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Efficient Wastewater Treatment via Aeration Through a Novel Nanobubble System in Sequence Batch Reactors

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The aerobic wastewater treatments depend on the aeration. Hence, the size of the bubbles used in the aeration system may play a crucial role in this regard. This study attempted to investigate the effects of aeration bubble size on wastewater treatment efficiency of a "sequence batch reactor" (SBR) system at a laboratory scale using a novel designed fine/nanobubble forming instrumentation system. Based on the presence of microorganisms in the stationary phase, chemical oxygen demand removal efficiency on the 15th day (80.0 and 95.0%) was majorly better than on the 10th and 15th days in fine and nanobubble aeration systems. Moreover, with increasing sludge age, the "sludge volumetric index" (SVI) increased up to 170.0 ml g^{-1} on the 15th day. In addition, sludge rate and F/M ratio were much higher and expressively less in the nanobubble system rather than in the fine-bubbles system in which sludge was majorly denser. Therefore, the sludge was more easily deposited and the percentage of dry sludge was higher compared with the fine-bubble system. Thus, oxygen and specific oxygen uptake rate consumption were significantly reduced. The efficiency of the phosphorus removal was estimated to be between 54.0–60.0% for nanobubble aeration, compared to the general systems such as the SBR (10–20%) under similar conditions. In addition, the efficiency of the nitrogen removal in the nanobubble aeration system with different densities of 40.0, 50.0, and 60.0 ml g^{-1} was found as 99.0%, relatively higher compared to fine bubble with 96.0% nitrogen efficiency. In conclusion, a nanobubble aeration system could give considerably promoted efficiencies in all terms of the tested treatment effective parameters.

Keywords: nanobubble, biological treatment, aeration, chemical oxygen demand, food/mass ratio, sludge volumetric

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1 INTRODUCTION

Population growth and urbanization along with the increasing growth of industries have brought about environmental issues (Leslie Grady et al., 2011). Untreated wastewater is one of the contaminants of the environment and water resources; hence, it should be collected, treated, and then returned to the flow of water in nature (Agarwal et al., 2011; Leslie Grady et al., 2011). Moreover, the reuse of wastewater should be taken into consideration due to the increasing water demand (Low and Chase, 1999; Agarwal et al., 2011; Leslie Grady et al., 2011). The biological treatment of wastewater involves changing the form of soluble and suspended organic contaminants to the form of the bacterial mass (biomass) and releasing gases such as CO_2, CH_4, N_2, and SO_2 (Ainsworth and Gill, 1987; Low and Chase, 1999).

Among the biological methods, the activated sludge process is widely considered and can be more efficient in treatment operations (Chu, 1999); however, it leads to heavy exploitation costs (Mace and Mata-Alvarez, 2002; Lindberg et al., 2006). One of the problems of the sludge process is the production of excess sludge so that in the process of biomass production, 0.50 kg of biomass is removed per kg of "chemical oxygen demand" (COD) treated and removing sludge in wastewater treatment plants accounts for about 50–60% of total wastewater treatment costs (Chu, 1999; Mace and Mata-Alvarez, 2002; Lindberg et al., 2006). The "sequencing batch reactor" (SBR) systems are also considered one of the aerobic biological wastewater treatments widely used in recent years for the treatment of both municipal and industrial wastewater (Mace and Mata-Alvarez, 2002; Elmolla and Chaudhuri, 2011). This is because of different features of this system such as very simple physical structure, high flexibility, low cost of construction, no need for a sedimentation tank, easy operation, and/or often optimal efficiency. This process consists of five stages, fill, react, settle, decant, and idle (Mace and Mata-Alvarez, 2002; Elmolla and Chaudhuri, 2011; Pan et al., 2014).

One of the key indicators for determining the quality of wastewater is the values of the "biochemical oxygen demand" (BOD) and the COD (Qasim, 1999). The "dissolved oxygen" (DO) is also a key parameter for determining these parameters (Qasim, 1999; Godos et al., 2010). In general, there are two main methods of oxygenating the wastewater including the bubbling aeration or diffused system, and the surface-mechanical aeration system (Qasim, 1999; Godos et al., 2010). Increasing the contact between the wastewater and the air often leads to dissolving more amounts of oxygen in the wastewater and, on the other hand, helps to transfer the harmful gases from wastewater to the air (Godos et al., 2010; Wang and Zhang, 2017).

Air bubbles are thin gas bubbles formed on the hydrostatic surfaces. They are usually a combination of atmospheric gases formed on water-based surfaces in water. "Fine bubbles" (*FB*) and "nanobubbles" (*NB*) are very tiny air bubbles with dimensions ranging from 10 to 50 μm and less than 200 nm in size, respectively (Zhuang et al., 2016; Kim et al., 2019). During the last decade, the FB and NB have been applied to improve the removal efficiency of contaminants during the process of wastewater treatments (Alkhalidi and Amano, 2015; Temesgen et al., 2017; Ahmadi et al., 2018; Atkinson et al., 2019). For instance, it has been reported that the FB-based aeration improved the removal efficiency of the COD, NH_4^+-N, and total phosphorus in the wastewater infiltration system (Wang and Zhang, 2017). The imminent air–water flow is in the premeditated integration of FB/NBs in industrial processes (Levitsky et al., 2022). In addition to FB aeration, NB aeration shows double the oxygen utilization rate and volumetric mass transfer coefficient as that of other bubble aerations; as a result, higher growth and decay rates were displayed in the NB aerator biomass system (Lee and Kim, 2013; Liu and Liu, 2006; Temesgen et al., 2017; 타텍, 2017). The application of NB in combination with forwarding osmosis as an energy-efficient technology to treat and reuse aquaculture effluent could result in nearly 98% treatment efficiency (Farid et al., 2022).

The FB and NB show unique behavior (Li et al., 2013) and have a vast variety of applications. (Wang et al., 2018; Dyett and Zhang, 2020; Fayyaz et al., 2021; Li et al., 2021). Compared with ordinary bubbles, the NB has advantages. For example, the NB often do not have high degradation power, while having a high shelf life and can move in all directions. The NB can extend the higher surface-to-volume ratio, improve the floatation of the particles, and clean the surfaces and pores (Holmberg et al., 2003; Li et al., 2014). In addition, owing to the large surface area and lack of buoyancy in solution, NBs have a great potential to reduce oxygen loss during aeration of biological processes (Yaparatne et al., 2022).

Considering the effectiveness of the air bubbles in the oxygen transfer coefficient, the air NB would cause an increase in the coefficient of oxygen transmission, K_{La} (Holmberg et al., 2003; Sumikura et al., 2007; Li et al., 2014) as a result of a greater volume than other bubbles, resulting in a higher contact surface and a slower rise in water (Sumikura et al., 2007; White et al., 2011; Li et al., 2013). Recently, a dextran-based oxygen nanobubble platform with 119.6 ± 44.9 nm in size and −35.54 ± 10.54 mV in potential has been adopted for intravitreal delivery of oxygen to rescue the inner retina from such ischemic damage at 5 ± 3°C temperature. (Fayyaz et al., 2021). In another study, NBs have been introduced for various strategies such as 1) ultrasound/photoacoustic cancer imaging, 2) photodynamic therapy of the tumors (Li et al., 2021), and 3) ultrasound triggered drug release (Batchelor et al., 2020) and 4) biomedical treatments. (Dyett et al., 2019). The study of gaseous products from the reaction at the nanodroplet surface with the nucleation phase also provides further understanding for wide applications of the droplets in the form of NBs, during, for instance, the liberation of hydrogen gas (Wang et al., 2018; Dyett and Zhang, 2020).

However, there is a lack of information about the comparison of the removal efficiency of pollutants in wastewater treatment systems using FB and NB aeration (Agarwal et al., 2022a; Agarwal et al., 2022b; Harsh Sharma and Nirmalkar, 2022; Li and Zhang, 2022). Hence, this research work aimed to experimentally compare the efficiency of FB and NB aeration in treating wastewater through the SBR system.

2 EXPERIMENTAL

2.1 Materials and Solutions

All the reagents were from their analytical grades. In the present study, we used two SBR containers (i.d.: 25.0 cm, height: 60.0 cm, and 20.0 L) from plexiglass (clear acrylic plexiglass 1.8" × 24" × 36" plastic sheet, China). The total volume, useful volume, and treatment capacity of each glass were 28.8, 20.0, and 10.0 L, respectively. Reactor one was equipped with nanobubble aeration, and reactor two was equipped with fine-bubble aeration. For this purpose, an A CO018 blower (3604 Model, Resun Co.) was used. The airflow in the path was divided into two lines. Flowline one was designed to produce air nanobubbles, and flow line two was developed to produce fine-bubbles. Moreover, the airflow 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 (**Supplementary Figure S1**).

Flowline 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 13 mm, the size of the used nanobubbles was 50–250 nm, and the size of the fine-bubbles was 1–3 mm. The airflow rates were identical on lines one and two. To adjust the airflow rate in inflow line one, an air volume control device was installed. In flowline two, we utilized a flow meter with a valve. To maintain the reactor feed and treated effluent of the reactor outputs, three plastic containers (100, 20, and 20 L) were used (Ahmadi et al., 2018). More details on instrumentation and controlling parameters are available in the Supplementary file.

The synthetic wastewater samples were prepared in the laboratory and standardized by following the related parameters according to the instructions and standard methods (Bajaj et al., 2008). Each of the two cylindrical SBR containers was filled with 10.0 ml of the wastewater samples as the selected treatment capacity per cycle. The outlet of the NB and FB was introduced to each container through the use of modified membrane diffusers, positioned at the end part of the bubble tubes. This system resulted in air aeration (bubbling) of the synthesized wastewater sample based on each fine and nanomechanism (Kim et al., 2019; Imura-Kishi et al., 2021; Sharma et al. 2022).

Answer: At this condition, the filamentous growth of the fine bubbles during the fine aeration can be controlled especially by the flow rate of air pumped into the water media as well as the diameter of the nuzzle on which fine bubbles are generated. Whereas, the size of nanobubbles is controlled by 1) template effect of the micelles, 2) the effective role of the microwave irradiation, 3) flow are of the pumping air, 4) the diameter of the nuzzle, and 5) the basal/edge plane properties of nanotubes modified on the nuzzle.

The DO of each wastewater was controlled using the DO meters via inducing their related probes into the wastewater samples.

In addition, to ensure a uniform frequency of air, especially at low aeration rates, an agitator using a blade of two flat wings with a 60.0 cm length, was placed vertically on the surface of the wastewater samples (with a 30.0 cm distance), whose speed was also controlled between 50–70 rpm.

For the storage of the feed, effluent, and additional sludge samples of the reactors, three PTFE containers (200.0, 60.0, and 20.0 L) were used, respectively. To maintain the temperature of the reactors beyond the lab's temperature (i.e., 25°C), a thermal element (40.0 V AC, 200 W, vs the GND, GEYSERWISE PTC, China) was used to control the different steps of the operation. All parts of the designed system were electronically automated using a PLC system (PLC Tutorial | Programmable Logic Controller, AVRPLC16 v6, Analog device) and controlled by a PC (Pentium 5) program written in Visual Basic 6 (VB_6).

Multi-walled carbon nanotubes (MWCNTs) with a purity of >99.0% were synthesized by the "chemical vapor deposition" (CVD) method. The related instrumentation system is presented in the supplementary file. Modification (immobilization) of the wind-bells air stone discs as a porous membrane diffuser was achieved by direct deposition of the carbon vapors (at 1,200°C in the Ar atmosphere) on the surface of the wind-bells air stone discs as a porous membrane diffuser, located at a temperature of around 200°C, partially, according to the procedure reported in our previous research (Temesgen et al., 2017; 타텍, 2017). The amount of the MWCNTs immobilized on the wind-bells air stone disc as a porous membrane diffuser was based on the maximum tightly supporting the carbon nanostructure as well as maximum airflow rate for having laminar airflow with Reynold's number below 2000 (Holmberg et al., 2003; Li et al., 2014).

3 RESULTS AND DISCUSSION

About the wastewater treatment process, the reduction in biological sludge production has been considered one of the most important factors. Recent research works show that moderating the expenditure of the activated sludge treatment and disposal has been taken into account greatly. On the other hand, new rules for the reuse and disposal of sludge on various organic, mineral, and pathogenic contaminants have made wastewater treatment authorities introduce novel methods or even modify the current existing biological treatment producing methodologies to consume less sludge (Temesgen et al., 2017; 타텍, 2017). In this study, therefore, the effect of NB/FB aeration on the wastewater treatment efficiency of an SBR system was evaluated in detail.

3.1 Characterization of the Nanobubble-Generating System

An important factor about the NB generation is the mesh size of the membrane diffuser. In this study, to control the size to access NB with an average diameter below 100 nm, the wind-bells air stone discs as a porous membrane diffuser were modified with MWCNTs. The TEM images of the NB and FB diffusers are shown in **Supplementary Figure S2**.

The selection of MWCNTs was attributed to the presence of plenty of edge planes on their matrix. These were generated especially when activated by HNO_3/H_2SO_4 solution (Merck Company, 0.1 mol L^{-1}, volumetric ratio: 1:1, during the refluxing process for 5.0 h at 70°C). This process caused the efficient formation of -OH and–COOH functional groups that played a role as an active site for the NB formation process.

3.2 Effect of Bubble Size on Different Operational Parameters

3.2.1. Size Distribution of Bubbles in the Nanobubble Aeration System

Based on the literature, the average frequent size of the FB is found as 1–3 mm (M. Matosic et al., 2019). Whereas, about the NB, at the optimum condition, the results (**Supplementary Figure S3**) show that this range was frequently estimated to be from five to a maximum of 100 nm with high enough frequency. This result was in good agreement with the estimate of the NB based on the previously published articles (i.e., 10–50 μm for the FB and <200 nm for the NB) (Holmberg et al., 2003; Li et al., 2014). This evidence pointed to the capability of the designed instrumentation system for efficiently generating plenty of nanobubbles at a large scale. This system can, therefore, be adopted for different purposes, especially the aeration process, which is the main aim of this research work. Laplace's equation states the size of the bubble is linked with the pressure inside it or the pressure difference with its environment. Smaller bubbles have higher internal pressures than external. The main factor that impacts the bubble's rising velocity is bubble size. The smaller bubble, the slower the rising velocity than that of a large one. A slower rising velocity forces longer HRT, which creates contact time between pollutants and bubbles; hence, the efficiency will be more (Suwartha et al., 2020).

3.2.2 Microorganisms and Clots in the Fine-Bubble and Nanobubbles Aeration System

The average size of the clots and the organisms laden in them for FB and NB aeration systems is shown in **Supplementary Figure S1**. As clearly shown, it is obvious that the size and number of the aerosol bubbles in the NB system are much lower than that estimated in the FB system. In the system, increasing the DO concentration resulted in a reduction in the sludge. First, increasing the concentration of DO up to at least 1.60%, caused DO to penetrate the internal layers of the clot, and in the peripheral clot, rich in oxygen and poor in the presence of any degradable materials such as polysaccharides. The acceleration in the auto-generated process and the autolysis process begins from the depth of the clot; consequently, this process majorly reduced the limit of sludge. This result was also in good agreement with some different estimations, predicated before (Ljunggren and Eriksson, 1997; Eriksson and Ljunggren, 1999; Abbassi et al., 2000; Sumikura et al., 2007).

In addition, in this study, the determination of SOUR was carried out by a simple calculation of DO vs time for a characteristic SBR cycle. This was considered a routine parameter, calculated at wastewater treatment plants; showing no important specification.

3.2.3 Effect of the Sludge Retention Time on the Chemical Oxygen Demand and Mixed Liquid Suspended Solid Concentrations

The effect of reaction time on COD removal and MLSS production in FB and NB aeration systems was investigated. In this part of the study, the effect of bubble size on COD and MLSS removal efficiency was investigated using an initial COD as large as 400.0 mg L^{-1} during five solids retention times (SRT) of the fifth, 10th, 15th, 20th, 30th, and 40th day. **Supplementary Figure S4** shows the results for SRT = 15 days for a reaction time of 4.0 h. The results showed that with increased SRT, the COD level decreased and the biomass production rate increased. These conditions, therefore, led to regard with the highest removal efficiency values for the COD in the FB and NB aeration systems as large as 85.0 and 95.0%, respectively, during the 15th-day SRT with a reaction time of 4.0 h. In the aeration system applied in an anaerobic effluent, it was reported that COD/BOD reduction dependent on the HRT and mass transfer of oxygen (Khan et al., 2011).

Because during SRT = 5 days or less, microorganisms live in the logarithmic growth phase, hence, proper floc production is not performed. In the SRT of 10–15 days, as the microorganisms are in the growth-reduction phase or the stationary phase, the COD removal efficiency was improved and reached approximately 95.0%. However, at higher SRT, especially over 20 days, due to the reduction of the F/M ratio, the growth of microorganisms increased, the sludge concentration was low and sludge sedimentation was not done well so the bulking phenomenon was evident. Therefore, the best removal efficiency occurred during the SRT = 15 days. This result was also agreed with those estimated by Helmerich et al. (2000) that reported similar results so that at the age of the 15 days, the daily rate of COD dropped from 1,000.0 to 64.0 mg L^{-1}, while the MLSS increased from 2,560.0 to 3,300.0 mg L^{-1} (Helmreich et al., 2000). These results, therefore, revealed the effective role of NB over the FB during the aeration process under similar conditions.

The effect of FB and NB aeration on the COD removal was also investigated under the same conditions (**Supplementary Figure S5**). It was again found that, at the SRT = 15 days, the COD removal efficiency improved over 5–10 days, reaching 85.0 and 95.0% in the FB and NB aeration systems, respectively. In this phase, the sludge volume index (SVI) was calculated to be 90.0 ml g^{-1}, indicating proper sedimentation of the sludge. Moreover, further increase in SRT did not improve the sedimentation as a result of the increase in the filamentous bacteria and the increase in the SVI, which was in good correlation with those predicted by Dockorn et al. that examined three complete mixing reactor systems, piston reactor, and SBR to investigate the effect of the reactor type on the COD removal efficiency at different sludge ages (Helmreich et al., 2000). The results also showed that with increasing sludge age, the concentration of COD in the effluent was reduced. The yield of COD in SBR with SRT = 20 days was found as 7.0–12.0% which was majorly higher than the amount of removal in the continuous flow units (Helmreich et al., 2000).

3.2.4 Effect of the Initial Chemical Oxygen Demand Concentration on the Removal Percentage

The effect of different initial concentrations of COD (400.0, 600.0, and 800.0 mg L^{-1}) on its removal efficiency was studied in both FB and NB aeration systems. **Supplementary Figure S6** shows that in both aeration systems, the removal efficiency decreased by increasing the pollution load (i.e., COD). This phenomenon is almost attributed to the shortage of DO inside the water medium, which is needed for the oxidation process. Introducing an efficient method for the promotion of the oxygen content of the water medium is important. At this stage, the bacterial growth curve, the existing phase, and SVI are very effective. It was reported that the removal efficiency of COD ranged from 80.0 to 86.0% when the FB aeration system was used (Zhuang et al., 2016). There may be based on two reasons:

- To explain this improvement in removal efficiency of organic matter. The flow rates with FB can result in the prevention of foam expansion, showing MLSS increment (Zhuang et al., 2016).
- Another reason is that the FB can enhance higher oxygen transfer efficiency, resulting in an improvement in biomass activity (Lee and Kim, 2013).
- However, as shown in **Supplementary Figure S6**, the removal efficiency of COD decreased with increasing COD. These results consequently suggest that the removal efficiency of COD can be reduced due to the increasing pollution burden (Bajaj et al., 2008).

3.2.5 Effect of Sludge Retention Time on Sludge Volumetric Index

The effect of SRT (5, 10, 15, 20, 30, and 40 days) on the SVI was investigated for both FB and NB aeration systems. **Supplementary Figure S7** shows that with increasing the SRT, SVI increased due to the growth of stranded microorganisms. It is known that sludge bulking may occur if SVI is over 150 and the settling property of sludge is satisfactory if SVI ranges from 70.0 to 150.0 (Abbassi et al., 2000; Attard, 2003; Eriksson and Ljunggren, 1999; Helmreich et al., 2000; Ljunggren and Eriksson, 1997; Simonsen et al., 2004; Takdastan et al., 2011; Tyrrell and Attard, 2001; Federation, 2005; Zheng et al., 2015). As shown in **Supplementary Figure S7**, at SRT = 10–15 days, the SVI was between 90.0–100.0 ml g^{-1} (Wang et al., 2006; Dutta and Sarkar, 2015).

However, after the 20th day, the SVI was over 150.0, suggesting the settling property of sludge is poor. When a long SRT was applied, filamentous bacteria can be more prosperous than the floc forming microorganisms, which was reported previously (Liu and Liu, 2006). Thus, as shown in **Supplementary Figure S7**, the SVI was increased along with increasing SRT. However, the previous study also indicated a significant increase up to around 500 v% in SVI was observed when SRT was long, suggesting the existence of filamentous bacteria in sludge (Liu and Liu, 2006). Interestingly, when the wastewater was aerated with NB, the SVI was higher than when aerated with FB (**Supplementary Figure S5**). This is probably due to the surface-to-volume ratio of NB that can cover a higher surface (Wei et al., 2003; Rodrigues and Rubio, 2007; Dutta and Sarkar, 2015; Ahmadi et al., 2018).

3.2.6 Effect of Sludge Retention Time on the Dry Weight Percentage of Sludge

The percentage of the dry weight of sludge (as routinely used and measured in the Iranian treatment plants) was investigated for SRT = 5, 10, 15, 20, 30, and 40 days using the FB and NB aeration systems. The results showed that, with increased sludge age, the percentage of dry sludge solids is reduced and sludge water content is increased (**Supplementary Figure S8**). During SRT> 20 days, the system enters the autolysis phase, and the corpses of microorganisms increases containing a significant percentage of organic matter (~90%) due to hydrophilicity, and the percentage of sludge water increases. Thus, for SRT = 5 days, in both FB and NB aeration systems, the percentage of dry sludge was estimated to be 1.60 and 1.65%, while it was reduced to 0.60 and 0.75%, respectively, at SRT = 15 days. However, it should be noted that the dry sludge percentage in the aeration system with NB was slightly greater than in the FB system as a result of the lower F/M ratio (Takdastan et al., 2011), which pointed to the economic potential of the NB vs FB.

3.2.7 Effect of F/M Ratio on Sludge Volumetric Index

The SVI variations were investigated at different F/M ratios using the FB and NB aeration systems. Based on **Supplementary Figure S9**, the longer the SRT, the lower the F/M ratio resulting in entering the microorganisms into the autolysis phase, thus increasing the carcass of microorganisms, which includes more than 90% of the organic matter. Therefore, the percentage of sludge water increased, in other words, the percentage of dry sludge decreased with increased SRT (Wei et al., 2003; Rodrigues and Rubio, 2007; Dutta and Sarkar, 2015; Zheng et al., 2015; Ahmadi et al., 2018). From the economic potential, these results are therefore significant and noticeable. This effect was attributed to the self-degradation of the microorganisms during an increase in the time scale, due to the shortage of the nutrient medium inside the wastewater. This result was completely evidenced in the NB aeration system in which the SVI was lower than that of the FB system. Consequently, the sedimentation was more convenient and the percentage of dry sludge was higher than in the FB system.

3.2.8 Effect of the Aeration System on Phosphorus Removal

The system efficiency was investigated for the removal of phosphorus (10.0–30.0 mg L^{-1}) using FB and NB aeration systems at SRT = 15 days. As plotted in **Supplementary Figure S9**, the removal efficiency of phosphorus in FB and NB aeration systems for these concentrations was in the range of 60.5–34.0%. While in the common sludge systems, this removal rate is up to 10.0–20.0% (Casellas et al., 2006). The FB had a better performance than NB in destroying contaminants, as destroying the FB in the middle of the path probably leads to the production of the OH radicals and shock waves in that area. This evidence therefore reveals the strong economic potential of the air aeration through the process of nanobubble formation, compared to the file bubble generation. Bursting FB can lead to the disintegration of the aqueous. However, FB does not have the high power to eliminate the pollutants. Meanwhile, it could be concluded that the bubble size did not show a significant difference in the phosphorous removal efficiency but this high efficiency, in general, might be attributed to the nature of SBR itself.

3.2.9 Efficiency of the Aeration System on the Removal of Total Nitrogen

The system efficiency was investigated for nitrogen removal using FB and NB aeration systems. The input N concentrations of 30.0, 40.0, 50.0, and 60.0 mg L^{-1} were used at SRT of 15 days. It was also found that the removal efficiency of FB and NB aeration systems was found between 84.0–96.0 and between 85.0–98.0%, respectively. (**Supplementary Figure S11**). In the NB and FB aeration systems, the efficiency was approximately equal and no significant difference was found in the efficiency. However, the high efficiency and effectiveness of the SBR system in nitrogen removal were caused by the denitrification process. Kundu et al. (2013) described the performance of the SBR system on a laboratory scale for the simultaneous removal of organic carbon and nitrogen in slaughterhouse waste and reported the removal efficiency of COD and nitrogen at 96.0 and 96.6%, respectively (Kundu et al., 2013).

3.4 Proposed Mechanism (Behavior)

The probable mechanism (behavior) behind this process is majorly attributed to 1) nucleation, 2) cavity formation, and 3) collapsing of air medium inside the generated bubbles. The competition between different factors such as 1) giant pressure of the air molecules trapped inside the bubble (that leads to having thermodynamic disobey of the generated NB) and 2) the electrical repulsion between the electrical excess surface charge (majorly generated during micelle formation and activation by the microwave irradiation) strongly makes the synthesized nanobubble to be considered as suitable containers for the effective mass transfer of the air medium during the aeration process according to the designed instrumentation system (Doroodmand and Mehrtash, 2014, Doroodmand and Mehrtash, 2015, Li et al., 2021, Imura-Kishi et al., 2021, Agarwal et al., 2011, Sharma et al., 2022).

4 CONCLUSION

In this study, for the first time, it was attempted to investigate the effects of aeration bubble size on wastewater treatment efficiency of an SBR system at a laboratory scale using a novel designed fine/nanobubble forming instrumentation system. For instance, based on the results, the aerobic wastewater treatments seriously depend on the aeration, hence, the size of the bubbles used in the aeration system plays a significant role in this regard. In addition, increasing the SRT in both NB and FB aeration systems reduced COD and increased the production rate of MLSS biomass. Moreover, it was found that increasing SRT reduced the F/M ratio, as a result, microorganisms entered the autolysis phase and the carcass of microorganisms increased. Therefore, the percentage of sludge water was increased. In another word, the percentage of the dry weight of the sludge decreased with increased SRT. The efficiency of phosphorus removal in aeration systems of FB and NB was about 50.0–60.0% respectively, which was estimated to be around twice higher than the conventional sludge treatment systems. All these results point to the economic potential of the air aeration through the process of nanobubble formation, vs the file bubble formation under similar conditions. The NB aeration was more effective in destroying the pollutants than FB, as a result of the production of OH radicals and shock waves. The SBR process had also a high ability to remove nitrogen because of the occurring nitrification process. As a final deduction about all the mentioned results, it was confirmed that the NB aeration system could give considerably promoted efficiencies in all terms of the tested treatment effective parameters (Agarwal et al., 2022a; Agarwal et al., 2022b; Harsh Sharma and Nirmalkar, 2022; Li and Zhang, 2022).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.884353/full#supplementary-material

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타텍 (2017). *Enhancing Gas-Liquid Mass Transfer and (Bio) Chemical Reactivity Using ultrafine/Nanobubble in Water and Wastewater Treatments TT -* 초미세/나노 버블을 이용한 물 및상수 및 폐수 처리에서의 기체액체 물질 전달 및 *(*생*)*화학적 반응 강화 *TA - Tatek Temesgen Terfasa*. 서울대학교 대학원.

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