



APPLICATION OF NANOBUBBLE AERATION TO MITIGATE GEOSMIN AND EUTROPHICATION IN AQUATIC SYSTEM

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Abstract: Eutrophication and geosmin contaminations are the worldwide problems for the aquatic environment. The aim of this experiment was to determine and mitigate the impact of the nanobubble aeration on geosmin and eutrophication. The four methods applied as ultrasound, nanobubble air, positive control, and negative control. ATP bioluminescence methods are used to measure plankton density, and geosmins are measured by gas chromatography mass spectroscopy (GC-MS). The treatment effects were assessed using multiple regression, correlation and ANOVA. The result showed that the water changed from eutrophic to oligotrophic, which was a significant decrease in the trophic state index (TSI: 36.02 ± 1.77), the reduction of plankton density by 75%, and geosmin from 300.66 ± 1.15 ng/L to (171.58 ± 0.017) ng/L). Therefore, it is the most effective method for removing inorganic elements from water. Correlation analyses showed that dissolved oxygen (DO) and geosmin had negative relationships, while eutrophication agents had positive correlations with plankton density. Regression analysis showed that geosmin was a significant contributor to DO. The results show that nanobubble aeration is the most effective, sustainable, and environmentally friendly method for reducing plankton and geosmin and improving overall water quality, thereby contributing to the long-term conservation of aquatic ecosystems.

Keywords: Aquatic ecosystem, Cyanobacteria, Eutrophication, Geosmin, Nanobubble aeration.

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INTRODUCTION

Eutrophication and long-term excessive nutrient loading are major constraints in semi-intensive aquaculture because they promote algal blooms and microbial proliferation, degrade water quality, and lead to the formation of undesirable metabolites. Geosmin (GSM) is a key earthy-musty compound and the most common cause of off-flavor in fish, producing taste and odor defects that reduce consumer acceptance (Juttner and Watson, 2007). They are

produced by several microorganisms, most notably by cyanobacteria may be discharged during senescence of a bloom, and they build up in production systems. Recirculating and pond-based systems are particularly prone to these problems because off-flavor compounds can concentrate in the water and subsequently partition into fish flesh, meaning sensory quality is tightly coupled to in-pond water conditions (Petersen *et al.*, 2011). Recirculating aquaculture systems that have been studied have



demonstrated that past 20 ng/L geosmin in water, the majority of fish develops a rather strong muddy flavor, highlighting that there is a very thin line between acceptable and unacceptable product.

The influence of relatively low concentrations of dissolved and particulate material can have significant effects on human odor perception, supporting the view that off-flavor is a complex, systemic, eutrophication symptom, in addition to that of unstable DO, changes in structure in the microbial community, and high nutrient levels that contribute to the reduce planktonic bloom (Chakraborty, 2023). Aquaculture system studies have also found that the prevalence of GSM is driven by crucial environmental and operational factors and that it is regulated by system-level factors, including nutrient loads, oxygen status, and biomass dynamics (Lee *et al.*, 2020). Consequently, GSM often acts as a quality bottleneck; farms may achieve biological production targets but still suffer economic losses because off-flavor reduces product desirability and market value (Petersen *et al.*, 2011).

Various mitigation solutions have been investigated such as mitigation of eutrophication and prevention of odor formation but none has significant limitations. Practically, off-flavor management will often be based on operational stages, including depurating fish in clean water, and enhancing the hygiene of the system, which are time-consuming, resource-intensive, and cannot be consistently applied on a large scale (Petersen *et al.*, 2011). Ultrasound is also a possible option, wherein acoustic cavitation can be used to remove Geosmin in recirculating water, yet its effectiveness is extremely sensitive to the quality of water and conditions of operation and does not always produce consistent results (Nam Koong *et al.*, 2016). Against this background, methods that act directly on fundamental water quality drivers, such as nutrient cycling, oxygenation and bloom suppression, while simultaneously limiting odor compound formation, are especially attractive for aquaculture. Nanobubble technology has recently emerged as a promising tool to target these underlying drivers in water treatment. Because micro and nanobubbles provide an extremely high gas-liquid interfacial area, they can markedly enhance gas transfer and have been widely reported as effective in a variety of water treatment processes (Agarwal *et al.*, 2011; Parmar and Majumder, 2013).

The enhancement of oxygen uptake and distribution is an important activity in aquaculture to plan the conditions that promote cyanobacteria rise and the danger of creating off-flavor, and nanobubble aeration

of the water by appropriate dosing can be useful in stabilizing the DO and other related parameters (Takarina *et al.*, 2020; Yaparathne *et al.*, 2022). It has been indicated that oxygen nanobubbles can eliminate GSM by combined aeration and mild oxidation, and therefore, nanobubbles can become a worthwhile alternative to odor control. Following on this, joint technologies have been suggested whereby ultrasound breaks up bloom biomass mechanically and nanobubbles maintain oxygen delivery and maintain physicochemical stability, in an attempt to have both quick and long-term management of blooms and metabolites (Mawarni *et al.*, 2023). However, significant practical doubts still seem related to the comparative benefits of nanobubbles, as well as combinations, to the optimization of working conditions, and the uniformity of performance in various waters (Wang *et al.*, 2023). In light of these gaps and requirements, the present research was designed to evaluate nanobubble-based water treatment in warm-water aquaculture systems, with the specific aim of reducing plankton abundance and geosmin incidence to improve both water quality and the sensory quality of aquatic products.

MATERIALS AND METHODS

1. Experimental setup

It starts with the installation of a 100 L aquarium in NARC, Khumaltar. It is inundated and spilling with algae. 7 days of continuous use of a BGR light increase algal growth, producing green water. Afterward, 6 L of algae in the rich water undergoes four treatments; a positive control (sunlight), a negative control (dark), an ultrasound unit, and a nanobubble unit. The process requires 7 days of treatment, which coincides with the peak of algal growth and the 14-day plankton cycle. Both the positive and negative controls are subjected to sunlight and darkness, respectively. Ultrasound and nanobubbles are applied daily, with a duration of 6 minutes. This week, water quality is monitored using the Pasco sensor and Eco Check strips to assess parameters including temperature, pH, dissolved oxygen, and nutrients. The number of algae is measured by the ATP method, in which relative light units (RLUs) are measured. Records are taken regularly. To separate and detect components, gas chromatograph is used (Agilent Intuvo 9000) and a mass spectrometer. The arrangement of GC and MS parameters was described by Ma *et al.* (2007). HP-5MS (5% phenylmethyl siloxane cross-linked 30 m x 0.25 mm i.d. x 0.25 m) was used. These tests were total phosphorus (TP), chlorophyll a (Chl-a) and total nitrogen (TN). The depth of the Secchi (SD) is taken. There are standard limnological protocols that provide procedures. Alteration in algal water growth and color

are observed and a comparison made across all the treatments with special focus to controls and to assessing the effects of treatment.

2. Statistical analysis

Statistical analyses were performed using Origin 2022 and XLSTAT 2019. Origin 2022 was used to compute descriptive statistics (means, standard deviations, and other dispersion measures) to characterize the central tendency and variability among treatments. XLSTAT 2019 was used to perform a one-way ANOVA to test for differences among treatments at the significance level $<.05$ and correlation analysis among variables, and the results were summarized in a correlation matrix. In this analysis, turbidity (NTU) was converted to SD following the approach of Xu *et al.* (2019), and cyanobacterial abundance measured in RLU was converted to colony-forming units (CFU) using the model proposed by Ivancic *et al.* (2008). The trophic status of the lakes was evaluated using Carlson's TSI (Carlson, 1977) and the modified Trophic Level Index (Burns *et al.*, 2005), which provide an integrated assessment of water quality and are widely applied in limnological studies. TN is explicitly incorporated into the TLI, providing information for systems in which nitrogen is a limiting factor. To interpret the density and the occurrence of geosmin, a multiple linear regression model was developed in XLSTAT 2019, with the general form (Equation 1):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon \quad \text{Equation 1}$$

Where;

γ denotes the response variable, χ^1 the explanatory variables, β^1 the regression coefficients, and ε the error term. The adequacy was assessed using the coefficient of determination (R^2) and standard diagnostic procedures (assessment of residual normality, independence, and homoscedasticity), ensuring consistency with the Completely Randomized Design (CRD; 4×3) adjusted in the experiment.

2.1 Carlson TSI CTSI

a) TP: TSI (P) = $14.42 \ln(\text{TP}) + 4.15$ Equation 2

b) Chlorophyll a (Chl-a): TSI (Chl) = $9.81 \ln(\text{Chl-a}) + 30.6$ Equation 3

c) SD: TSI (SD) = $60 - 14.41 \ln(\text{SD})$ Equation 4

d) Average formula: Average TSI = $[\text{TSI(P)} + \text{TSI(Chl)} + \text{TSI(SD)}] / 3$ Equation 5

2.2. Nutrient-Based Index Calculations

a) For lakes (10 TN / TP 30): TSI = $[\text{TSI(Chl-a)} + (\text{TSI(TN)} + \text{TSI(TP)}) / 2]$ Equation 6

b) Phosphorus-limited lakes (TN/TP > 30): TSI = $[\text{TSI(Chl-a)} + \text{TSI(TP)}] / 2$ Equation 7

c) Nitrogen-limited lakes (TN/TP < 10): TSI = $[\text{TSI(Chl-a)} + \text{TSI(TN)}] / 2$ Equation 8

The Trophic State Index (TSI) was classified and categorized in indexing level by the University of South Florida Water Atlas (2020) where the nutrient status and overall water quality of lakes and reservoirs. A TSI value between 0 and 59 indicates oligotrophic to mid-eutrophic conditions and represents good water quality. Values ranging from 60 to 69 correspond to mid-eutrophic to eutrophic conditions, signifying fair water quality. When the TSI falls between 70 and 100, the water body is considered hypereutrophic, reflecting poor water quality due to excessive nutrient enrichment.

RESULTS

This study showed that nanobubble aeration has a high potential to improve water quality, especially by reducing nutrient content and eutrophication through increased oxygen levels, as summarized in Table 1. Nitrogen indicators under nanobubble treatment were also reduced; nitrogen by 36.6%, nitrate by 57.4%, and ammonia by 22.7%. These changes indicate qualitative improvements in the nitrogen cycle and nutrient regulation. Biological indicators reflected almost the similar effects. The plankton density in nanobubble-treated water decreased compared to the negative controls ($6.3 \times 10^6 \pm 2.7 \times 10^6$ CFU/mL to $1.5 \times 10^6 \pm 9.4 \times 10^5$ CFU/mL), possibly due to better water quality and less microbial growth.

In contrast, plankton density decreased by only about 24.6% in the positive control and 38.6% in the ultrasound treatment, suggesting weaker bloom control. The reduction in plankton density under nanobubble treatment could help restore ecological balance by managing uncontrolled microbial growth. Nanobubble aeration also resulted in a minimum geosmin conc. of 171.58 ± 0.017 ng/L, roughly 43% lower than the positive treatment (239.31 ± 0.030 ng/L) and ultrasound (263.73 ± 0.035 ng/L). Since geosmin causes earthy off-flavors, its reduction suggests nanobubble treatment can improve water sensory quality and lower off-flavor risks in fisheries. The DO level in nanobubble treatment measured 9.78 ± 1.11 mg/L, higher than the positive control at 7.39 ± 0.51 mg/L and the ultrasound treatment at 7.70 ± 0.60 mg/L.

The increased DO promotes aerobic processes and overall water quality. Nanobubbles also significantly decreased carbon dioxide (CO_2) to 0.80 ± 0.70 mg/L, about 89.6% below the negative control level of 7.70 ± 3.40 mg/L, helping optimize the aquatic environment. Nanobubble treatment increased temperature by a small margin, $33.3 \pm 1.82^\circ\text{C}$, or about 4.7 percent higher than the positive treatment $31.8 \pm 1.44^\circ\text{C}$, yet sufficiently within acceptable limits in warm water systems operate at temperatures as low as 33.3°C ($p < 0.0002$). All treatments had a mildly

alkaline pH, with positive control having an optimum of 7.2 ± 0.1 , but the chemical water quality was not affected. The number of oxidants- ozone and hydrogen peroxide- was more intense in the nanobubble and ultrasound treatment that contributed to the disinfection and degradation of pollutants.

$$\text{Geosmin (ng/L)} = 212.37 - 9.12 \text{ DO} + 3.93 \text{ nitrate} + 7.14 \text{ Nitrite} - 65.11 \text{ Phosphate} + 4.20 \times 10^6 \text{ Plankton Density}$$

$$\text{Plankton density (cfu / ml)} = 5.884 \times 10^6 - 5.036 \times 10^5 \text{ DO} - 1.367 \times 10^5 \text{ Nitrite} - 1.76 \times 10^4 \text{ Nitrate} + 7.302 \times 10^6 \text{ Phosphate}$$

Plankton growth is highly sensitive to DO and phosphate. Combining these models, it appears that improving oxygen level enhancement and nutrient

regulation, particularly phosphorus control, in water is essential for eutrophication management, providing direct and practical guidance for reducing geosmine-related biomass and reducing the availability that supports blooming biomass. This study showed that nanobubble aeration has high potential to improve water quality, particularly by reducing nutrient concentrations and mitigating eutrophication through increased oxygen, as summarized in Table 3 and Figure 1. The TSI in the nanobubble treatment was the lowest (36.02 ± 1.77) among all treatments, about 39.5 % lower than that of the positive controls (59.65 ± 2.24). This indicates that the water's trophic state has improved significantly and that the nanobubble system can effectively contribute to pollution management by reducing nutrient loading.

Table 1: Effects of negative, positive, ultrasound, and nanobubble treatments on geosmin concentration and physicochemical water quality parameters.

Parameter	Treatments				P<0.05
	Negative	Positive	Ultrasound	Nanobubble	
Geosmin (ng/L)	300.66 ± 1.15 ^c	239.31 ± 0.30 ^b	263.73 ± 0.35 ^b	171.58 ± 0.17 ^a	0.0011
Plankton density (CFU/mL)	6.3x106 ± 2.7x106 ^c	4.8x106 ± 1.8x106 ^{bc}	3.9x106 ± 1.7x106 ^b	1.5x106 ± 9.4x105 ^a	< 0.0001
DO (mg/L)	3.42 ± 1.03 ^a	7.39 ± 1.51 ^b	7.70 ± 0.60 ^b	9.78 ± 1.11 ^c	< 0.0001
Temperature (°C)	32.80 ± 1.51 ^b	31.80 ± 1.44 ^a	32.80 ± 1.61 ^b	33.30 ± 1.82 ^c	0.0002
pH	7.00 ± 0.20 ^a	7.20 ± 0.10 ^b	7.10 ± 0.10 ^b	7.10 ± 0.10 ^b	< 0.0001
Nitrite (mg/L)	1.65 ± 0.18 ^b	1.79 ± 0.80 ^b	1.59 ± 0.28 ^b	0.76 ± 0.47 ^a	0.0003
Nitrate (mg/L)	26.26 ± 3.64 ^b	24.07 ± 3.85 ^b	27.09 ± 1.87 ^b	16.65 ± 4.42 ^a	< 0.0001
Phosphate (mg/L)	0.33 ± 0.22 ^{ab}	0.47 ± 0.29 ^c	0.39 ± 0.22 ^{bc}	0.20 ± 0.06 ^a	< 0.001
Ozone (mg/L)	0.40 ± 0.04 ^a	0.71 ± 0.03 ^b	1.01 ± 0.06 ^c	0.56 ± 0.07 ^{ab}	0.0042
Total Hardness (mg/L CaCO)	85.50 ± 3.12 ^b	86.46 ± 5.39 ^b	84.69 ± 2.11 ^{ab}	82.51 ± 1.26 ^a	< 0.0001
Alkalinity (mg/L CaCO)	185.48 ± 22.74 ^b	148.55 ± 45.90 ^a	197.97 ± 24.45 ^b	189.14 ± 27.28 ^b	0.0004
Turbidity (NTU)	14.90 ± 4.30 ^a	15.19 ± 4.33 ^b	16.22 ± 9.66 ^b	14.66 ± 4.35 ^a	0.1231
Nh ₃ (mg/L)	0.21 ± 0.03 ^a	0.18 ± 0.08 ^b	0.18 ± 0.07 ^b	0.22 ± 0.03 ^a	< 0.0001
CO (mg/L)	7.70 ± 0.40 ^b	2.80 ± 0.30 ^a	3.00 ± 0.70 ^a	0.80 ± 0.07 ^a	< 0.0001

Note: The different superscript letters within the row are significantly different at α 0.05.

Table 2: Relationships among various commonly used measurements to assess water quality and living organisms in aquaculture water.

Symbol	Variables	Symbol						
		A	B	C	D	E	F	G
A	TSI	1						
B	Nutrient-Balanced Lakes (10 to 30)	0.98***	1					
C	Phosphorus-Limited Lakes (> 30)	0.99***	0.97***	1				
D	Nitrogen-Limited Lakes (< 10)	0.87***	0.95***	0.85***	1			
E	DO (mg/L)	-0.15	-0.24	-0.13	-0.35	1		
F	Cyanobacteria cfu/ml	0.63***	0.62***	0.64***	0.55**	-0.55**	1	
G	Geosmin (ng/l)	0.36	0.47*	0.34	0.60***	-0.87***	0.64***	1

Note: Strength of the correlation (r) = 0.0-0.1 = no correlation; 0.1-0.3 = low correlation; 0.3-0.5 = medium correlation; 0.5-0.7 = high correlation; 0.7-1 = very high correlation. * Significant at 0.05, ** significant at 0.01 and *** significant at 0.001

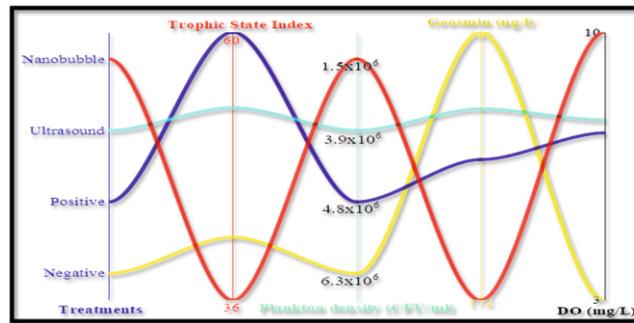


Fig. 1: Relation of various treatments to dissolved oxygen, plankton density, and geosmin levels in aquatic environments.

Table 3: Effects of Experimental Treatments on Lake Trophic Status and Plankton Density.

Parameter	Treatments				P<0.05
	Negative	Positive	Ultrasound	Nanobubble	
Trophic State Index	41.58 ± 3.47 ^c	59.65 ± 2.24 ^a	53.00 ± 4.41 ^b	36.02 ± 1.37 ^d	< 0.0001
Nutrient-Balanced Lakes (10-30)	26.62 ± 2.84 ^c	41.01 ± 1.42 ^a	35.73 ± 3.39 ^b	22.62 ± 0.74 ^c	< 0.0001
P-Limited Lakes (> 30)	36.67 ± 5.55 ^c	62.93 ± 2.98 ^a	53.59 ± 6.65 ^b	29.06 ± 1.66 ^c	< 0.0001
N-Limited Lakes (< 10)	16.57 ± 0.59 ^c	19.09 ± 0.66 ^a	17.88 ± 0.71 ^b	16.17 ± 0.18 ^c	< 0.0001

Note: The different superscript letters within the row are significantly different at α 0.05.

DISCUSSION

The current experiment (Table 1) indicates that nanobubble treatment produced clear and desirable changes in water quality, with particularly strong effects on geosmin (GSM) and eutrophication indicators. In eutrophic aquaculture systems, the primary producers of GSM are cyanobacteria and their associated microbial communities (Gerber and Lechevalier, 1965; Guttman and Rijn, 2008), and in the present study, geosmin levels closely followed plankton abundance, with the highest geosmin concentrations observed under the highest nanobubble treatment. Such a strong decrease in the level of geosmin is biologically and economically important, as the human sensory thresholds of geosmin are very low; hence, the improvement in fish sensory quality and marketability by any modest change in the concentration of such a compound is disproportionate (Petersen *et al.*, 2011); thus, the observed drastic decrease in the level of geosmin.

The biological reactions can be measured in terms of a mechanistic explanation whereby nanobubbles change dissolved gas relationships with higher oxygen influx and interfaces of the water column, which redesigns the redox conditions. In this experiment it was possible to maximize DO by nanobubble treatment which was three times more than the control and ten times more than the positive and ultrasound

treatment, and dissolved CO₂ was minimized by nanobubble treatment with a nearly ten-fold difference between the negative controls. Large DO encourage aerobic breakdown of organic matter and represses anaerobic and low-oxygen-tolerant cyanobacteria and therefore the severity of a bloom and metabolite production (Lee *et al.*, 2020; Wu *et al.*, 2021), and a high amount of CO₂ can stimulate cyanobacteria growth and change pH dynamics, thus its depletion is probably to be favorable to a more stable, oxidative setting (Zhao *et al.*, 2024). Collectively, such a combination of a high-oxygen, low CO₂ environment causes the system to be less suitable to attentive geosmin-producing cyanobacteria and more suitable to efficient biogeochemical processes that inhibit off-flavor formation.

In addition to influencing dissolved gases, the nanobubble treatment resulted in the lowest concentrations of nitrite and nitrate, indicating an efficient and complete conversion of inorganic nitrogen species. High inorganic nitrogen is one of the established factors that have triggered eutrophication, cyanobacterial growth, and off-flavor problems in aquaculture and the recorded reductions in high inorganic nitrogen species under nanobubbles hence limit the nutrient base that can support excessive primary production (Guttman and Rijn, 2008). This tendency follows the works of other researchers who

have already shown that nitrogen cycling can be improved by nanobubble aeration, and the storage of nutrients in the aquatic environment is reduced (Soyluoglu *et al.*, 2022; Yaparantne *et al.*, 2022), which confirms the idea that nanobubbles can modify both the gas and nutrient size of water quality.

During the experiment, basic physicochemical parameters were within manageable limits in all treatments, but there were minor differences in temperature among the normal temperature range of warm-water aquaculture, and the pH levels were mostly neutral and alkaline. Notably, treatment with nanobubbles kept the pH range very narrow and constant with sufficient alkalinity to counteract the vast changes and stay within the range preventing low pH and worse buffering which endanger the physiological homeostasis of the fish the stress. Total hardness and calcium concentrations did not vary significantly and this demonstrates that the advantages of nanobubbles could not be associated with significant changes in mineral composition. There was no significant difference in turbidity among treatments indicating that apparent visual clarity is not a sufficient measure of the significant chemical and biological changes caused by nanobubbles. Treatment with ultra sound that created more ozone and lower plankton density through mechanical disturbance did not produce similar decreases in dissolved gas concentration and geosmin inhibition meaning that mechanical destruction of cells cannot be sustainable in managing cyanobacteria and their metabolites without associated changes in redox status and gas exchange (Mawarni *et al.*, 2023).

The proposed mechanism is confirmed by the correlation analysis (Table 2), where there is a consistent pattern of trophic enrichment, cyanobacterial abundance, DO, and geosmin. The abundance of cyanobacteria and geosmin had positive relationships with higher trophic state indicators. These two variables had negative relationships with DO as it is also reported that DO is one of the important negative predictors of geosmin and that cyanobacteria is one of the important positive predictors (Zhao *et al.*, 2024). Though these relationships are not causal, the existing knowledge supports that these nutrients eutrophic with nitrogen and phosphorus encourages geosmin-producing cyanobacteria, like *Anabaena*, *Aphanizomenon*, and *Oscillatoria*, which results in more of the off-flavor metabolites accumulating in fish at extremely low but detectable levels (Petersen *et al.*, 2011; Zhao *et al.*, 2024). This negative correlation between DO and geosmin is in line with those literature studies that have demonstrated that the

depletion of oxygen in eutrophic waters is due to high biological oxygen consumption during algal growth, and death, as well as, low DO supports cyanobacterial survival and ecosystem distress (Petersen *et al.*, 2011; Zhao *et al.*, 2024). Therefore, in the present study, geosmin can be considered a symptom of oxygen-depleted eutrophic rather than independent pollutant and nutrient enrichment, cyanobacterial growth, oxygen depletion, geosmin occurrence are closely related processes in a network.

The regression analysis demonstrates that the geosmin dynamics are strongly correlated with almost water-quality parameters that regulate eutrophication, plankton development and oxygen equilibri. In the models, the increase in DO was always linked to the decrease in the biomass of planktons and geosmin, and the availability of phosphorus was a primary predictor of plankton growth and, therefore, geosmin, which were ecologically consistent with evidence suggesting that phosphorus and nitrogen enrichment leads to cyanobacterial blooms and the production of off flavors, and oxygen saturation conditions are typical indicators of less eutrophic systems with few blooms and low geosmin levels (Zhao *et al.*, 2024).

Nanobubble treatment gives credence to the interpretation that the management of eutrophication by improving oxygenation and nutrient removal can be one viable avenue toward mitigating the growth of cyanobacteria and geosmin in aquaculture waters (Zhao *et al.*, 2024). The sun key diagram (Fig. 1), which indicates that the DO is the strongest negative correlate with the cyanobacterial abundance is the strongest positive correlate of geosmin, which reminds their key roles in the process of geosmin dynamics in eutrophic environments.

The experiment (Table 3) indicates that nanobubble treatment shows favorable water quality and geochemical status improvements among the treatments. Specifically, the significantly lower total TSI at conditions of high nanobubble concentration evidences the shift of the eutrophic system toward the mesotrophic one, with the most pronounced reactions in the waters with phosphoric enrichment and nutrient balance (University of South Florida Water Atlas, 2020). Since eutrophication is one of the major causes of cyanobacterial proliferation and off-flavor compounds, this decline in trophic status is a significant advancement in the quality of aquaculture waters (Guttman and Rijn, 2008). This trophic shift was accompanied by a pronounced decline in plankton density, with total plankton abundance decreasing and suppressing. The traditional methods of high-intensity oxidation, including high costs and

operational complexity, therefore it appears as a promising, scalable, and environmentally friendly approach to improving water quality in eutrophic warm-water aquaculture systems (Parmar and Majumder, 2013; Povich *et al.*, 2024).

CONCLUSIONS

All these findings demonstrate that nanobubble treatment decreases the trophic state, suppresses plankton and geosmin, improves the DO, decreases the CO₂, and decreases the inorganic nitrogen, and preserves pH which indicate that nanobubbles modify the aquatic environment at a fundamental physico-chemical level to inhibit cyanobacterial domination and the formation of off flavors. The overall effect of the nanobubble treatment showed that, as the water shifted toward an oligotrophic and more oxygen-rich state, the levels of both bloom/plankton abundance and geosmin decreased markedly. This indicates that enhanced gas transfer and high DO concentrations are the central mechanisms underlying the effectiveness of nanobubbles. The correlation patterns confirmed that a higher trophic enrichment is positively associated with higher cyanobacterial abundance and geosmin, and negatively associated with DO. Nanobubble technology appears to provide a more effective and durable method for controlling eutrophication and reducing geosmin in eutrophic aquaculture waters, compared with other treatments, which were only partially successful in stabilizing the aquatic ecosystem.

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CONFLICT OF INTEREST

The authors state that they do not have any conflict of interest related to this article.

REFERENCES

1. Agarwal A., Ng W.J. and Liu Y. (2011). Principles and applications of microbubble and nanobubble technology for water treatment. *Chemosphere*. 84:1175-1180. <https://doi.org/10.1016/j.chemosphere.2011.05.054>
2. Burns N., McIntosh J. and Scholes P. (2005). Strategies for the lakes of the Rotorua district, New Zealand. *Lake and Reservoir Management*. 21(1): 61-72. <https://doi.org/10.1080/07438140509354413>
3. Carlson R.E. (1977). A trophic state index for lakes. *Limnology and Oceanography*. 22(2): 361-369. <https://doi.org/10.4319/lo.1977.22.2.0361>
4. Chakraborty B.K. (2023). Status of Plankton and Benthos in the Aquaculture field of Bangladesh. *International Journal of Biological Innovations*. 5(1): 91-102. <https://doi.org/10.46505/IJBI.2023.5107>
5. Gerber N.N. and Lechevalier H.A. (1965). Geosmin an earthy-smelling substance isolated from actinomycetes. *Applied Microbiology*. 13(6): 935-938. <https://doi.org/10.1128/am.13.6.935-938.1965>
6. Guttman L. and van Rijn Jaap van (2008). Identification of conditions underlying the production of geosmin and 2-methylisoborneol in a recirculating system. *Aquaculture*. 279(1-4): 85-91. <https://doi.org/10.1016/j.aquaculture.2008.03.047>
7. Ivancic V., Mastali M. and Percy N. (2008). Rapid antimicrobial susceptibility determination of uropathogens in clinical urine specimens by use of ATP bioluminescence. *Journal of Clinical Microbiology*. 46(4): 1213-1219. <https://doi.org/10.1128/JCM.02036-07>
8. Juttner F. and Watson S.B. (2007). Biochemical and ecological control of geosmin and 2-methylisoborneol in source water. *Applied and Environmental Microbiology*. 73(14): 4395-4406. <https://doi.org/10.1128/AEM.02250-06>
9. Lee J.E., Youn S-J., Byeon M. and Yu S. (2020). Occurrence of cyanobacteria, actinomycetes, and geosmin in drinking water reservoir in Korea: A case study from an algal bloom in 2012. *Water Supply*. 20(5):1862-1870. <https://doi.org/10.2166/ws.2020.102>
10. Ma X., Gao N., Chen B., Li Q., Zhang Q. and Gu G. (2007). Detection of geosmin and solid phase extraction-gas chromatograph mass spectrum SPE-GCMS. *Frontiers of Environmental Science & Engineering in China*. 1(3): 286-291. <https://doi.org/10.1007/s11783-007-0048-7>
11. Mawarni D.I., Ristiyanto H.G. and Deendarlianto D. (2023). Review on swirl-type microbubble generator: Concept, technology, and applications. *Mechanical Engineering for Society and Industry*. 3(3): 191-205. <https://doi.org/10.31603/mesi.10565>
12. Nam-Koong H., Schroeder J.P., Petrick G. and Schulz C. (2016). Removal of the off-flavor compounds geosmin and 2-methylisoborneol from the recirculating water of the aquaculture

- system by ultrasonically induced cavitation. *Aquacultural Engineering*. 70:73-80.
<https://doi.org/10.1016/j.aquaeng.2015.10.005>
13. **Parmar R. and Majumder S.K.** (2013). Microbubble generation and microbubble-aided transport process intensification: A state-of-the-art report. *Chemical Engineering and Processing: Process Intensification*. 64: 79-97.
<https://doi.org/10.1016/j.cep.2012.12.002>
 14. **Petersen M.A., Hyldig G., Strobel B.W., Henriksen N.H. and Jorgensen N.O.G.** (2011). Chemical and sensory quantification of geosmin and 2-methylisoborneol in rainbow trout. *Journal of Agricultural and Food Chemistry*. 59(23): 12561-12568.
<https://doi.org/10.1021/jf2033494>
 15. **Povis A.A.L., Pérez E. A. S., Quispe K.A.O. and Yanqui P.V.G.** (2024). Effect of the concentration of dissolved oxygen on biomass production in wastewater. *Revista Ambiente & Água*. 19: e2937.
<https://doi.org/10.4136/ambi-agua.2937>
 16. **Soyluoglu M., Kim D., Zaker Y. and Karanfil T.** (2022). Mechanisms of removal of geosmin and MIB by oxygen nanobubbles during water treatment. *Chemical Engineering Journal*. 443: 136535.
<https://doi.org/10.1016/j.cej.2022.136535>
 17. **Takarina N.D., Utomo S.W. and Susanti L.** (2020). Trends in phytoplankton biodiversity in nanobubble aerated shrimp farming. *Biodiversitas Journal of Biological Diversity*. 21(12): 5906-5914.
<https://doi.org/10.13057/biodiv/d211256>
 18. **University of South Florida Water Atlas** (2020). Trophic State Index (TSI). Orange/CHNEP Water Atlas.
https://orange.wateratlas.usf.edu/library/learn-more/learnmore.aspx?toolsection=lm_tsi
 19. **Wang Y., Zheng J., Cheng J., Zhou R., Li X., Hu J. and Lu, J.** (2023). Nanobubbles can modulate microbial communities and sedimentary ecosystems during the treatment of pond water. *Environmental Science: Water Research & Technology*. 9(7): 1804-1812.
<https://doi.org/10.1039/D3EW00257H>
 20. **Wu J., Zhang K., Cen C., Wu X., Mao R. and Zheng Y.** (2021). Role of bulk nanobubbles in removing organic pollutants in wastewater treatment. *AMB Express*. 11(1):96.
<https://doi.org/10.1186/s13568-021-01254-0>
 21. **Xu M., Liu H., Beck R., Reif M., Emery E. and Young J.** (2019). Regional analysis of lake and reservoir water quality with multispectral satellite remote sensing image.
<https://doi.org/10.21079/11681/34933>
 22. **Yapatatne S., Doherty Z.E., and Magdaleno A.L.** (2022). Effect of air nanobubbles on oxygen transfer, oxygen uptake, and diversity of the aerobic microbial consortium. *Bioresource Technology*. 351: 127090.
<https://doi.org/10.1016/j.biortech.2022.127090>
 23. **Zhao Z., Huang X. and Zhang Z** (2024). The efficiency and mechanism of geosmin removal by modified micro-nano bubbles. *Journal of Water Process Engineering*. 60: 105125.
<https://doi.org/10.1016/j.jwpe.2024.105125>