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Nanobubble ozonation for waterbody rejuvenation at different locations in India: A holistic and sustainable approach

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ABSTRACT

In this study, four different sites of ponds at different time period were analysed to show to the effect of Nanobubble ozonation (NBO). NBO is one of novel technologies which is environmentally friendly only using air, ozone, and requiring virtually no chemicals. All the case studies have been performed in real time in different seasons and locations which gives the idea of importance of NBO for the treatment of water bodies with completely natural, environmentally sustainable, cost effective, and less time-consuming technology. Three case studies have been investigated *in-situ* (Site 1, 2, 4) and one ex-*situ* (site-3), which verify the efficacy of NBO in treating pond water. NBO treated water was determined to be in the standard limits, odour was eliminated, and water was cleaned enough to be consumed by the animals. The test results show that ozone nanobubble (NBO) in wastewater treatments achieved 85–99% reduction in total soluble solids (TSS), 80–90% reduction in biochemical oxygen demand (BOD), and 55% chemical oxygen demand (COD) reduction at site 3 and 82% COD reduction at site 4. Improved dissolved oxygen suitable for the living beings was achieved. Hence, this paper emphasizes the efficacy of NBO treatment to reclaim the water bodies and ecological restoration and to achieve the sustainable goals of clean water and environmental sustainability. DO level in all the ponds improved significantly after NBO treatment and showed the value of 14.5 mg/L when measured even after 50 h. Nanobubble gas dissolution system not only able to improve the dissolved oxygen up to supersaturation level but also able to retain it consistent more than 14–15 h. The vary reason for maintaining such consistency is the size of nanobubbles which is around <0.5 μm and NB doesn't follow the buoyancy, hence move in water in Brownian motion. NBG systems are future of our lakes and ponds rejuvenation and maintain the water quality.

1. Introduction

The quantity of water required for running our livelihood on daily basis is unimaginable. Human consumption, animals, agriculture, industrial process, everywhere we need enormous quantity of water to make every process run smoothly. To meet the needs of humans, farm animals, zoo animals, fishing etc. We need to create water body artificially, which needs a lot of attention and knowledge to keep the waterbody clean and useable for consumption. Municipality is investing crores of money on daily basis to provide safe drinking water for us while wild animals are mostly dependent on natural water bodies. At the places such as zoo, local small forests, temples build artificial ponds or lakes to provide water to the animals as well as for human activities such as washing, cleaning, gardening etc. Animals at the zoo needs extreme attention because they are from different climates and require native habitat like environment to survive at non-native places. All our animals need a clean supply of drinking or bathing water every day. Usually tap water is used for filling up the artificial ponds which is tested good for human consumption. The problem is that, tap water may be harmful for sensitive animals, especially fish and amphibians. They can be killed by the chlorine, fluoride, nitrates, and hormones that are found in our water. There are some contents in water that can have drastic effects on other animals such as estrogen, that can turn male bullfrogs into fertile females [8]. Artificially created pond/lake water needs to be treated time to time. It requires a lot of attention to make sure that, the water is good for consumption. Several places natural pond or lakes are also being used to drain the industrial wastewater in small towns where that water becomes hazardous for aquatic life, agriculture as well as for human beings [7]. Different methods of treatment are available such as highly reactive ozone (O_3) or activated oxygen has been used for the treatment of dye-polluted water. Ozonation not only remove contaminants but also improves both colour and taste of the water [15].

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However, ozone is unstable gas, and its low solubility limits its application when it comes to practicality. Mixing ozone/any other gas in the form of nanobubbles make it much more stable than the usual, hence it extends the usability of ozone in thousands of applications such as cleaning, sanitation, wate treatment, agriculture [16], aquaculture [11,18,26] etc. Other methods such as adsorption, chemical treatment [19], advanced chemical oxidation are also effective ways of treating waterbodies [1,15]. Efficient and cost effective bio-adsorbents such as chitosan [17], lignocellulosic material, alginate [15], other bio originated sorbents such as apricot kernel shells [21] used in adsorption processes to remove heavy metals and dyes from aqueous medium.

Apart from chemical contamination, growing algae in pond water is also a big problem which currently solved by the addition of many algae dependent fishes like Tilapia, Lionhead and Koi. However, this process is oxygen consuming and lead to the depletion of oxygen which badly affects fish. Water hyacinth/other kinds of water weed growth in waterbody due to the excessive nutrient concentration into such waterbodies is also a great concern. Eutrophication process turns the waterbody into a dead entity by converting it into land. Dire need to manually clean the lakes and ponds time to time and maintain the water quality to preserve them and to maintain the ecological balance of the surroundings. It is required to explore the applications of NBO to solve the current political, environmental, and economic situation in India [13]. The growing demand for water treatment technologies lead us to improvise day by day in existed technologies and to face the environmental challenges such as degradation and depletion of water resources. Microbubble (MB) and nanobubble (NB) technologies have shown promising results in wastewater (WW) treatment as problem-solving alternative for various challenges [25–28]. Ozonation is one of the most encouraging treatment methods for water bodies [1,2]. However, the produced ozone is unstable compound, and it decays rapidly because of short half-life. The half-life of ozone in water is a lot shorter than in air for instance, half-life of ozone in water having temperature 25 °C and 30 °C is 15 and 12 min, respectively. In countries like India where average air temperature is around 25°C–28 °C and average water temperature is around 30 °C, ozone treatment is not much effective because of short half-life. Ozone readily breaks down in OH-radicals, when these OH-radicals are the dominant particles in the solution, it is called an advanced oxidation process (AOP). First decay of ozone in OH-radicals is very fast which result in decrease in concentration, followed by a first order kinetics decay of ozone (Report by Lenntech). To overcome this issue of off-gassing of ozone while water treatment, NBO has come up as a wonderful technology which has enormous application in industries including agriculture [4,16]. NBO has ample of applications in treating natural water bodies [9]. Microbubble ozonation, oxygenation has already been reported for better quality of water treatment plants, nanobubbles applications are coming up recently in different industries, the current status of research has not reached its true potential [12].

This paper shows the case studies of four sites where nanobubble ozonation (NBO) has proved to be the best alternative to tedious, costly, and high maintenance processes for keeping the water quality in ponds, lakes, or artificial water bodies. NBO, because of their extraordinary fundamental properties, such as bubble stability (as tiny entities in water solutions), easy generation methods, and various chemical and physical features. Accelerated Cleaning Systems India Private Limited (ACS) has nanobubble generation (NBG) system which efficiently produced nanobubbles into the selected waterbodies and formed nanobubble aqueous ozone effectively reducing the contaminants and improved the water quality which is fit for consumption by animals. NBO can help reaching the goals of water treatment by keeping the waterbodies such as ponds pristine and ecologically balanced.

2. Nanobubble ozonation (NBO)

Almost all life on earth survives due to the oxygen and hence it is one of the most important chemical parameters to measure. Oxygen concentration in waterbody varies greatly during the day; e.g., in afternoon, level of oxygen is at the peak because of photosynthesis process, which decreases during the nightfall [16]. Decomposition of organic matter by bacteria will also lead to the oxygen depletion. The water quality deteriorates as the oxygen content gets depleted in the pond. Ozone consists of three oxygen atoms, sometimes is referred as activated oxygen. O_3 molecule is very unstable hence it degrades rapidly into oxygen gas and a free radical oxygen atom. Ozone solubility in water is less than that of chlorine and it does not create germicidal residuals to prevent regrowth of pathogens in the water.

Nanobubbles (NB) are small gaseous entities that are found on surfaces and in bulk when solutions are supersaturated with gas. Nanobubble technology involves the injection of nanobubbles (<200 nm) with a chosen gas ($O_2/O_3/CO_2/N_2$) into water. Such entities have neutral buoyancy, highly dissolved in water due to the bubbles' large surface area to volume ratio (SA:V). Upon implosion regular bubbles become NBs, attaining a negative charge which helps them to increase dispersion through water by repelling each other. O_3 in nanobubble form is stable for days and provide superfast reactions to degrade the contaminants. It also enhances the dissolved oxygen concentration in water and attain supersaturation. Generated oxygen free radical is highly reactive and has greater oxidative potential than the most commonly used disinfectant such as chlorine [9,10]. As a result, NBO can be used in industrial and private applications such as water treatment, disinfection, and odour removal [9]. Due to the shorter shelf-life of the ozone, its applications are restricted and that we can overcome using gas dissolution technology achieved by NBG system. Solution through NBO is environmentally sustainable and cost effective as it doesn't add chemicals to the water, and eliminates many taste and odour problems in treated water. Normal ozonation requires pre-treatment of the water to reduce hardness while nanobubble ozonation can be directly applied to the wastewater. ACS's nanobubble generation (NBG) system provides maximum gas dissolution (up to>96%) without off-gassing of ozone. NBO is much more stable in water and provide cleaning action due to advanced oxidation process (AOP). Nanobubbles have comparatively large surface area than fine bubble and coarse bubbles. NB follow the Brownian motion in the water which allows maximum interaction of water with the NB to breakdown/remove the contaminants. For instance, 13 k billion Nanobubbles can fit in 1 coarse bubble and >60 billion Nanobubbles can fit in one fine bubble (as shown in Fig. 1). NBG system saves us the cost of building large towers and other equipment to maximize ozone dissolution and capture and destroy off-gassed ozone, respectively. NBG proved to be the best solution to reclaim water bodies which are habitat of numerous zooplanktons and phytoplankton, and ecological restoration.

3. Materials and methods

3.1. Site selection for experiments

3.1.1. Site 1: guruvayur temple, Kerala, India

Guruvayur Temple is a Hindu temple dedicated to the Lord Guruvayurappan (four-armed form of the Lord Vishnu) which is named as Rudratheertham after the name of Lord Shiva. According to legend, for thousands of years, the southern bank of this pond was the place of bathing for Lord Shiva used to bath on this pond. Hence, it is very popular temple situated in Guruvayur town in Kerala (Southern part of India), India. The temple tank or pond of dimensions 61 m × 60 m × 6 m is situated on the northern side of the temple (10° 35′ 40.2″ N, 76° 2′ 20.4″ E). As one of the most important places of worship for Hindus, cleanliness of the pond is extremely important for all the devotees. The temple's pond is in high maintenance, but it's excessive algae growth was observed there which made pond water green and fishes were not able to survive because of low dissolved oxygen level (as can be seen in the Picture 2a (Fig. 2)). It was difficult for aquatic animals to survive there as pollution level of waterbody was too much. All the parameters

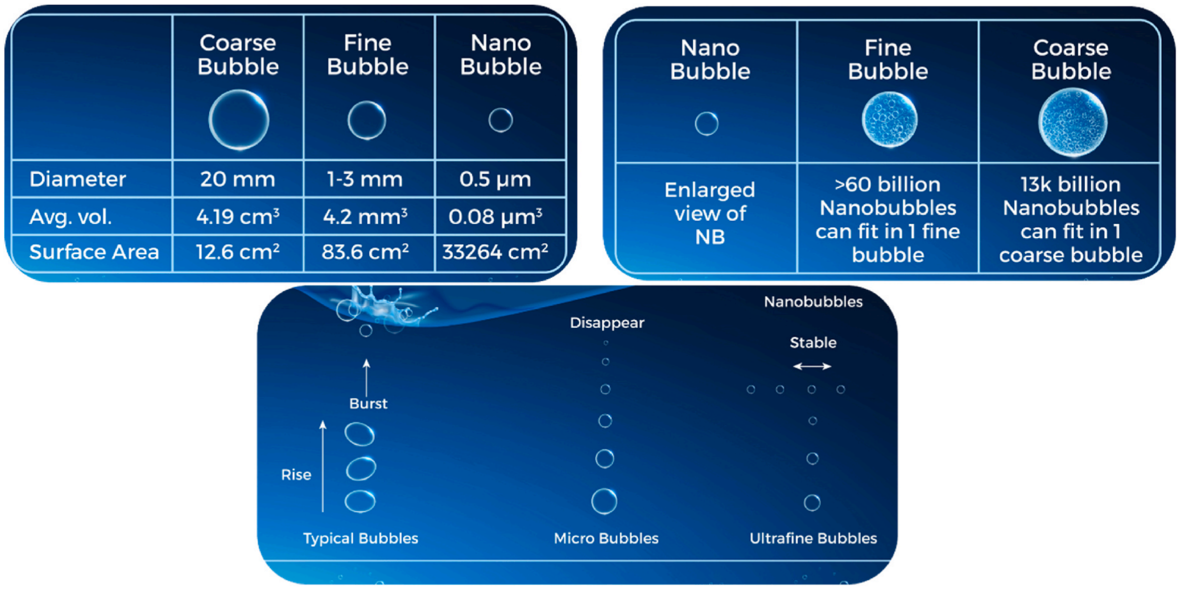

Fig. 1. A graphic comparison of coarse bubble, fine bubble, and nanobubble in terms of their diameter and surface area (A), Brownian motion of the NB (B), and pictorial demonstration of the extremely small size of NB (C).

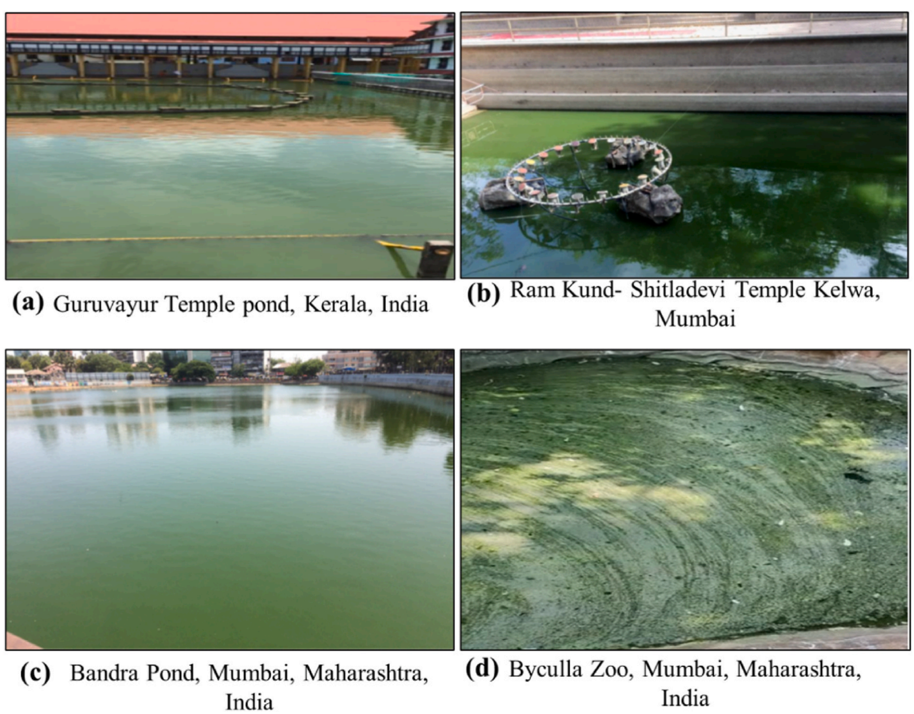

Fig. 2. Sited selected for the case studies, a) Guruvayur temple, Kerala, India, b) Ram Kund- Shitladevi Temple, c) Bandra public pond, and d) Byculla Zoo Pond, Mumbai.

such as BOD, DO, pH, TSS were taken into consideration to check the water quality before treatment which are provided in the table in results and discussion section.

3.1.2. Site 2: Shitladevi Temple kelwa, Maharashtra, India

Shitladevi Temple, Kelwa is town coasts of a very ancient temple of the Goddess Shitala-Mata (19.614254, 72.73206). The township of Kelwa is situated on the Western Railway, nearly 75 km from Mumbai Central Railway Station about 6 km away from Kelwa Road Railway Station. There is a pond in front of the temple which adds to the beauty of the temple. This pond is named as Ram-Kund, the quality of water got degraded due to the algal growth. High TDS, TSS, low DO was some of the issues observed in the pond. NBO treatment was given directly to the pond for 72 h.

3.1.3. Site 3: Bandra Talao, Maharashtra, India

Bandra Talao and Swami Vivekanand Talao both the names are used interchangeably for a 200 years old small lake (Coordinates 19.056424°N 72.838245°E) located in Bandra, Mumbai. It was constructed by a rich Konkani Muslim from Navpada (also spelt Naupada or Naopara) village but now it is maintained by the Municipal Corporation of Greater Mumbai, India. The lake was formerly known as Lotus Tank and is a Grade II heritage structure. This spread across 7.5 acres and hence it was named as "Motha Sarovar" in earlier times. Sample was collected from the pond from five different points including from the middle of the temple. The experiments were done in 140 L acrylic tank in the lab. All the water parameters such as BOD, TSS, DO, pH, TDS, and colour were checked before Ozone treatment and found to be out of the standard limit set by CPCB, India. Collected samples were green in colour because of the excessive algal growth in the pond.

3.1.4. Site 4: Byculla Zoo aquatic pond, Maharashtra, India

An artificial pond called Aquatic Birds' Pond of the capacity of 1.0 Lakh L is created in Byculla Zoo or Veermata Jijabai Bhonsale Udyan (18.9781154°N 72.8367457°E) (formerly known as Victoria Gardens). The zoo area is covering 50 acres and located at Byculla, in the heart of Mumbai, India. Since it is the oldest public garden in Mumbai, it is the site of attraction. In 1890, the garden was extended by 15 acres especially for the zoo. This Aquatic Birds' reservoir has a closed, circulating system, and the water is constantly moved through filters. There was a problem of smell, algal growth, rotten organic matter because of the decomposable organic remains after birds feeding. The water had to be changed twice a week which cost a lot to the authority. We have done the trials to extend the water retaining capacity without degrading the quality of water or without adding any chemicals. All the pictures of the sites where experiments were performed/samples were collected are shown in Fig. 2(a–d).

3.2. Water parameters testing

Water temperature, dissolved oxygen (DO) (mg/L) was analysed by Pro20i DO meter, pH, chemical oxygen demand (COD) (mg/L), biochemical oxygen demand (BOD) (mg/L), turbidity (nephlometric turbidity unit) (NTU), total soluble solids (TSS) mg/L, hardness (mg/L), and oxidation reduction potential (ORP) etc. Were tested by Varni Analytical Laboratory, Mumbai, India. Tests were performed on the collected samples before and after performing NBO tests. Nanobubble ozone treatment was given for different time at different locations. The experiments performed in the pond at Guruvayur Mandir premises in the month of oct–nov (2017), Ram Kund- Shitladevi Temple during June (2017), Bandra public pond sample was collected in the month 2018, and treatment of Byculla zoo aquaculture pond was done in oct–nov (2021). All the parameters were compared before and after treatment which are shown separately for different sites in results and discussion section Table 3.

3.3. Experimental setup for the study

Nanobubble (NB) ozonation system of Accelerated Cleaning Systems (ACS) Private limited, Mumbai, India provides highest possible gas dissolution through the generation of >80% of nanobubbles with the diameter of 100–200 nm. It is tested as one of the best water-cleaning technologies in the world that create significant quantity of hydroxyl radicals with enhanced ozonation. All the experiments were performed with the same NBO system. ACS's NB system fitted with the intake pump and mixing pump in a stainless-steel chamber. Intake pump is connected to the water tank which connects to the mix pump through a vernutri which creates the suction. Water gets into the intake pump through suction which is further transported to the mix pump by mixing O_3 (ozone) generated by ozone generator connected in between mix pump and intake pump. NBs are generated and mixed in the water through mix pump and transported back to the water body/tank in the form of nanobubble water or nanobubble aqueous ozone (NAO) as shown in Fig. 4. The experimental setup for *in-situ, ex-situ* experiments and photograph of a typical ACS's NBG system are given in Fig. 3(a–c) and Fig. 4(a–c), respectively. Fig. 4 (c) showed the typical mechanism of O_3 generation using electricity through our system with the help of ozone generator. When O_3 mixed with aqueous media, advanced oxidation process is taking place to degrade the contaminants. The experimental parameters of the four studies used during the tests are given in Table 1 along with the dosage of ozone used.

4. Results and discussion

Results for the experiments at different experimental conditions are given in this section. As standard procedure, all the samples were collected before pilot scale experiments and analysed for the standard parameters such as BOD, COD, TSS, hardness, etc. Representative

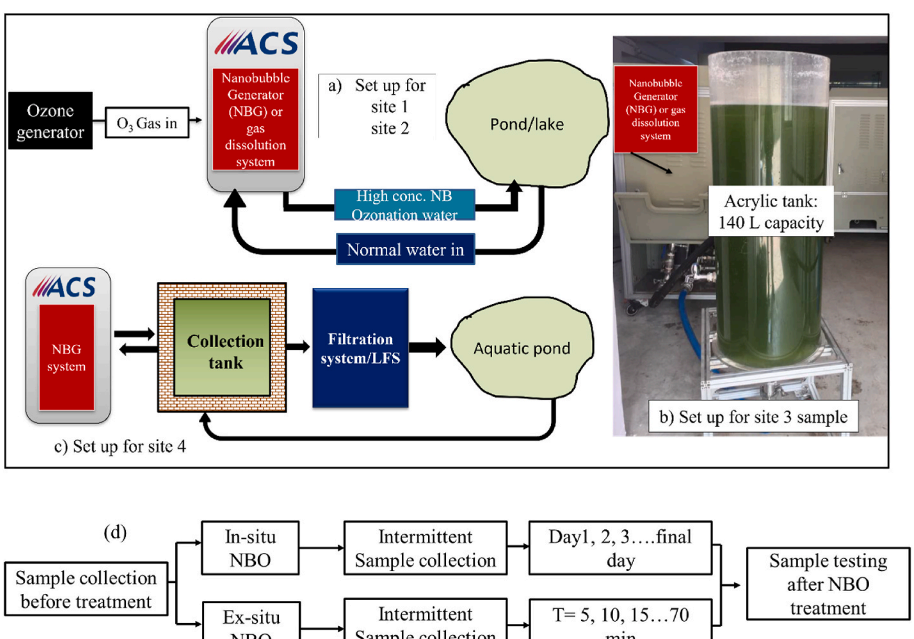

Fig. 3. Experimental setup for a) site 1 and site 2 (Guruvayur temple, Ram Kund-Shitladevi Temple), b) site 3 (Bandra Pond), and c) site 4 (Byculla Zoo pond), (d) Experimental scheme of the present study in ex-situ and in-situ mode.

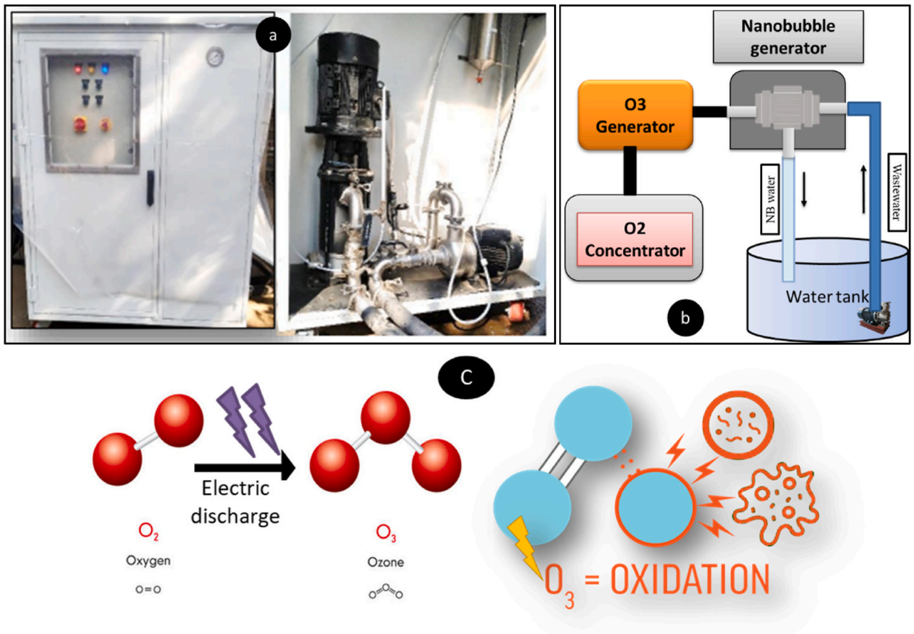

Fig. 4. a) Photograph of a typical ACS's NBG system equipped with ozone generator, (b) flow diagram of the NBG system with the parts, (c) Basic mechanism followed by ACS's NBG system to generate NB ozone and its role in removing contaminants.

Table 1
The experimental parameters of NBG tests for different case studies.

Parameters of the treatment	Site 1	Site 2	Site 3	Site 4
	Guruvayur Mandir	Ram Kund-Shitladevi Temple	Bandra public pond	Byculla zoo aquaculture pond
Treatment Provided	NBO	NBO	NBO	NBO
Treatment site	*In-situ*	*In-situ*	*Ex-situ*	*In-situ*
Ozone Dosage	1.0 mg/L	1.0 mg/L	1.0 mg/L	1.0 mg/L
Time of treatment	30 Days	5 Days/72 h	30 min	71 Hrs.
Month and year of treatment	Oct–Nov 2017	June 2017	Oct 2018	June 2021
Capacity of the pond/area of the pond	61 m × 60 m × 6 m	80 m × 40 m	111.0 L	1.0 Lakh Liter

picture of the experiments for NAO (nanobubble aqueous ozone) generation through NBG system in ACS's facility as well as on site is shown in Fig. 5 (a and b). Figure (a) comprises of four pictures which shows the ozone nanobubble generation in a container having 45 gallons of tap water. As soon as the NBG system starts, it generates numerous bubbles of nano size (<5 μm) which gives the appearance of milky white colour. After 30 s of the system run, water is full of nanobubbles and appear white in colour however it becomes transparent after few minutes. Figure (b) shows the on-site NB generation in pond water.

4.1. Site 1 and site 2

Site 1 and 2 which are the ponds of two temples viz., Guruvayur pond and Ram-Kund have been given the ozone treatment for 30 days (10th oct-9th Nov 2017) and 3 days (June 2017), respectively. It was found that, DO concentration on site 1 during daytime was 3.7 mg/L and it was even lower (1.9 mg/L) at early morning 5.0 a.m. However, pH was found to be around neutral and no biological contamination such as *E.Coli* was found in the water body. The concentration of DO at site 1 was very low for living beings. As per the Central Pollution Control Board (CPCB), India, DO in wildlife and fisheries water should be > 4.0 mg/L. TSS and ammonia concentation before experiment was found to be 118 mg/L and 1.44 mg/L, respectively. BOD test showed 94.3 mg/L which was higher than the permissible limit i.e., 10 mg/L (should not exceed 30 mg/L). According to CPCB's permissible limit of standards free ammonia in water should be less than 1.2 mg/L [3]. The test was run for 30 days and water parameters were checked in between as per the experimental scheme provided in Fig. 1. Table 2 shows the pond water characteristics before and after NB ozone treatment. Graphical representation of the same results is also given in Fig. 6 (a). During treatment the parameters were checked in the interval of 10 days, and it was found that, all the parameters were brought below the permissible limit in the initial treatment of 5 days. The test result after the series of nanobubble treatments revealed that, the ammonia level of treated water has decreased considerably (62%) from 1.44 mg/L to 0.18 mg/L which is within the permissible limit set by CPCB. Other parameter like BOD was reduced by 91%, TSS was reduced by 89%, and turbidity by 82%. DO level was raised from 3.7 to 6.4 during daytime and the concentration of DO at 5.00 a.m. was found to be 5.3 mg/L at the end of the experiment. These results demonstrate the effectiveness of nanobubble ozone in treating pond water. After NBO treatment, fishes and turtles were survived in the ponds as the water quality was improved manifolds and it was considered as ft for consumption.

NBO treatment given to the Ram-Kund at Shitladevi temple also showed significant improvement in the water quality. Difference was clearly visible with the naked eyes as can be seen in Fig. 7(c–d). The pond water is now being used for growing fishes which was little difficult before NBO treatment. All the samples were analysed in ACS's internal facility as well as in Varni Analytical Laboratory, Mumbai, India (Deals with the testing of food, water, natural products and shelf-life study) for cross verification of the results.

4.2. Site 3

The experiments of the Bandra Public Pond water were performed in the ACS's laboratory with the acrylic tank of 140 L capacity filled with the 111.0 L of pond water from the site. The intake parameters such as pH was 8.4, temperature recorded at the time of experiment was 32 °C, DO measured was 4.0 mg/L. The colour of the collected sample was dark green, which was clearly visible, it can be seen in Fig. 3 (b). NB ozone

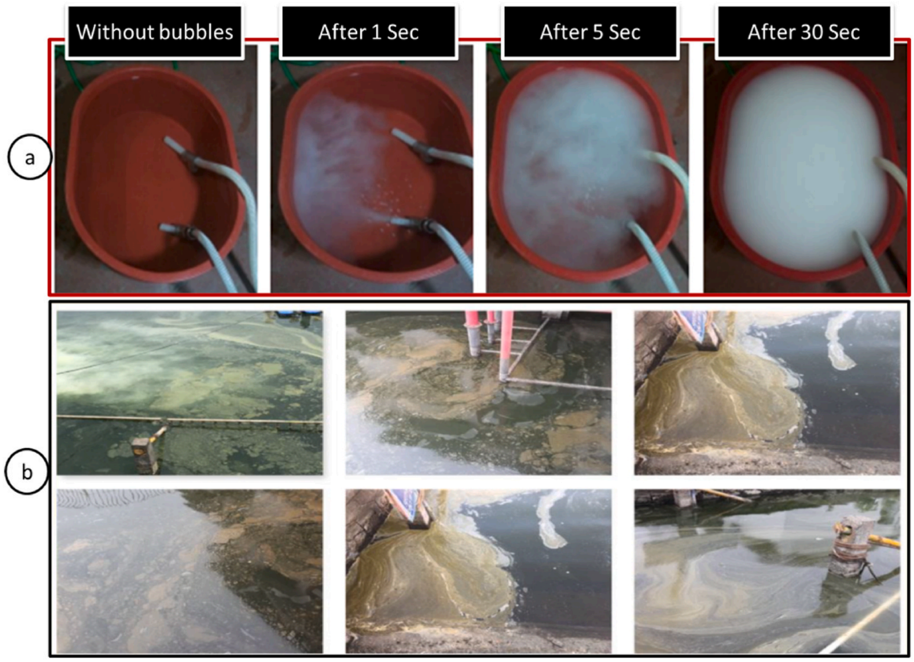

Fig. 5. (a) Representative pictures of the experiments for NAO (nanobubble aqueous ozone) generation through NBG system in ACS's facility with 45 gallons of tap water, (b) on-site NB generation by ACS's NBG system in pond water.

Table 2
Water parameters before and after nanobubble ozone treatment on site 1 along with the % reduction in the parameters.

Parameter (Guruvayur pond)	Unit	Before NBO treatment	After NBO treatment			Final reduction in values
		Oct 10, 2017	Oct 15, 2017	Oct 25, 2017	Nov 09, 2017	% Reduction
BOD	mg/L	94.3	7.8	6.6	8.4	91%
TSS	mg/L	118	6	19	13	89%
Turbidity	NTU	50.0	12.5	10.6	8.9	82%
DO	mg/L	3.7	6.6	6.4	6.4	42% increment
pH		7.34	7.47	7.67	7.7	–
E. Coli	–	NA	NA	NA	NA	–
Free ammonia	mg/L	1.44	0.55	0.41	0.18	62

Table 3
Water parameters before and after NBO treatment at ACS's facility for Bandra Pond water.

Parameters	Unit	Raw pond water	After 15 min of NBO treatment	After 30 min of NBO treatment	% Reduction
COD	mg/L	233	168	104	55%
BOD	mg/L	75.0	50	28	62.6%
TSS	mg/L	12.0	4.0	2.0	83.33%
Turbidity	NTU	1.0	0.05	0.05	95%
DO	mg/L	2.0	6.0	20	70% increment

treatment time for this ex-situ pilot scale experiment was 30 min with the input of 1.0 mg/L. Parameters of water before and after treatment are demonstrated in Table 3 and graphical representation is given in Fig. 6 (b). Results elucidate that, COD was reduced from 233 mg/L to 104 mg/L which is 55% reduction in total. Five days BOD result showed the reduction of almost 63% and final value was 28 mg/L, which is in the permissible limit of pond water BOD. TSS was reduced 83.3% and turbidity reduced to 0.05 with the 95% reduction. NB ozonation proved to be very effective just after 30 min of ozonation while experimented in ex-situ conditions. Colour of water was completely removed from dark green to colorless (Fig. 7(e–f)).

4.3. Site 4

Aquatic pond at Byculla Zoo has the water holding capacity of 1.0 Lakh L which is connected to a larger pond/collection tank through the filtration system named as FS. Water is recirculated through the FS from collection tank to the aquatic pond. ACS's NBG system was set up with the collection tank. NBO treatment was given for the period of 70–72 h. BOD, COD, TSS, and DO (mg/L) were measured before and after the treatment. Kinetic study was also performed by taking the sample at regular time intervals (5 samples in 72 h) as shown in Table 4. Results demonstrated the commendable changes in the parameters after the NB ozone treatment which shows the effectivity of NB ozonation for cleaning such water bodies with the minimal cost. There was a problem of odour due to the biological contamination in pond. After NBO treatment BOD was reduced from 50.77 to 7.16 mg/L, which is nearly 86% reduction from the original BOD. Approximately 82% COD reduction was obtained, TSS reduction was almost 100%. Before NBO treatment the DO value obtained was 1.8 mg/L which is detrimental to the planktons and harmful for animals. DO level in pond water had been improved significantly after NBO treatment and showed the value of 14.5 mg/L when measured after 50 h. Nanobubble gas dissolution system was able to dissolve oxygen up to supersaturation level and it remained consistent near about 14–15 h. Graphical representation of the obtained data is shown in Fig. 6 (c).

Fig. 7 shows the pictures of the sites before and after NBO treatment and it is clearly visible from the photographs that, the water quality has

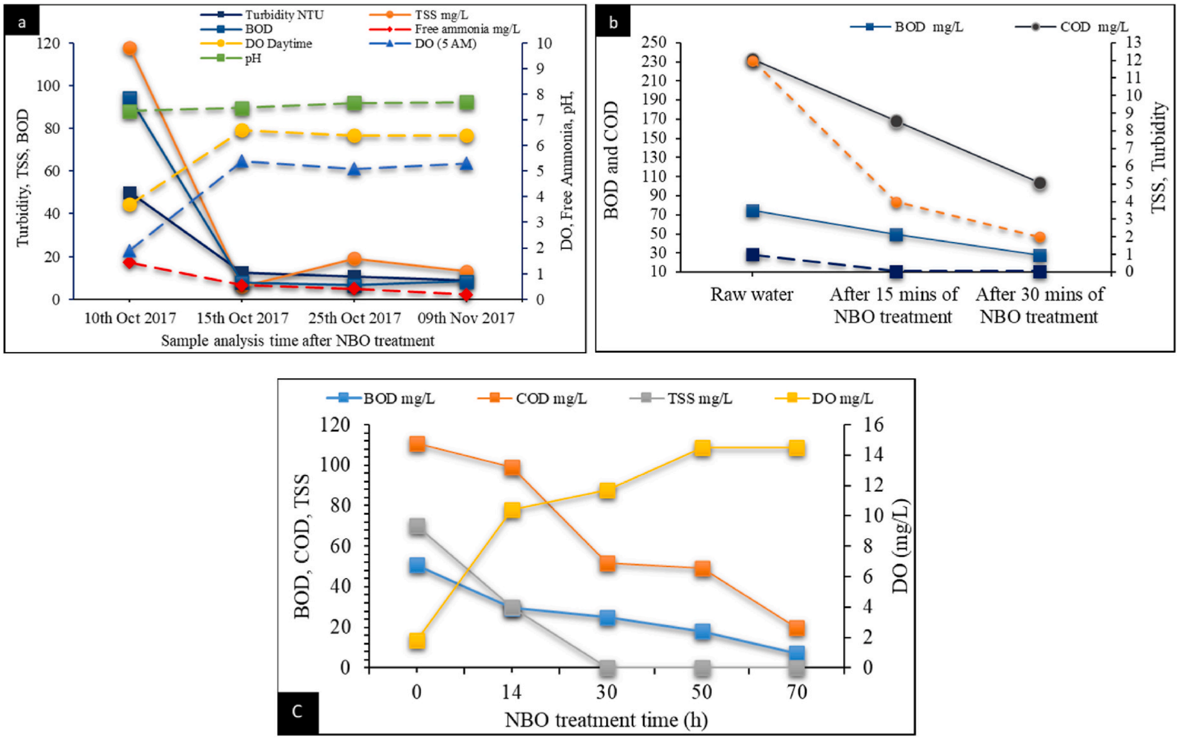

Fig. 6. Graphical representation of the data obtained from sample analysis at (a) site 1 (Guruvayur temple), (b) site 3 (Bandra Pond sample off-site treatment), (c) site 3 (Byculla Zoo pond).

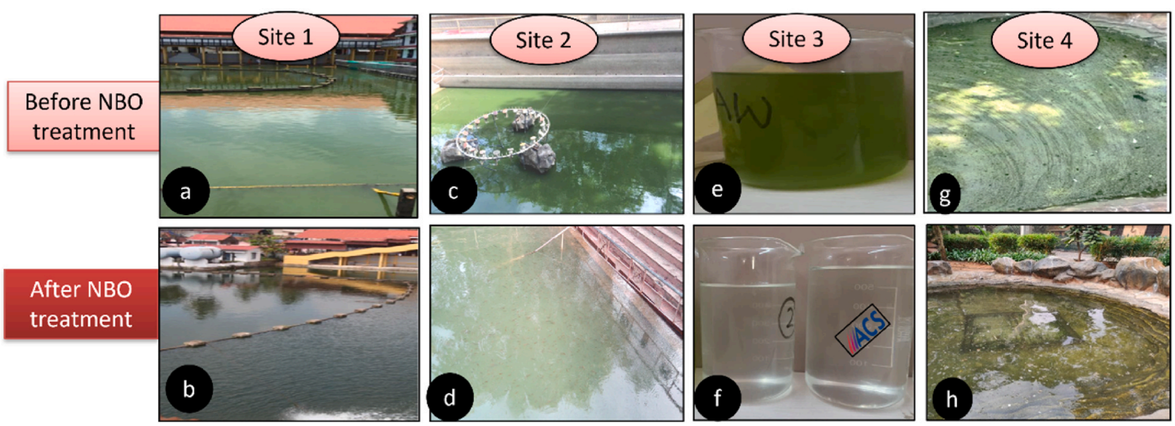

Fig. 7. Photographs of the experimental sites before and after the NB ozone treatment. (a–b) Guruvayur temple, (c–d) Shitladevi temple, (e–f) Bandra public pond, and (g–h) Byculla Zoo.

Table 4
Parameters of Byculla Zoo aquatic pond water before and after 72 h NB ozone treatment.

Parameter	Unit	Time Interval for sample collection (h)					% Reduction
		0	14	30	50	70	
COD	**mg/L**	110.7	98.9	51.8	49.4	20	81.93
BOD	**mg/L**	50.77	29.67	25	18	7.16	85.89
TSS	**mg/L**	70	30	0.1	0.1	0.1	99.86
DO	**mg/L**	1.8	10.4	11.7	14.5	14.5	87.59 increment

been considerably improved. Ozone in the form of NB has higher stability because of the nano scale size [23]. At this scale, NB have extremely large surface area and they overcome the regular characteristics of the matter and shows extra ordinary properties [6,12].

5. Improvement in water quality parameters after the NB ozonation system

All the water bodies taken for the experiments have shown improved water quality after NBO treatment. NBO provides chemical free solution for water treatment without getting affected by the experimental conditions and location unlike chemical treatment [14]. This may be the reason of getting excellent results in meeting our water parameters in limits set by CPCB and Environmental Protection Agency [25]. It is evident that, NBO proved to be 2000 times stronger than ozone and 180 times stronger than the ultraviolet rays [22]. As shown in Fig. 4 (c), when ozone come in contact with water it immediately reduces and release one free radical which works as strong oxidising agent. Here, the basic phenomenon which is happening is advanced oxidation process which helps in reducing the pollutants into simpler compounds and ultimately converting them into CO_2 and H_2O [20,24].

ACS Pvt. Ltd. Offers the dissolution system which has highest and the fastest absorption rate of any infused gas which allows the reduction in energy costs by up to 60%. This system delivers air, CO_2, oxygen, and/or any other gas to water with an absorption rate above 90%. The technology works on the principle of shear force. The gas splits into nano size by the shear force generated at the interface of the object. The ultrafine bubbles generated by this NBG system is < 5 μm hence they are termed as nanobubbles. These NBs exists in water for a long time without degassing, and hence the dissolved gas is maintained high for a long time which helps in rapid degradation of contaminants present in water. With natural production of pure O_2 and O_3 by ACS's NBG system, waterways are disinfected naturally with no chemicals and no additives. We found that, upon implosion regular bubbles become NBs, attaining a negative charge which helps them to increase increasing dispersion through water by repelling each other and following Brownian motion [5]. As mentioned before, NBs attracts positively charged elements and make them transport through the surface of the plants or bacteria and helps in better assimilation of nutrients. Nanobubbles have ample of applications in environmental engineering which can save crores for the industrial processes. It has revolutionization potential some of which are still to be known [14]. NBG system provides 100% natural and eco-friendly solution to most of the existing problems such as water and wastewater treatment, improving agricultural yield, quality of food, food storage, algal growth, ethanol production, etc. Without using chemicals.

6. Conclusions

In this paper, an efficient attempt was made to reclaim different ponds at different sites in India through nanobubble ozonation by using NBG system of Accelerated Cleaning System India Pvt. Ltd., India. Water treatment based on gas dissolution system created ozone nanobubbles in ponds. NBO has been tested successfully for the treatment of four different pond water. The proposed system is effective and environmentally friendly because the treated water met all CPCB's pond water standards and recycling requirements without addition of chemicals at all the sites. This technology is simple, cost effective, and yet efficient in the reduction of ammonia, TSS, turbidity, BOD, and COD. DO level has considerably improved to the saturation level with this NBG/gas dissolution system. DO reached up to supersaturation level of 26.5 mg/L at the end of the experiment which remained stable for days and reduced very slowly because of the presence of oxygen in the form of NBs. As shown in Fig. 8, 55–82% reduction in COD was achieved and observed 63–91% reduction in BOD, 83–99% reduction in TSS. DO level of water bodies were increased in the range of 42–88%. Nanobubble technology is the game changer in such scenarios as NBG not only dissolves oxygen gas multiple times better than the best available conventional technologies. NBG's high gas dissolution rate (95%) makes it possible to use gases like ozone at the site without fretting about the safety issues like off gassing etc. Installing NBG system with the pond facility will reduce the maintenance cost as NBG system is affordable. Such a system is expected to serve the pond's algal blooming problem where nutrient quantity is discharged. The result of this work should encourage the government for wide installation of the system to keep the environment clean and healthy.

Credit author statement

Dr. Preeti Pal, Technical Manager, RnD: Methodology, Investigation, Writing- Original Draft, Review & Editing and visualization; Mr. Amey Joshi: Investigation, data curation, Project administration; Mr. Harish Anantharaman: Supervision, funding acquisition.

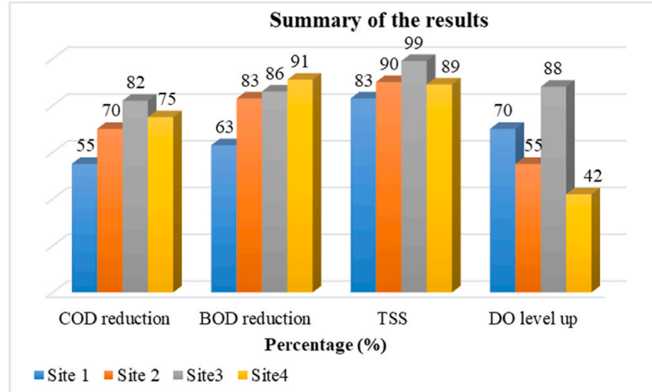

Fig. 8. Graphical representation of the summary of results obtained in this study. 55–82% reduction in COD, 63–91% reduction in BOD, 83–99% reduction in TSS, and DO level increased range 42–88%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have provided the data in the uploaded MS

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References

[1] O.J. Ajala, J.O. Tijani, R.B. Salau, A.S. Abdulkareem, O.S. Aremu, Results in Engineering A review of emerging micro-pollutants in hospital wastewater : environmental fate and remediation options Advanced oxidation processes, Results in Engineering 16 (2022), 100671, https://doi.org/10.1016/j.rineng.2022.100671. July.

[2] J.H. Batagoda, S.D.A. Hewage, J.N. Meegoda, Nano-ozone bubbles for drinking water treatment, J. Environ. Eng. Sci. 14 (2) (2018) 57–66, https://doi.org/10.1680/jenes.18.00015.

[3] Cpcb, Guidelines for Water Quality Monitoring, vol. 32, Parivesh Bhawan East Arjun Nagar, Delhi, 2007.

[4] X. Dong, L. Sun, G. Maker, Y. Ren, X. Yu, Ozone treatment increases the release of VOC from Barley, which modifies seed germination, Agricultural and Environmental Chemistry (2022), https://doi.org/10.1021/acs.jafc.1c06812.

[5] K. Ebina, K. Shi, M. Hirao, J. Hashimoto, Y. Kawato, S. Kaneshiro, T. Morimoto, K. Koizumi, H. Yoshikawa, Oxygen and air nanobubble water solution promote the growth of plants, fishes, and mice, PLoS One 8 (6) (2013) 2–8, https://doi.org/10.1371/journal.pone.0065339.

[6] E.P. Favvas, G.Z. Kyzas, E.K. Efthimiadou, A.C. Mitropoulos, Bulk nanobubbles, generation methods and potential applications, Curr. Opin. Colloid Interface Sci. 54 (2021), 101455, https://doi.org/10.1016/j.cocis.2021.101455.

[7] G.C. Fico, A.R.G. de Azevedo, M.T. Marvila, D. Cecchin, G. de Castro Xavier, B. A. Tayeh, Water reuse in industries: analysis of opportunities in the Paraíba do Sul river basin, a case study in Presidente Vargas Plant, Brazil, Environ. Sci. Pollut. Control Ser. (2022) 66085–66099, https://doi.org/10.1007/s11356-022-20475-9, 2022.

[8] T.B. Hayes, V. Khoury, A. Narayan, M. Nazir, A. Parka, T. Brown, L. Adame, E. Chan, D. Buchholz, T. Stueve, S. Gallipeau, Atrazine induces complete feminization and chemical castration in male African clawed frogs (Xenopus laevis), Proc. Natl. Acad. Sci. U.S.A. 107 (10) (2010) 4612–4617, https://doi.org/10.1073/pnas.0909519107.

[9] I. Hung, Ultrafine Bubble-Enhanced Ozonation for Water Treatment in Partial Fulfillment of the Requirements in the Graduate College, The University of Arizoana, 2016. http://hdl.handle.net/10150/621853.
[10] H. Ilyas, I. Masih, J.P. van der Hoek, Disinfection methods for swimming pool water: byproduct formation and control, Water (Switzerland) 10 (6) (2018), https://doi.org/10.3390/w10060797.
[11] C. Jhunkeaw, N. Khongcharoen, N. Rungrueng, P. Sangpo, W. Panphut, A. Thapinta, S. Senapin, S. St-Hilaire, H.T. Dong, Ozone nanobubble treatment in freshwater effectively reduced pathogenic fish bacteria and is safe for Nile tilapia (Oreochromis niloticus), Aquaculture 534 (2021), 736286, https://doi.org/10.1016/j.aquaculture.2020.736286. December 2020.
[12] P. Khan, W. Zhu, F. Huang, W. Gao, N.A. Khan, Micro-nanobubble technology and water-related application, Water Sci. Technol. Water Supply 20 (6) (2020) 2021–2035, https://doi.org/10.2166/ws.2020.121.
[13] T. Khatib, S. Qalalweh, R. Ameerah, I. Warad, An efficient method for water treatment of artificial ponds in Jordan valley based on photovoltaic pumping system, Agriculture 9 (7) (2019) 1–12, https://doi.org/10.3390/agriculture9070151.
[14] T. Lyu, S.W. Orcid, R.J.G. Mortimer, G.P. Orcid, Nanobubble Technology in Environmental Engineering: Revolutionization Potential and Challenges [News], Environmental Science & Technology, 2019, pp. 9–10, https://doi.org/10.1021/acs.est.9b02821.
[15] P. Olusakin, T. Oladiran, E. Oyinkansola, O. Joel, Results in Engineering Methylene blue dye : toxicity and potential elimination technology from wastewater, Results in Engineering 16 (2022), 100678, https://doi.org/10.1016/j.rineng.2022.100678. August.
[16] P. Pal, H. Anantharaman, CO2 nanobubbles utility for enhanced plant growth and productivity: recent advances in agriculture, J. CO2 Util. 61 (2022), 102008, https://doi.org/10.1016/j.jcou.2022.102008, 2022.
[17] P. Pal, A. Pal, Enhanced Pb2+ removal by anionic surfactant bilayer anchored on chitosan bead surface, J. Mol. Liq. 248 (2017) 713–724.
[18] A. Powell, J.W.S. Scolding, Direct application of ozone in aquaculture systems, Rev. Aquacult. 10 (2) (2018) 424–438, https://doi.org/10.1111/raq.12169.
[19] F.J.H.T.V. Ramos, M. de F.V. Marques, J.G.P. Rodrigues, V. de O. Aguiar, F.S. da Luz, A.R.G. de Azevedo, S.N. Monteiro, Development of novel geopolymeric foam composites coated with polylactic acid to remove heavy metals from contaminated water, Case Stud. Constr. Mater. 16 (September 2021) (2022), https://doi.org/10.1016/j.cscm.2021.e00795.
[20] M. Sakr, M.M. Mohamed, M.A. Maraqa, M.A. Hamouda, A. Aly Hassan, J. Ali, J. Jung, A critical review of the recent developments in micro–nano bubbles applications for domestic and industrial wastewater treatment, Alex. Eng. J. 61 (8) (2022) 6591–6612, https://doi.org/10.1016/j.aej.2021.11.041.
[21] I. Shaikhiev, K. Shaykhieva, S. Sverguzova, E. Fomina, Y. Vinogradenko, R. Fediuk, M. Amran, A.P. Svintsov, A.R.G. de Azevedo, M. Gunasekaran, Removing pollutants from sewage waters with ground apricot kernel shell material, Materials 15 (10) (2022) 3428, https://doi.org/10.3390/ma15103428.
[22] Summerfelt, S., & Vinci, B. (n.d.). Ozonation and Ozonation and UV Disinfection UV Disinfection.
[23] S. Tanaka, Y. Naruse, K. Terasaka, S. Fujioka, Concentration and dilution of ultrafine bubbles in water, Colloids and Interfaces 4 (50) (2020) 1–15, https://doi.org/10.3390/colloids4040050.
[24] A. Tekile, I. Kim, J.-Y. Lee, Applications of ozone micro- and nanobubble technologies in water and wastewater treatment: review, Journal of the Korean Society of Water and Wastewater 31 (6) (2017) 481–490, https://doi.org/10.11001/jksww.2017.31.6.481.
[25] US EPA, Wastewater Technology Fact Sheet Ozone Disinfection, United States Environmental Protection Agnecy, 1999, pp. 1–7.
[26] L.H. Wen, A. Bin Ismail, P.M. Menon, J. Saththasivam, K. Thu, N.K. Choon, Case studies of microbubbles in wastewater treatment, Desalination Water Treat. 30 (1–3) (2011) 10–16, https://doi.org/10.5004/dwt.2011.1217.
[27] J. Wu, K. Zhang, C. Cen, X. Wu, R. Mao, Y. Zheng, Role of bulk nanobubbles in removing organic pollutants in wastewater treatment, Amb. Express 11 (1) (2021), https://doi.org/10.1186/s13568-021-01254-0.
[28] Z. Xia, L. Hu, Treatment of organics contaminated wastewater by ozone micro-nano-bubbles, Water (Switzerland) 11 (1) (2018), https://doi.org/10.3390/w11010055.