect of Al_2O_3 NPs on the circularity of flocs is stronger than that induced by Al_2O_3 MPs.
2. The size of activated sludge flocs depends on the concentration of Al_2O_3 MPs or Al_2O_3 NPs added and the size of particles (MPs or NPs). The addition of Al_2O_3

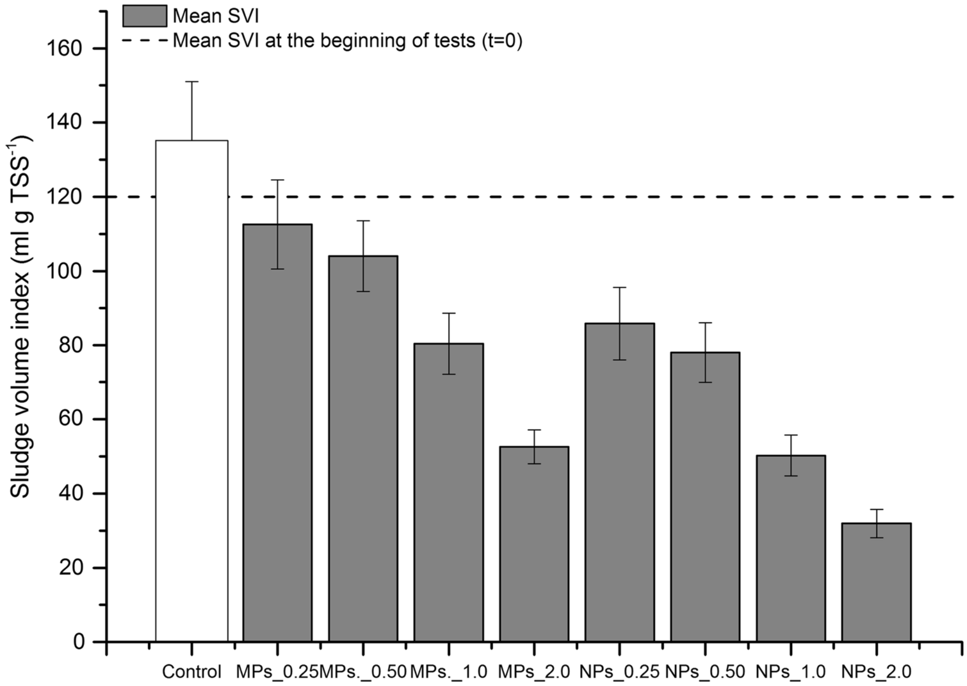

Fig. 4 Effect of Al_2O_3 MPs and NPs on settling properties of activated sludge; the bars reflect the standard deviation of SVI

Table 1 Benefits and drawbacks of the use of mineral MPs or NPs in activated sludge systems

Benefits	Drawbacks
Improvement in settling properties of activated sludge (this work; Cervantes-Avilés and Cuevas-Rodríguez 2017)	The presence of additional contamination, i.e., mineral particles, in the sludge (particularly in the excess sludge removed from the system)
Negligible effect or no deterioration of the removal of organic compounds expressed as COD from wastewater (this work; Chen et al. 2012; Wang et al. 2012; and Qiu et al. 2016)	Decrease in nitrogen removal from wastewater (Chen et al. 2012; Cervantes-Avilés and Cuevas-Rodríguez 2017; and Wang et al. 2016)
No effect or enhancement of phosphorus removal from wastewater (Cervantes-Avilés and Cuevas-Rodríguez 2017; Xiao et al. 2017)	Decrease in the activity of activated sludge microorganisms (Cervantes-Avilés et al. 2017; Wang et al. 2016)

MPs at the concentration up to 0.5 g l^{-1} or Al_2O_3 NPs at the concentration up to 0.25 g l^{-1} to activated sludge system contributes to the increase in flocs size, while higher concentrations of Al_2O_3 MPs or Al_2O_3 NPs contribute to the destruction of flocs and decrease in their size.

3. The changes in morphology of flocs induced by Al_2O_3 MPs or Al_2O_3 NPs act positively on settling properties of activated sludge and simultaneously do not deteriorate the efficiency of organic pollutants removal.

Summing up, the addition of Al_2O_3 MPs or NPs at the appropriate concentrations improves the efficiency of separation processes in the wastewater treatment systems and facilitates the sludge management.

Acknowledgement This work was supported by the own funds (Grant No. I612/W6/TUL) of Faculty of Civil Engineering, Architecture and Environmental Engineering, Lodz University of Technology, Poland.

References

Amaral AL, Ferreira EC (2005) Activated sludge monitoring of a wastewater treatment plant using image analysis and partial least squares regression. Anal Chim Acta 544:246–253. https://doi.org/10.1016/j.aca.2004.12.061

APHA-AWWA-WEF (2012) Standard methods for the examination of water and wastewater, 22nd edn. APHA-AWWA-WEF, Washington DC

Bitton G (2005) Wastewater microbiology, 3rd edn. Wiley, Hoboken

Cervantes-Avilés P, Cuevas-Rodríguez G (2017) Changes in nutrient removal and flocs characteristics generated by presence of ZnO nanoparticles in activated sludge process.

Chemosphere 182:672–680. https://doi.org/10.1016/j.chemosphere.2017.05.074

Cervantes-Avilés P, Camarillo Piñas N, Ida J, Cuevas-Rodríguez G (2017) Influence of wastewater type on the impact generated by TiO_2 nanoparticles on the oxygen uptake rate in activated sludge process. J Environ Manag 190:35–44. https://doi.org/10.1016/j.jenvman.2016.12.054

Chen Y, Su Y, Zheng X, Chen H, Yang H (2012) Alumina nanoparticles-induced effects on wastewater nitrogen and phosphorus removal after short-term and long-term exposure. Water Res 46:4379–4386. https://doi.org/10.1016/j.watres.2012.05.042

Chen J, Tang Y-Q, Li Y, Nie L, Hou X-Q, Li Wu X-L (2014) Impacts of different nanoparticles on functional bacterial community in activated sludge. Chemosphere 104:141–148. https://doi.org/10.1016/j.chemosphere.2013.10.082

Eikelboom DH (2000) Process control of activated sludge plants by microscopic investigation. IWA Publishing, London

Etschmann MMW, Huth I, Walisko R, Schuster J, Krull R, Holtmann D, Wittmann C, Schrader J (2015) Improving 2-phenylethanol and 6-pentyl-α-pyroneproduction with fungi by microparticle-enhanced cultivation (MPEC). Yeast 32:145–157. https://doi.org/10.1002/yea.3022

Gendaszewska D, Liwarska-Bizukojc E (2013) Comparison of imidazolium ionic liquids and traditional organic solvents: effect on activated sludge processes. Water Sci Technol 68(12):2654–2660. https://doi.org/10.2166/wst.2013.546

Hou J, Miao L, Wang C, Wang P, Ao Y, Lv B (2015) Effect of CuO nanoparticles on the production and composition of extracellular polymeric substances and physicochemical stability of activated sludge flocs. Bioresour Technol 176:65–70. https://doi.org/10.1016/j.biortech.2014

Kowalska A, Boruta T, Bizukojć M (2018) Morphological evolution of various fungal species in the presence and absence of aluminum oxide microparticles: comparative and quantitative insights into microparticle—enhanced cultivation (MPEC). MicrobiologyOpen 7(5):1–16. https://doi.org/10.1002/mbo3.603

Krull R, Wucherpfennig T, Esfandabadi ME, Walisko R, Melzer G, Hempel DC, Kampen I, Kwade A, Wittmann C (2013) Characterization and control of fungal morphology for improved production performance in biotechnology. J Biotechnol 163:112–123. https://doi.org/10.1016/j.jbiotec.2012.06.024

Li S, Gao S, Wang S, Ma B, Guo L, Li Z, Xu Q, She Z, Gao M, Zhao Y, Gao F, Jina Ch (2017) Performance evaluation and microbial community shift of a sequencing batch reactor under silica nanoparticles stress. Bioresour Technol 245:673–680. https://doi.org/10.1016/j.biortech.2017.09.018

Liwarska-Bizukojc E, Klepacz-Smółka A, Andrzejczak O (2015) Variations of morphology of activated sludge flocs studied at full-scale wastewater treatment plants. Environ Technol 36(9):1123–1131. https://doi.org/10.1080/09593330.2014.982717

Qiu G, Wirianto K, Sun Y, Ting Y-P (2016) Effect of silver nanoparticles on system performance and microbial community dynamics in a sequencing batch reactor. J Clean Prod 130:137–142. https://doi.org/10.1016/j.jclepro.2015.10.051

Qu X, Alvarez PJJ, Li Q (2013) Application of nanotechnology in water and wastewater treatment. Water Res 37:3931–3946. https://doi.org/10.1016/j.watres.2012.09.058

Santhosh Ch, Velmurugan V, Jacob G, Kwan Jeong S, Grace AN, Bhatnagar A (2016) Role of nanomaterials in water treatment applications: a review. Chem Eng J 306:1116–1137. https://doi.org/10.1016/j.cej.2016.08.053

Wang Y, Westerhoff P, Hristovski KD (2012) Fate and biological effects of silver, titanium dioxide, and C_{60} (fullerene) nanomaterials during simulated wastewater treatment processes. J Hazard Mater 201–202:16–22. https://doi.org/10.1016/j.jhazmat.2011.10.086

Wang S, Gao M, She Z, Zheng D, Jin Ch, Guo L, Zhao Y, Li Z, Wang X (2016) Long-term effects of ZnO nanoparticles on nitrogen and phosphorus removal, microbial activity and microbial community of a sequencing batch reactor. Bioresour Technol 216:428–436. https://doi.org/10.1016/j.biortech.2016.05.099

Wilén BM, Balmér P (1999) The effect of dissolved oxygen concentration on the structure, size and size distribution of activated sludge flocs. Water Res 33:391–400. https://doi.org/10.1016/S0043-1354(98)00208-5

Xiao X, Liu S, Zhang X, Zheng S (2017) Phosphorus removal and recovery from secondary effluent in sewage treatment plant by magnetite mineral microparticles. Powder Technol 306:68–73. https://doi.org/10.1016/j.powtec.2016.10.066