DOI: 10.22102/JAEHR.2018.135459.1086

ORIGINAL PAPER

Effects of nanobubble aeration in oxygen transfer efficiency and sludge production in wastewater biological treatment

Mehrdad Ahmadi[1,✉], Gholamreza Nabi Bidhendi[2], Ali Torabian[2], Nasser Mehrdadi[2]

1. PhD Scholar, Department of Environmental Engineering, Graduate Faculty of Environment, University of Tehran, Tehran, Iran
2. Professor, Department of Environmental Engineering, Graduate Faculty of Environment, University of Tehran, Tehran, Iran

Date of submission: 11 Jun 2018, ***Date of acceptance:*** 06 Oct 2018

ABSTRACT

Low efficiency of conventional aeration techniques and the excessive production and disposal of sludge are great concerns in biological wastewater treatment systems. The present study aimed to evaluate the active sludge method using batch reactors under continuous operation to determine the efficiency of aeration and sludge production through microbubble and nanobubble aeration. The results indicated that compared to microbubble aeration, nanobubble aeration increased the concentration of dissolved oxygen in the mixed liqueur of the reactor (from 2 to 4.5 mg/l), while reducing the production of excess sludge from 100 to 40 ml/g (SRT: 15-40 d). With the same SRT duration, these values were within the range of 160-70 ml/g using fine-bubble aeration. According to the results, nanobubble aeration could increase the efficiency of aeration, thereby increasing the capacity of the treatment plant and reducing the costs of biological wastewater treatment.

Keywords: Air Nanobubbles, Dissolved Oxygen, Excess Sludge, Biological Wastewater Treatment

Introduction

Biological treatment is considered to be among the optimal treatment methods, and sequencing batch reactor (SBR) system is one of the most efficient and promising modifications of activated sludge for wastewater treatment.[1] Aeration is critical in these reactors and could significantly affect the efficiency of treatment plants and treatment costs.[2] Energy consumption in aeration often constitutes 50-90% of the total required energy and more than 30% of the total operation costs.[3, 4] Therefore, selecting proper aeration methods is essential to maximal efficiency.[5]

Active sludge systems are widely applied in municipal and industrial wastewater treatment plants worldwide.[6] One of the main problems associated with conventional activated sludge is the excess sludge production.[7] Among various byproducts of municipal wastewater treatment plants, sludge is regarded to be the most voluminous and challenging component in terms of treatment and disposal.[8] The equipment used for sludge treatment and disposal accounts for 40-60% of construction costs and up to 50% of the operation costs in treatment plants, while secondary sludge treatment accounts for 35-65% of the total operation costs.[9, 10] The issue of excess sludge production could be resolved by reducing sludge production in the biological processes of wastewater treatment.[11] This method is preferred over sludge treatment due to cost-efficiency.[12]

One of the main techniques used to control excess sludge in active sludge systems is the high-dissolved oxygen process in the aeration tank. One of the approaches to providing high-dissolved oxygen is to decrease the size of the air bubbles that are blown into the aeration tank. Due to the reduction of the air bubble size as a result of increased contact surface and mass transfer coefficient (K_la), the concentration of dissolved oxygen increases.[13] On the other hand, the gas solubility is proportional to the gas pressure, which is reversely proportional to the bubble dimensions. Therefore, reducing the size

✉ *Mehrdad Ahmadi*
ahmadim@shirazu.ac.ir

Citation: Ahmadi M, Nabi Bidhendi Gh, Torabian A, Mehrdadi N. Effects of Nanobubble Aeration in Oxygen Transfer Efficiency and Sludge Production in Wastewater Biological Treatment. J Adv Environ Health Res 2018; 6(4): 225-233

of the bubbles enhances the process of gas dissolution through the movement and displacement of the bubbles and their contraction.[14]

High concentrations of dissolved oxygen produce more active biomass, increasing the deep release of oxygen in the floc mass, as well as the volume of the inner aerobic section. This hydrolyzed biomass in the floc mass achieves the potential of aerobic decomposition, ultimately decreasing the produced sludge. In addition, the dissolved oxygen accelerates the autolysis process in bacteria and reduces sludge production.[15]

At high concentrations of dissolved oxygen, the anoxic zone of the flocs collapses, thereby increasing the rate of biological lysis reactions. The concentration of the contaminants in the wastewater compartment correlates with the oxygen consumption rate and is directly affected by the influx of oxygen into the active sludge flocs.[16]

The findings regarding pure oxygen process in activated sludge have indicated that compared to the conventional activated sludge system, the high rate of sludge loading could be reduced to 54%. Increased dissolved oxygen from 1.8 to 6 mg/l lead to excess sludge production (from 0.29 to 0.2 mg MLSS/mg BOD).[17]

Increasing dissolved oxygen in an active sludge system (from 0.5 to 4.5 mg/l) has been shown to decrease excess sludge to 25%.[13] In another study, increased concentration of dissolved oxygen from 2 to 6 mg/l resulted in the reduction of sludge production to 25%.[17] The present study aimed to assess the effects of nanobubble aeration on the efficiency of oxygen transfer and amount of sludge production in a pilot-scale wastewater biological treatment.

Materials and Methods

In the present study, we used two rectangular cubic cylindrical Plexi glass reactors with the length, width, and height of 19, 19, and 80 centimeters, respectively. The total volume, useful volume, and treatment capacity of each glass were 28.8, 20, and 10 liters, respectively.

Reactor one was equipped with nanobubble aeration, and reactor two was equipped with fine-bubble aeration. For this purpose, an A CO-018 blower (3604 Model, Resun Co.) was used. The air flow in the path was divided into two lines. Flow line one was designed to produce air nanobubbles, and flow line two was developed to produce fine bubbles. Moreover, the air flow was classified as flow line one for generating nanobubble air and flow line two for fine-bubble air generation. Line one entered the nanobubble generation instrument, and after converting air into nanobubbles, entered reactor two. Flow line two produced fine bubbles by installing a tubular diffuser on its end, which was located on the bottom of reactor two.

The size of the hollow diffuser pores was 1-3 millimeters, the size of the used nanobubbles was 50-250 nanometers, and the size of the fine bubbles was 1-3 millimeters. The air flow rates were identical on lines one and two (one liter per minute). In order to adjust the air flow rate in flow line one, an air volume control device was installed. In flow line two, we utilized a flow meter with a valve. To maintain the reactor feed and treated effluent of the reactor outputs, three plastic reservoirs (100, 20, and 20 liters) were used.

Control System and Accessories

The control system was composed of an FBS-20 MA PLC device, a DC-24 relay, a finder, air electric and gate electric valves (diameter: 1.2 inches) (model: UNI-DO Model) for evacuating the reactors, and two floating pumps for filling the reactors. Moreover, two aquarium heaters (JAGER, Germany) were used to maintain the temperature of the solution inside the reactors (Figure 1).

Operation Conditions of the Reactor

In order to investigate the effects of the air bubble size on the efficiency of the activated sludge system (SBR type), other conditions than the size of the blown air bubbles into the reactors were identical in both reactors. In addition, the changes that were simultaneously applied to each reactor were similar in order to assess the effects of the selected parameters.

These changes included three levels of reactor input chemical oxygen demand (COD) (400, 600, and 800 mg/l), and three sludge retention times (20, 30, and 40 days).

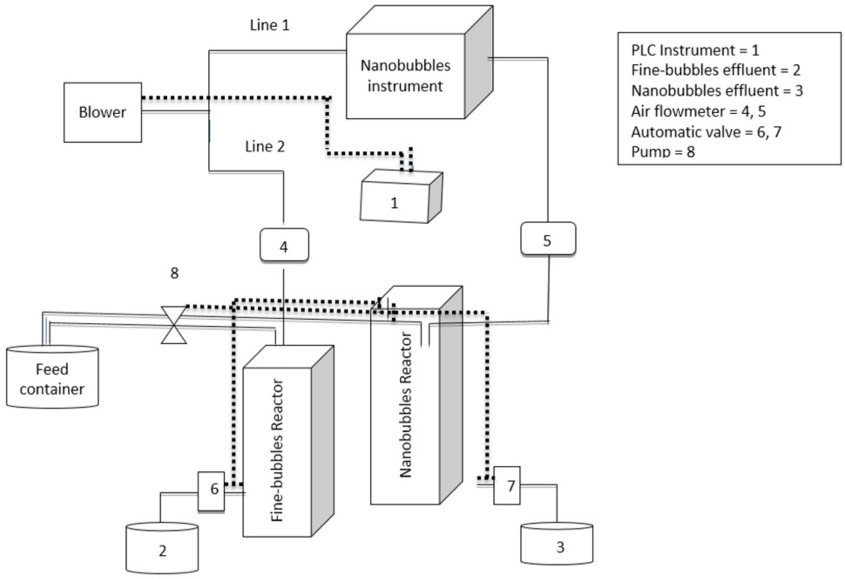

Fig. 1. Schematic diagram of pilot

Work Periods

The work periods for each of the reactors were as follows: Fill (four minutes), React (five hours and 45 minutes), Settle (45 minutes), and Decant (30 minutes).

Characteristics of Wastewater

The wastewater used in the current research was synthetic in order to control the concentrations in the reactor feeds. Components of the wastewater are presented in Table 1. The pH of the mixed liquor inside the reactor was 7±0.5, which was adjusted by adding soda to the reactor inlet. The temperature of the mixed liquor in the reactors was controlled within the range of 25±0.25 ºC using an acoustic heater.
daily. Subsequently, the SBR pilot system was initiated with the four stages of ‘Fill’, ‘React’, ‘Settle’, and ‘Decant’.

The COD effluent was monitored and controlled, and the results were compared each time with the previous findings. Two weeks after initiating the SBR system,

Reactor Setup

In order to set up the reactors, the activated sludge seed was initially prepared from the return line of the sludge collected from the treatment plant in the west of Tehran (Iran), which had no operational problems (e.g., balking, rising, and pinpoint phenomenon). Approximately four liters of activated sludge seed was added to each reactor, and the rest of the reactor was filled with up to 20 liters of synthetic sewage with the COD concentration of 500±20 mg/l.

Aeration and reaction were performed for one week to form sludge or biomass without discharging wastewater and sludge, so that sufficient substances could be fed to the reactors the effluent COD results were similar, indicating a stable condition. In order to ensure the stabilization of the reactors, another sampling period was carried out at a three-day interval, and the obtained results confirmed the stabilized status of the reactors.

Table 1. Characteristics of synthetic wastewater[18]

	Components	Chemical formula	Molecular weight (g/mol)	Concentration (mg/l)
Organics and nutrients	Glucose	$C_6H_{12}O_6$	180	280
	Ammonium sulfate	$(NH_4)_3SO_4$	132.1	72
	Potassium phosphate	KH_2PO_4	136.1	13.2
Minerals	Calcium chloride	$CaCl_2{\cdot}2H_2O$	147	0.368
	Magnesium sulfate	$MgSO_4{\cdot}7H_2O$	246.5	5.07
	Manganese chloride	$MnCl_2{\cdot}4H_2O$	197.9	0.275
	Zink sulfate	$ZnSO_4{\cdot}7H_2O$	287.5	0.44
	Ferric chloride	$FeCl_3$	162.2	1.45
	Copper sulfate	$CuSO_4{\cdot}5H_2O$	249.7	0.391
	Cobalt chloride	$CoCl_2{\cdot}6H_2O$	237.9	0.42
	Sodium molybdenum dihydrate	$Na_2MoO_4{\cdot}2H_2O$	242	1.26

Changing the Conditions

To adapt the system to new conditions, a minimum of one week was considered after changing the COD and SRT each time. Measurements were performed after the stabilization of the conditions. Concentration of the suspended matter inside the reactors and treated output COD were considered as the indicators of stabilized conditions.

Sampling

To conduct the experiments, sampling was performed from the reactor feed, treated effluent from the reactors, and inside the reactors at specific periods based on the Standard Methods for Water and Wastewater Examination.[19] Sampling was carried out using 100-milliliter plastic bottles.

Data Analysis

The samples prepared from the mixed liquor inside the reactor were first filtered through a Whatman grade 40 filter paper. The concentration of dissolved oxygen was measured using the Martini DO meter (model: Mi 605 model), and a pH meter (model: Metrohm, 691) was used to measure the pH. In addition, a particle size analyzer (model: Malvern ZEN3600) was applied to determine the size of the nanobubble air, and the levels of COD, total nitrogen, nitrate nitrogen, and total phosphor were measured using the DR5000 spectrophotometer (HACH, Germany). The other analyses were performed based on standard methods.[19] The results of the experiments were recorded in tables, and plots were drawn using the Origin 8.1 software.

Results and Discussion

Effect of Nanobubble Aeration on Oxygen Transfer Efficiency

Unlike continuous complete mixed systems, where aeration rate and dissolved oxygen concentration in the system are constant, if the aeration rate is constant in continuous system reactors, the dissolved oxygen concentration changes over time. This is due to the changes in the rate of oxygen consumption by microorganisms throughout the process.[20]

As is depicted in Figure 2, in the aeration and react phases, three zones were detectable in the variations of the dissolved oxygen concentration, including the first zone, which initiated immediately after aeration, taking several seconds to several minutes depending on the type of the air bubbles. In this zone, despite the aeration of the system, the dissolved oxygen concentration inside the reactor remained at a constant minimum level.

The second zone began after the first zone with a rapid increase in the concentration of dissolved oxygen. In this zone, the increased concentration of dissolved oxygen inside the system followed an exponential curve, which remained almost constant after reaching a certain value. The sum of the first and second zones was referred to as the ‘transitional zone’.

After the second zone, the third zone initiated with a relative increase in the concentration of dissolved oxygen.

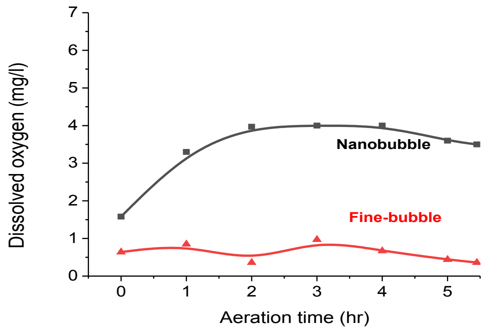

Fig. 2. Changes in Dissolved Oxygen in Reactor Mixed Liquor (SRT=20 d, COD=600 mg/l)

In a study, Pavselj *et al.* reported no clear explanation for the first zone, while they claimed that the end of the second zone indicated the disappearance of ammonia, and the end of the third zone showed the end of the reaction phase.[21]

According to the findings of the current research, the first zone was present in both of the aeration processes, while its duration reduced in the nanobubble aeration process by a few minutes. In the fine-bubble aeration process, the duration of the first zone covered the entire duration of the reaction (Figure 3). The previous studies in this regard have demonstrated that the formation of this zone may be due to the consumption of the soluble portion and the readily biodegradable food by bacteria.[22]

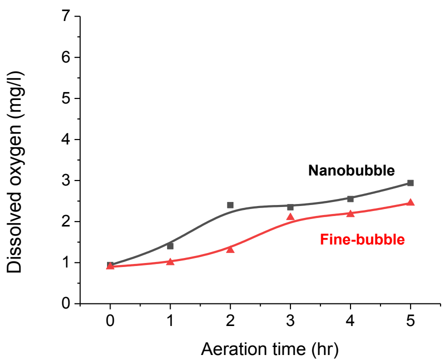

Fig. 3. Changes in Dissolved Oxygen in Reactor Mixed Liquor (SRT=20 d, COD=800 mg/l)

In the aeration process with fine bubbles and at the beginning of the reaction phase of the aeration with nanobubbles, the level of the available oxygen to the bacteria was limited, which acted as an inhibitory factor. In other words, the oxygen consumption rate was higher than the oxygen supply rate; therefore, despite aeration, the dissolved oxygen concentration inside the reactor remained at a constant minimum level (Figure 4).

According to Pavselj *et al.*[21], the end of the second zone corresponds to the end of the disappearance of ammonia inside the system (Figure 5). In the nanobubble aeration process, the duration of this phase was shortened compared to the fine-bubble aeration process. In nanobubble aeration, determining the boundary between the second and third zone was difficult due to the rapid and significant increase in the concentration of dissolved oxygen inside the reactor. On the other hand, determining the boundary between the first and second zone was difficult fine-bubble aeration due to the limited oxygen supply.[23]

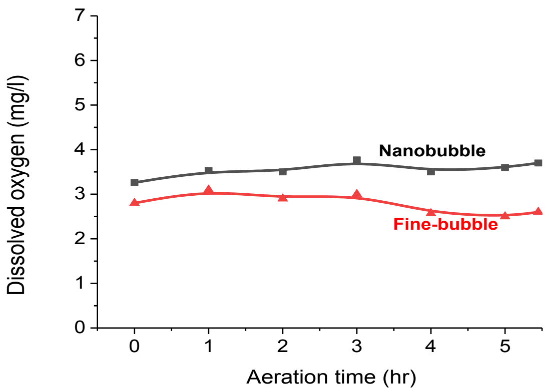

Fig. 4. Changes in Dissolved Oxygen in Reactor Mixed Liquor (SRT=20 d, COD=400 mg/l)

According to the plots depicted in figures 2-4, the end of the third zone corresponded to the end of the React phase. At the end of this phase, the provision of adequate oxygen resulted in the complete nitrification and removal of organic matter. In fine-bubble aeration, due to the limited oxygen supply, the removal processes of organic matter, particularly nitrification, could not be completed. However, there was no oxygen limitation in nanobubble aeration, and other food substances were considered to be the inhibitory factors.[24] Due to the increased oxygen supply in the mixed liquor of the reactor in this process, the duration of the transition zone was observed to reduce.

Our findings indicated that in the nanobubble aeration process, the concentration of dissolved oxygen in the mixed liquor inside the reactor was higher compared to fine-bubble aeration. This could be attributed to the fact that reducing the size of the air bubbles at the nanoscale increased the surface-to-volume ratio of the bubbles, as well as the survival of the bubbles in the reactor mixed liquor. As a result, the effective contact time and contact between the bubbles and surrounding liquor increased, which in turn incremented the mass transfer coefficient of oxygen from the bubbles to the liquor inside the reactor, as well as the dissolved oxygen concentration. Furthermore, the rate of this process increased by the moving, displacing, and contraction of the bubbles. On the other hand, with the size of the bubbles shrinking to the nanoscale, the pressure of the oxygen gas inside the bubble increased, thereby incrementing the dissolution of the oxygen gas in the liquor surrounding the air bubbles, which is consistent with the previous findings in this regard.[17]

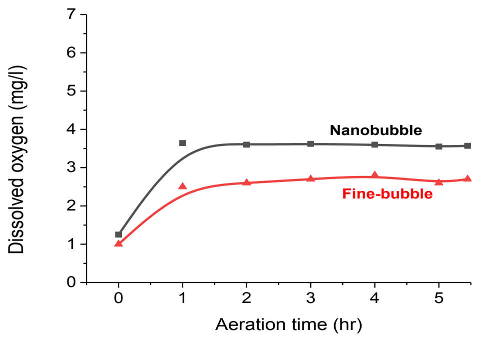

Fig. 5. Changes in Dissolved Oxygen in Reactor Mixed Liquor (SRT=40 d, COD=800 mg/l).

Effect of Nanobubble Aeration on Sludge Production

The organic materials that are available to microorganisms are divided into two groups of external organic matters and internal organic matters. External organic matters are those entering the reactors, and internal organic matters are fed through the digestion of the biomass from dead bacteria, as well as the stored organic matters in the mass of the bacteria as polyhydroxyls.

The soluble and biodegradable parts of external organic matters were immediately used by bacteria in the early stages of the reaction, leading to a rapid drop in COD. Following that, the insoluble and biodegradable portions and organic materials stored in the cell were consumed at the second stage of the reaction.[25]

Based on the growth and death curve of microorganisms, although the second phase represents the logarithmic growth of microorganisms, the target for the removal of organic matters was not fulfilled due to the fact that the organic matter concentration in the system should be maximal. Regarding the autolysis phase, organic matter removal was completed since in this phase, the food-to-microorganism ratio decreased, and microorganisms fed on the cytoplasm due to food shortage, which in turn reduced sludge production. It seems that if sufficient dissolved oxygen is available to microorganisms, the intensity of the sludge reduction is likely to increase.

In biological wastewater treatment reactors, microorganisms are active in biofilm or aggregate namedactive floc.[26] If the microbial flocs in the active sludge are examined, various microorganisms (e.g., bacteria, fungi, and protozoa) could be observed. Bacteria play the major role in this regard, followed by protozoa. Numerous bacterial species (mainly chemoheterotroph and aerobic facultative) grow in the active sludge process.[27]

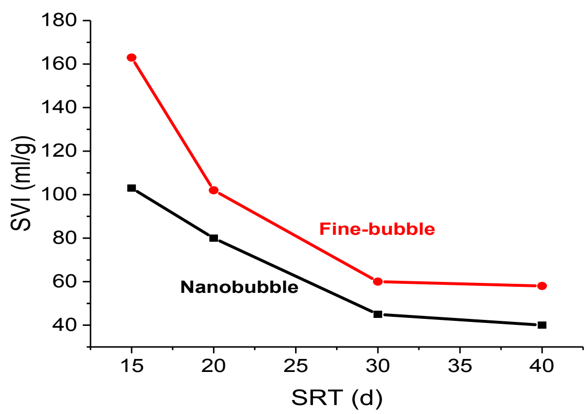

Fig. 6. Changes in Sludge Volume Index versus SRT

Under appropriate conditions, bacteria are dominant in the environment and form a large body. Along with bacteria, other microorganisms are also able to grow in this process. On the other hand, fungi cannot compete with bacteria. Protozoa are mainly aerobic, and as predatory organisms, they feed on bacteria or other organisms and solids.

According to the literature, increasing the concentration of dissolved oxygen leads to the higher rate of cell mass lysis, as well as the increased anoxic zone in the floc in aerobic conditions due to the higher concentration of dissolved oxygen and biological lysis rate.[28]

According to the results of the present study, sludge volume index (SVI) in the nanobubble aeration process significantly decreased compared to the sludge production in fine-bubble aeration. In fact, SVI was significantly lower in nanobubble aeration (100 ml/g) at the SRT of 15 days although SRT increased later (up to 40 d), and the SVI for both aerations reduced gradually (Figure 6).

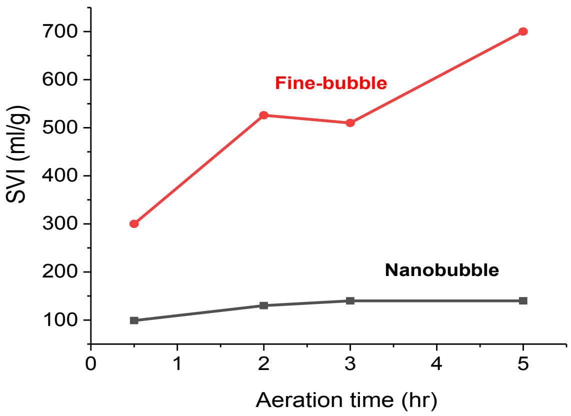

Fig. 7. Changes in SVI versus Aeration Time

It seems that reducing the size of the air bubbles to the nanoscale, along with increasing the dissolved oxygen concentration in the reactor mixed liquor, adds to the penetration of the air bubble into the biological flocs, creating aerobic conditions in the wider depths and breadths of the flocs.[29] This could increase the number of the active bacteria in the floc mass, which accelerates and intensifies the decomposition and destruction of the organic matters entering the reactors compared to fine-bubble aeration. Consequently, the amount of the produced sludge decreases. In the case of nanobubble aeration, SVI was observed to be almost similar (mean SVI=120 ml/g) during five hours of aeration, while in the case of microbubble aeration, it increased significantly (from 300 ml/g after one hour of aeration to 700 ml/g after five hours of aeration) (Figure 7).

Under such circumstances, the bacteria were observed to grow faster and enter the autolysis phase earlier, and the bacterial autolysis was more intense as well. On the other hand, other microorganisms such as protozoa, which are aerobic and bacterial hunters, were found to be more active. In general, the conditions resulting from the nanobubble aeration caused the biomass lysis phenomenon and the hunting of the bacteria by the protozoa, which in turn reduced the production of sludge more significantly than fine-bubble aeration.

Conclusion

Based on a pilot-scale study, we investigated the effect of the size of air bubbles (nanobubbles versus microbubbles) on the oxygen transfer energy and sludge production of SBR. According to the obtained results, nanobubble aeration decreased the duration of the transition zone due to the increased oxygen supply in the mixed liquor of the reactor. However, the increase had no significant difference with microbubble aeration. Moreover, the COD concentration (400-600 mg/l) had no visible effect on the oxygen transfer efficiency. Nanobubble aeration significantly reduced the sludge production compared to microbubble aeration. Mean SVI for nanobubble aeration was estimated at 150 ml/g after five hours of aeration, while it increased to 700 ml/g after the same period. In addition, the SVI versus SRT was significantly lower in nanobubble aeration (100-40 ml/g for 15-40 d, respectively) compared to microbubble aeration (160-80 ml/g for 15-40 d, respectively). Therefore, it could be concluded that nanobubble aeration not only increases the oxygen transfer efficiency, but it also decreases the sludge production in SBR systems.

Acknowledgements

This article was extracted from a PhD dissertation conducted by the first author. Hereby, we extend our gratitude to the Faculty of Engineering at Shiraz University and School of Pharmacy at Tehran University of Medical Sciences for providing laboratory facilities. We would also like to thank the laboratory staff for assisting us in this research project.

References

1. Fernandes H, Jungles MK, Hoffmann H, Antonio RV, Costa RHR. Full-scale sequencing batch reactor (SBR) for domestic wastewater: performance and diversity of microbial communities. Bioresour Technol 2013; 132: 262-268.
2. Au MT, Pasupuleti J, Chua KH. Strategies to improve energy efficiency in sewage treatment plants. IOP Conf Ser: Earth Environ Sci 2013; 16012033.
3. Guerrini A, Romano G, Indipendenza A. Energy efficiency drivers in wastewater treatment plants: a double bootstrap DEA analysis. Sustainability 2017; 9: 1126.
4. Gandiglio M, Lanzini A, Soto A, Leone P, Santarelli M. Enhancing the energy efficiency of wastewater treatment plants through co-digestion and fuel cell systems. Front Environ Sci 2017; 5(70).
5. Rajasulochana P, Preethy V. Comparison on efficiency of various techniques in treatment of waste and sewage water- A comprehensive review. Resour Efficient Technol 2016; 2(4): 175-184.
6. Hayet C, Saida BA, Youssef T, Hédi S. Study of biodegradability for municipal and industrial Tunisian wastewater by respirometric technique and batch reactor test. Sustain Environ Res 2015; 26(2): 55-62.
7. Wei Y, Houten RTV, Borger AR, Eikelboom DH, Fan Y. Minimization of excess sludge production for biological wastewater treatment. Water Res 2003; 37(18): 4453-4467.
8. Hamawand I, Ghadouani A, Bundschuh J, Hamawand S, Al Juboori RA, Chakrabarty S, et al. A critical review on processes and energy profile of the Australian meat processing industry. Energies 2017; 10(5): 731.
9. Arcivala SJ. Wastewater treatment for pollution control. Third ed, McGraw-Hill Inc. 2003.
10. Benefield LD, Randall CW. Biological process design for wastewater treatment. Englewood Cliffs, NJ: Prentice- Hall, 1980.
11. Velho VF, Daudt GC, Martins CL, Belli Filho P, Costa RHR. Reduction of excess sludge production in an activated sludge system based on lysis-cryptic growth, uncoupling metabolism and folic acid addition. Brazil J Chem Eng 2015; 33(1): 47 – 57.
12. Irvine RL, Busch AW. Sequence batch reactors and overview. J WPCF. 1979; 51(2): 235 – 243.
13. Stams A, Elferink S. Understanding and advancing wastewater treatment. Curr Opin Biotech 1997; 8(3): 328-334.
14. Michelin S, Guérin E, Lauga E. Collective dissolution of microbubbles. Phys Rev Fluids 2018; 3(4): 43601.
15. Semblante GU, Phan HV, Hai FI, Xu ZQ, Price WE, Nqhiem LD. The role of microbial diversity and composition in minimizing sludge production in the oxic-settling-anoxic process. Sci Total Environ 2017; 607-608: 558-567.
16. Li B, Bishop PL. Micro-profiles of activated sludge floc determined using microelectrodes. Water Res 2004; 38(5): 1248-1258.
17. Abbasi B, Dullstein S, Rabiger N. Minimization of excess sludge production by increase of oxygen concentration in activated flocs: experimental and theoretical approach. Water Res 2000; 34: 139-146.
18. Patsios SI, Karabelas AJ. An investigation of the long-term filtration performance of a membrane bioreactor (MBR): The role of specific organic fractions. J Membr Sci 2011; 372: 102-115.
19. APHA. Standard methods for the examination of water and waste water, 21st ed. American Public Health Association, Washington, DC., 2005.
20. Huang JYC, Cheng MD, Mueller JT. Oxygen uptake rates for determining microbial activity and application. Water Res 1985; 19(3): 373-381.
21. Pavselj N, Avatar N, Kocijan J, Ros M, Subelj M, Music G, et al. Experimental design of all optimal please duration control strategy used in batch biological wastewater treatment. ISA Trans 2001; 40: 41-56.
22. Yoo H, Ahn KH, Lee HJ, Lee KH, Kwak YJ, Song KG. Nitrogen removal from synthetic wastewater by simultaneous nitrification and denitrification (SND) via nitrite in an intermittently aerated reactor. Water Res 1999; 33(1): 145-154.
23. Garcia-Ochoa F, Gomez E. Bioreactor scale-up and oxygen transfer rate in microbial processes: an overview. Biotech Adv 2009; 27:

153-176.
24. Ebina K, Shi K, Hirao M, Hashimoto J, Kawato Y, Kaneshiro S, et al. Oxygen and air nanobubble water solution promote the growth of plants, fishes, and mice. PLoS ONE 2013; 8(6): e65339.
25. Muhammadi, Shabina, Afzal M, Hameed S. Bacterial polyhydroxyalkanoates-eco-friendly next generation plastic: Production, biocompatibility, biodegradation, physical properties and applications. Green Chem Lett Rev 2015; 8(3-4), 56-77.
26. Weber SD, Ludwig W, Schleifer KH, Fried J. Microbial composition and structure of aerobic granular sewage biofilms. Appl Environ Microbiol 2007; 73(19): 6233-6240.
27. Hiraishi A, Kitamura H. Distribution and phototrophic purple nonsulfur bacteria in activated sludge systems and other aquatic environments. Bull Japan Soc Sci Fish 1984; 50(11): 1929-1937.
28. Schmit CG, Jahan K, Schmit KH, Debik E, Pattarkine V. Activated sludge and other aerobic suspended culture processes. Water Environ Res 2010; 88(10): 1073-1123.
29. Wei C. Nutrient removal and fouling reduction in electrokinetic membrane bioreactor at various temperatures. PhD Thesis. Department of Civil Engineering, University of Manitoba, Winnipeg, Canada. 2016.