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Ammonia Influence on Bromate Development and Nitrogen Oxidation in Ozonated Seawater

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ABSTRACT

This study evaluated the impact of ozonation on seawater, concentrating on the generation of bromate, oxidation of nitrate and nitrite, and alterations in dissolved oxygen and pH levels. Experiments were performed with 1, 2, 3, and 4mg/ L ammonia concentrations to determine their effect on bromate development during ozonation. The results demonstrate that elevated ammonia levels caused a longer delay in the generation of bromate by 15, 30, 45, and 60 minutes, respectively. These results indicate that the concentration of ammonia available can significantly impact the suppression of bromate development. The nitrite and nitrate levels decreased during the ozonation process. Specifically, nitrite concentration decreased from initial values of 0.05, 0.10, and 0.15mg/ L to final values of 0.003, 0.049, and 0.107 mg/L, respectively. Similarly, the concentration of nitrate dropped from initial values of 1, 2, and 3mg/ L to final values of 0.63, 1.64, and 2.57mg/ L, respectively, after a duration of 60 minutes. Over 360 minutes, ozonation elevated DO from 6.03 to 14.77mg/ L. This was followed by a decrease in pH from 8.35 to 7.99. These findings highlight that adjusting ammonia loading and ozonation parameters can improve water quality, limit bromate development, and contribute to sustainable marine aquaculture.

INTRODUCTION

Ozonation is a highly effective water treatment technique that is generally acknowledged for its potent oxidative capabilities and its capacity to enhance water quality in several environments, such as drinking water treatment and aquaculture. In marine aquaculture, it is essential to ensure that the water quality is maintained at a suitable level in order to promote the survival, health, and growth of aquatic organisms. However, implementing ozonation in seawater poses several constraints, particularly regarding the development of potentially toxic byproducts such as bromate that can harm aquatic life and human health **(Tango & Gagnon, 2003; Liltved *et al*., 2006; Gonçalves**

& Gagnon, 2018; Gorito *et al*., 2022). Bromate is produced from the reaction between ozone and naturally occurring bromide in seawater under specific circumstances. Previous research has pointed out the function of ammonia (NH_3) as a remover of reactive oxygen species, which could potentially impact the generation of bromate **(Haag & Hoigne, 1983; Berne *et al*., 2004; Rahmadi & Kim, 2014)**. Hence, comprehending the impact of ammonia concentration on the development of bromate is crucial for establishing procedures that minimize bromate threats in marine aquaculture systems.

Ozonation not only contributes to the development of bromate but also affects nitrogen-containing substances, including nitrate and nitrite, which are essential factors in managing aquaculture water quality. Nitrate and nitrite are byproducts of the nitrogen cycle. They can potentially elevate to lethal concentrations in marine aquaculture systems, negatively impacting aquatic life **(Colt, 2006; Monsees *et al*., 2017; John *et al*., 2020)**. Oxidation of nitrate and nitrite through ozonation may minimize their levels, contributing to enhanced water quality. However, to maximize ozonation application in aquaculture, more research is needed to fully understand the effectiveness of these oxidation processes and the possibility of intermediate product development.

Moreover, the ozonation process has an impact on essential water quality parameters, including dissolved oxygen and pH. The decomposition of ozone in water generates oxygen, which may improve dissolved oxygen levels, a key factor for cultured species' respiration and health. Nevertheless, ozonation induces an alteration in pH due to the accumulation of acidic byproducts, which might impact the ability of nutrients to dissolve and the physiological functions of aquatic animals **(Tucker & D’Abramo, 2008; Kroeker *et al*., 2013)**. Maintaining the equilibrium of these alterations is crucial for supporting a stable and sustainable aquaculture ecosystem.

The objective of this study was to investigate the multifaceted impacts of ozonation on seawater. This study examined the influence of ammonia concentration on the generation of bromate, the oxidation of nitrate and nitrite, and the subsequent alterations in dissolved oxygen and pH levels. By investigating these interactions, the study aimed to deliver insights that may assist in optimizing ozonation application in marine aquaculture, with the purpose of improving water quality and promoting sustainable aquaculture practices.

MATERIALS AND METHODS

System design

The treatments were conducted within a fume hood to eliminate excessive ozone from the cylinders (Fig. 1). Four acrylic cylinders with a capacity of 10 liters each were filled with 7 liters of seawater each. An ozone generator (Ozonetech, PC57L-10) with a 13L/ min capacity was linked to each of the acrylic cylinders, which had an ozone diffuser (air stone) installed. A separate airflow meter was fitted for each cylinder to quantify and regulate the quantity of ozone introduced into the water. The experimental room was equipped with an air conditioning unit to maintain the temperature at 20°C. A temperature of 20°C was designated, considering that it represents the average temperature of seawater used in aquaculture systems within temperate regions.

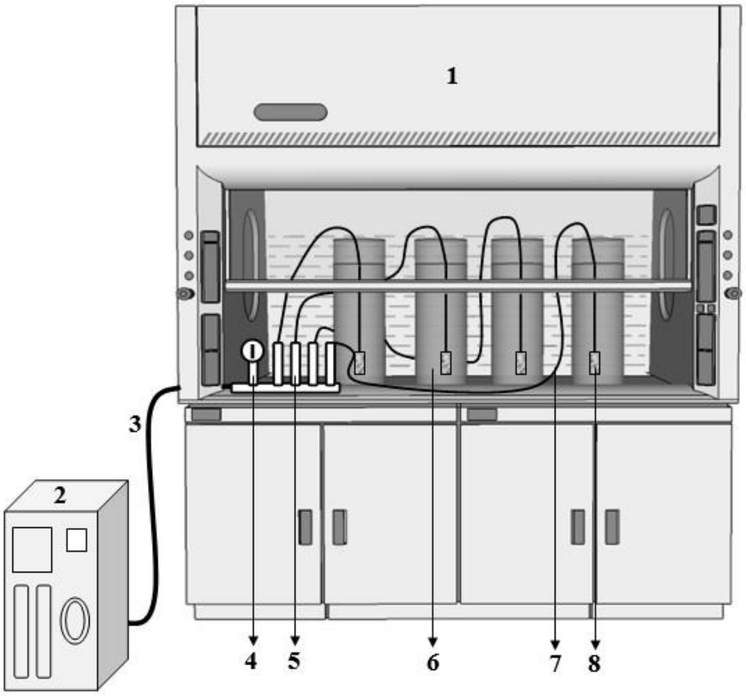

Fig. 1. Schematic drawing of experimental system. (1) Fume hood; (2) Ozone generator; (3) Connector hose; (4) Pressure gauge; (5) Air flow meter; (6) Acrylic cylinder; (7) Aeration hose; (8) Air Stone

Experimental procedure

Once the system was assembled, seven liters of filtered seawater were added to each acrylic cylinder. Before injecting ozone, the temperature was adjusted to 20°C, and the initial amounts of pH and dissolved oxygen were determined. After the system was stabilized and initial water quality parameters (NH_3, BrO_3, NO_2, NO_3) were measured, ozone was continuously injected into the water at 0.1mg/ L. The ozone concentration used in this experiment is based on the effective concentrations for sterilization of microorganisms and toxic levels to fish in aquaculture water **(Ebeling & Timmons, 2010)**. Water samples were obtained regularly to examine water quality parameters.

Inhibition of bromate formation by ammonia addition

The ammonia source was prepared using anhydrous ammonium chloride (NH_4Cl). Using the Manual Phenate Method, the spectrophotometer OPRON 3000 was used to measure total ammonia at a wavelength of 640 nm. Six reagent solutions were prepared to determine the total ammonia concentration. The reagents used were phenol, ethyl alcohol, sodium nitroprusside, trisodium citrate, sodium hydroxide, sodium hypochlorite, alkaline citrate, and ammonium chloride **(American Public Health Association *et al.*, 1995)**. The spectrophotometer was used to measure the amounts of bromate at a wavelength of 590nm **(American Public Health Association *et al.*, 1995)**. The reagents used were acetate buffer solution, phenol red indicator solution, chloramine-T solution, sodium thiosulfate, and stock of bromide solution. The bromate level was measured by comparing the data to the bromate calibration curve. Experiments were conducted in 2 different procedures and the treatment was run in triplicate with one control.

The first experiment observed the correlation between the concentration of ammonia and bromate development by “single application” of ammonia during the process of ozonation. The ammonia concentrations in the first experiment were 1, 2, 3 and 4mg/ L. Afterward, each concentration of ammonia was applied to the ozone-treated water, and water samples were collected at 0, 15, 30, 45, 60, 120, and 360 minutes. Ammonia and bromate concentrations were analyzed.

The second experiment investigated the correlation between ammonia concentration and bromate development through “multiple applications” of ammonia throughout the ozonation process. The interval time of ammonia addition was according to the results of single application experiment. The application time intervals for the tested ammonia concentrations of 1, 2, 3, and 4mg/ L were every 15, 30, 45 and 60 minutes, respectively. Water samples were collected at intervals of 0, 15, 30, 45, 60, 75, 90, 105 and 120 minutes to determine the ammonia and bromate concentrations.

Nitrite oxidation

Sodium nitrite ($NaNO_2$) with the starting dosages of 0.5, 1 and 1,5mg/ L were used as the nitrite source. Samples were collected at intervals of 0, 10, 20, 30, 40, 50, and 60 minutes. Nitrite concentration was measured by the spectrophotometer, HACH DR-2000.

Nitrate oxidation

Potassium nitrate (KNO_3) with the initial concentration 1, 2 and 3 mg/L were used as the nitrate source. Oxidation of nitrate was measured by spectrophotometer, HACH DR-2000

pH changes during ozonation

The Ecomet P25 pH meter was utilized to quantify the alterations in pH. Three buffer solutions were used to calibrate the pH meter. Those buffer solutions are buffer of

4, 7 and 10 pH buffer solution from the Samchun chemical company. pH level was measured at 0, 1, 2, and 6 hours.

DO changes during ozonation

DO levels were measured *in situ* to get a more accurate measurement and reduce bias at 0, 1, 2, and 6 hours. In this measurement, Oxyguard oxygen meter "Handy Mk III" was used.

RESULTS AND DISCUSSION

Inhibition of bromate formation by ammonia addition

The addition of ammonia (in single application) delayed the development of bromate for a certain period. This experiment utilized a range of 1, 2, 3, and 4mg/ L concentrations of ammonia, but actual concentrations were maintained at 1.07, 2.02, 3.03, and 4.02mg/ L. For 1.07mg/ L of ammonia concentration, ammonia was oxidized within 15 minutes, and other concentrations (2.02, 3.03, and 4.02) were oxidized within 30, 45, and 60 minutes, respectively, with an average oxidation rate of ammonia of 0.069±0.006 mg/L per minute. Bromate concentration increased in all treatments after ammonia was completely oxidized. Since complete oxidation was accomplished within the specified time frames, no residual ammonia was found at the end of the experiment for any of the tested concentrations. Fig. (2) demonstrates the impact of ammonia addition (single application) on the formation of bromate.

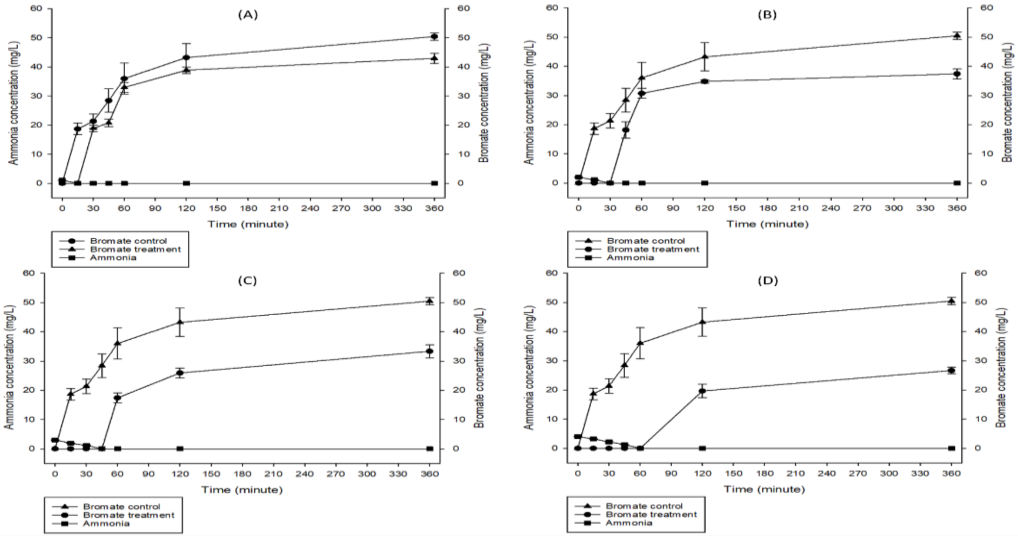

Fig. 2. The effect of ammonia addition (single application) on bromate formation (A: 1 mg/L; B: 2 mg/L; C: 3 mg/L; D: 4 mg/L)

Regarding the delay time of bromate formation in the “single application” experiment, ammonia was added continuously (multiple application) every 15, 30, 45, and 60 minutes for 1, 2, 3, and 4mg/ L of ammonia concentrations, respectively. In this experiment, continuous addition of ammonia in seawater during ozonation succeeded in suppressing bromate formation (Fig. 3).

Ammonia performs a crucial role in the suppression of bromate formation. Ammonia significantly ($P < 0.05$) suppressed bromate formation in seawater ($y = 15.210x – 1.0592$ $r^2=0.99$). The suppression of bromate formation by ammonia addition increased linearly with the time (Fig. 4).

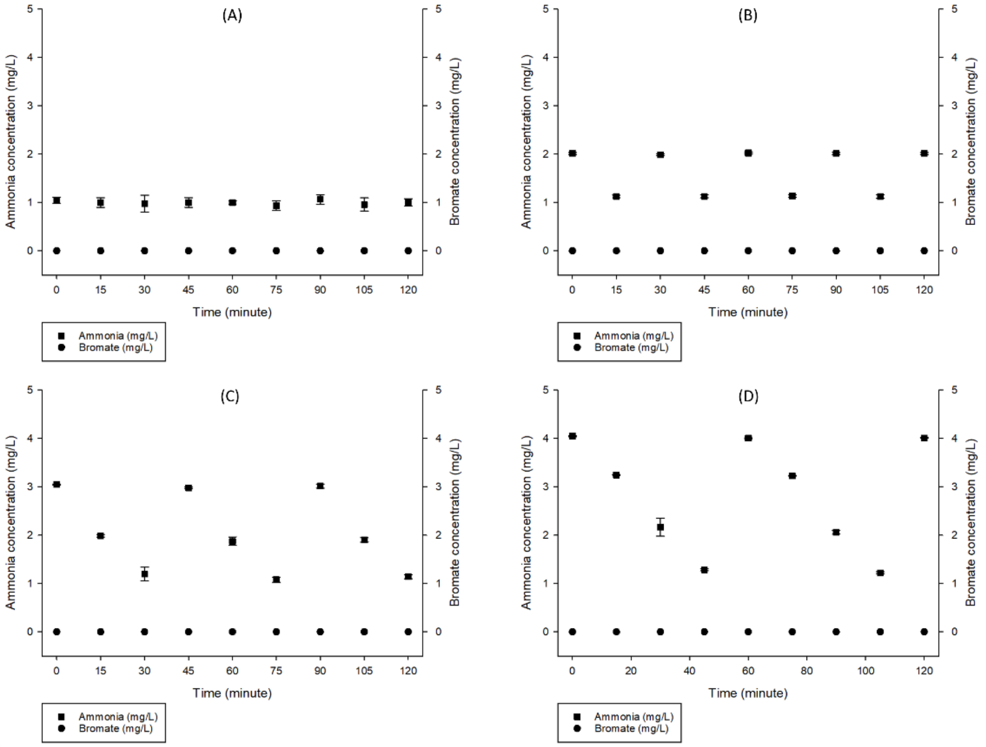

Fig. 3. The effect of ammonia addition (continuous application) on bromate formation (A: 1 mg/L; B: 2 mg/L; C: 3 mg/L; D: 4 mg/L)

Previous studies have demonstrated that there are three main mechanisms responsible for bromate formation during the ozonation of waters containing bromide: the direct mechanism, which involves only molecular ozone, and the direct-indirect and indirect-direct mechanisms which involve both molecular ozone and hydroxyl radicals generated from ozone decomposition, as summarized in Fig. (5) **(Von Gunten & Hoigne, 1994; Song *et al*., 1997; Berne *et al*., 2004)**. In the direct-indirect process, ozone oxidizes bromide to produce hypobromite BrO^- (in equilibrium with hypobromous acid HOBr). BrO- may further react with hydroxyl radicals to generate BrO^o, which disproportionately contributes to forming bromite BrO^{2-}. Through the oxidation of Br^- to

Br^o, the indirect-direct mechanism is initiated by hydroxyl radicals, which is further oxidized to BrO^o. Ammonia facilitates the rapid synthesis of bromamines (monobromamine NH2Br, dibromamine $NHBr^2$, and tribromamine NBr^3) by reacting with free bromine ($HOBr/\ BrO^-$). In contrast, the direct mechanism leads to bromate development when ammonia is absent. It is essential to acknowledge that free bromine is necessary as an intermediary in the synthesis of bromate through both mechanisms (direct and direct-indirect). Therefore, ammonia has the ability to impact these mechanisms. The bromamines are subsequently degraded to bromide and nitrate, thus establishing a second process for the redevelopment of bromide. The existence of ammonia promotes these processes to maintain control over the system **(Berne *et al*., 2004; Bouland *et al*., 2004)**.

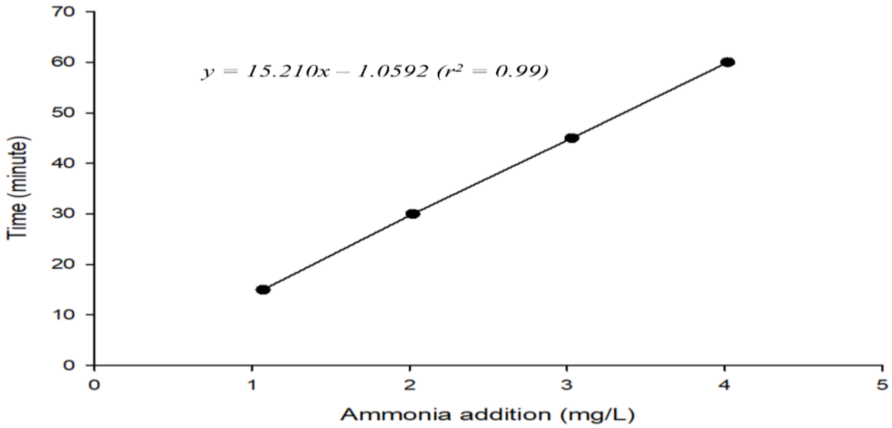

Fig. 4. Relationship between ammonia concentrations and bromate suppressing time

This study's findings show an obvious relationship between the concentration of ammonia and the delay in bromate formation during ozonation in seawater. The observed delays indicate that increased levels of ammonia limit the generation of bromate, either due to the competition between ammonia and ozone or the byproducts developed during the ozonation process. This conclusion aligns with the study of **Von Gunten (2003)**, who demonstrated that ammonia may perform as a scavenger of reactive oxygen species, limiting their ability to integrate with bromide to generate bromate. These findings are important because they suggest that regulating ammonia levels in seawater could be an effective approach to reducing the creation of bromate, a disinfection byproduct known to have negative health effects on aquatic organisms **(Hutchinson *et al*., 1997; Fisher e*t al*., 2014)**.

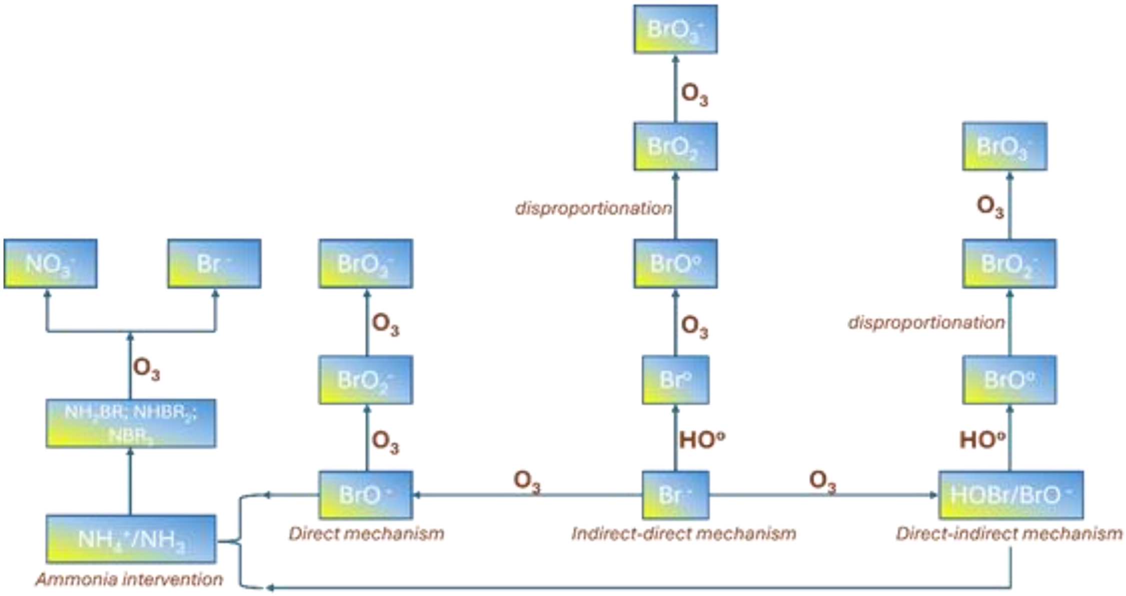

Fig. 5. Bromate development mechanisms and ammonia intervention during ozonation Adapted from **Berne *et al*. (2004)**

The implications of these studies are substantial for the application of ozonation in marine recirculating aquaculture systems (RAS). Ozonation is a commonly employed technology in marine RAS to enhance water quality through the elimination of pathogens and the oxidation of organic contaminants. Nevertheless, the generation of bromate as a secondary product during ozonation presents a challenge because of its potential adverse effects on aquatic organisms. The capability to delay bromate production by adjusting ammonia levels and ozone contact time may provide a viable approach to improving the safety and effectiveness of ozone application in marine aquaculture systems.

Controlling ammonia levels in aquaculture systems can enhance the ozonation process, ensuring efficient disinfection while reducing the possibility of bromate generation. This process is especially important in RAS, where water is consistently recycled, and ensuring water quality is critical for the survival and growth of aquatic species **(Summerfelt *et al*., 2009)**. Furthermore, the concept of ammonia loading rate is critical in this context. The ammonia loading rate, or the amount of ammonia that enters the system over a certain period, has a direct impact on the ammonia concentration in the water. Aquaculture operators can regulate the level of ammonia in the system by closely monitoring and regulating the ammonia loading rate. This adjustment, in turn, may affect the ozone contact time required for effective disinfection. For instance, in order to guarantee sufficient disinfection and prevent the formation of bromate, longer ozone contact times may be required in response to higher ammonia loading rates **(Pinkernell & Von Gunten, 2001; Jarvis *et al*., 2007; Aljundi, 2011; Arvai *et al*., 2012)**.

Nitrite oxidation

This study demonstrated that ozone significantly ($P < 0.05$) oxidized nitrite during the ozonation process in seawater. During this study, three initial concentrations of nitrite (0.05, 0.10, and 0.15mg/ L) were oxidized to 0.003±0.005, 0.049±0.001, and 0.107±0.004 mg/L within 60 minutes, respectively (Fig. 6). During ozonation, the nitrite concentration was decreased at an average reduction rate of $y = -0.0008x + 0.1002$ ($r^2=0.95$) by 0.1mg/ L of ozonation. These results align with the previous knowledge that ozone is a potent oxidizing agent that can transform nitrite (NO_2^-) into nitrate (NO_3^-) through a sequence of oxidative processes **(De Vera *et al*., 2017)**. The decrease in nitrite level found is consistent with other research that has confirmed the conversion of nitrite into other compounds through ozonation in different water samples **(Lin & Yen, 1995, 1997; Tango & Gagnon, 2003; Van Gijn *et al*., 2021)**. In this study, the nitrite oxidation rates were 94, 51, and 28,7% for initial nitrite concentrations of 0.05, 0.10, and 0.15mg/ L, respectively. The findings demonstrate that oxidation efficiency declines as the initial nitrite level increases. The best yield of nitrite oxidation reached 94% at an initial concentration of 0.05mg/ L, suggesting that this level is optimum for maximizing nitrite reduction under the experimental conditions applied.

The substantial decrease in nitrite levels has important implications for the utilization of ozonation in marine aquaculture systems. High concentrations of nitrites can have detrimental effect on aquatic organisms, leading to the development of methemoglobinemia (a condition characterized by high-level methemoglobin in the blood) and other unfavourable effects on health **(Tomasso, 1994; Kocour Kroupová *et al*., 2018; Kim *et al*., 2019; Ciji & Akhtar, 2020)**. Hence, ozonation's capacity to decrease nitrite concentrations can improve the overall water quality in RAS, which promotes more favorable conditions for the cultivated species.

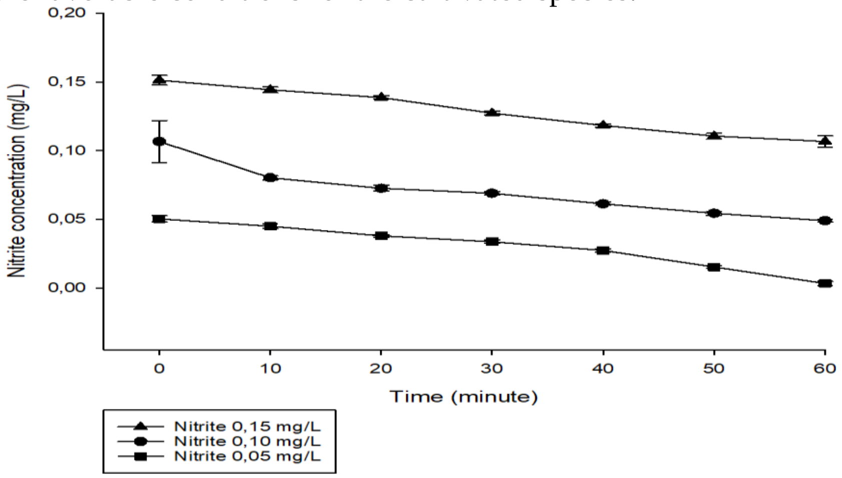

Fig. 6. Effect of 0.1mg/ L ozonation on nitrite oxidation

Furthermore, the study's results indicate that ozonation could be strategically incorporated into the broader nitrogen control plan in aquaculture systems. For example, integrating biological filtration systems with ozonation could improve the efficiency of nitrogen removal. Biofilters efficiently convert ammonia into nitrite and nitrate by nitrification **(Summerfelt & Sharrer, 2004)**. The addition of ozone afterward can further oxidize any remaining nitrite, preventing it from reaching harmful concentrations.

Moreover, the synthesis of nitrate as a byproduct of nitrite oxidation needs close monitoring. Even though nitrate is less dangerous than nitrite, elevated amounts of nitrate can nevertheless be toxic to aquaculture species and contribute to ecological issues like eutrophication when released into natural water bodies **(Camargo *et al*., 2005)**. Utilizing denitrification mechanisms, which transform nitrate into nitrogen gas, could be a viable approach for controlling nitrate development.

Nitrate oxidation

In addition to analyzing nitrite oxidation during ozonation, this study also observed nitrate oxidation in seawater. Tests were conducted with three initial concentrations of nitrate (1, 2, and 3mg/ L). After 60 minutes of ozonation, the nitrate concentration was oxidized to 0.63±0.01, 1.64±0.005, and 2.57±0.01 mg/L, respectively, with an average removal rate at y = -0.0069x + 1.9846 (r^2=0.90) (Fig. 7). Nitrate oxidation rates of 42.7, 19.7, and 14.3% have been obtained for initial nitrate levels of 1, 2, and 3mg/ L, respectively. These results show that oxidation performance decreases as the starting nitrate level increases. The lowest concentration (1mg/ L) had the highest oxidation efficiency of 42.7%, indicating that it provides the greatest conditions for nitrate removal under the measured parameters.

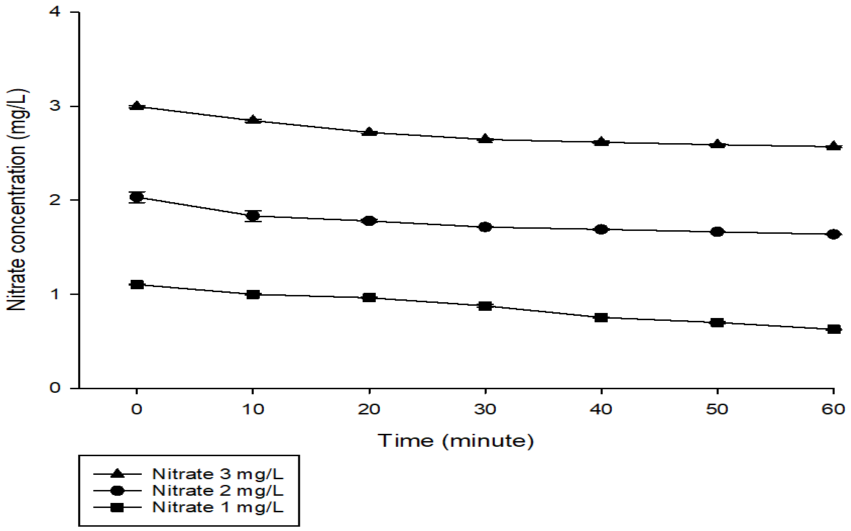

Fig. 7. Effect of 0.1mg/ L ozonation on nitrate oxidation

During ozonation, nitrate oxidation is promoted by several complex mechanisms. Through the ozonation process, hydroxyl radicals are produced, which may play an essential component in the oxidation of nitrate. These radicals have the capability to oxidize nitrate to nitrite (NO_2^-) as an intermediate phase. Nitrite can subsequently be further oxidized to nitrogen gas or other harmless compounds. The effectiveness of this process is influenced by various factors, which include the level of nitrate, the existence of different reactive species, and the composition of the water matrix. The presence of chloride and bromide ions in seawater could impact the development and reactivity of hydroxyl radicals, which may have an impact on the overall effectiveness of nitrate oxidation **(Mellouki *et al*., 1988; Leitner *et al*., 1999; Son *et al*., 2011; Von Sonntag & Von Gunten, 2012)**. The primary reactions involved in this process are as follows:

$$O_3 + H_2O \rightarrow 2 \cdot OH + O_2$$
$$NO_3^- + \cdot OH \rightarrow NO_2^- + OH^-$$
$$NO_2^- + \cdot OH \rightarrow NO + OH^-$$
$$2NO + \cdot OH \rightarrow N_2 + H_2O$$

This study investigation suggested a partial decrease in nitrate levels, indicating that the oxidation process might be incomplete or restrained by the existence of insufficient ozone and hydroxyl radicals. This condition emphasizes the significance of adjusting the ozonation applications to enhance nitrate removal's efficacy **(Tango & Gagnon, 2003; Dodd *et al*., 2006)**. Gaining insight into the process of nitrate oxidation during ozonation is necessary for the development of efficient water treatment methods in marine aquaculture systems. Modifying variables such as the concentration of ozone, the duration of contact, and the addition of catalysts or enhancers is feasible to enhance the effectiveness of nitrate oxidation and reduce the synthesis of intermediate products. For instance, the introduction of hydrogen peroxide (H_2O_2) has been demonstrated to improve the production of hydroxyl radicals, which could potentially accelerate the process of nitrate oxidation. Additionally, combining ozonation with other advanced oxidation processes (AOPs) may synergistically affect the removal of nitrates. For example, combining photocatalysis or ultraviolet (UV) irradiation with ozonation may enhance the generation of reactive oxygen species and elevate the overall efficiency of oxidation **(Poyatos *et al*., 2010; Son *et al*., 2011)**. Moreover, adsorption process have demonstrated efficacy as viable techniques for nitrogen removal. **Belhouchet *et al*. (2024)** exhibited considerable efficacy in simultaneously eliminating toxic nitrogen species by novel geomaterial adsorbents, which might be used to support ozonation process in aquaculture effluents.

Dissolved oxygen and pH changes

Significant differences in dissolved oxygen (DO) abd pH levels were noticed during the ozonation process. After 60 minutes of ozonation, the initial level of dissolved oxygen elevated from 6.03±0.06 mg/L to 9.63±0.11 mg/L. The DO levels increased to 14.73±0.06 mg/L after an extra 60 minutes and, after 360 minutes, subsequently stabilized at 14.77±0.05 mg/L (Fig. 8). In contrast, pH levels gradually decreased during the ozonation process. The pH began at an initial level of 8.35±0.005 and declined to 8.30±0.01 in the first 60 minutes, 8.19±0.005 in the following 60 minutes, and 7.99±0.005 in the final 360 minutes (Fig. 9).

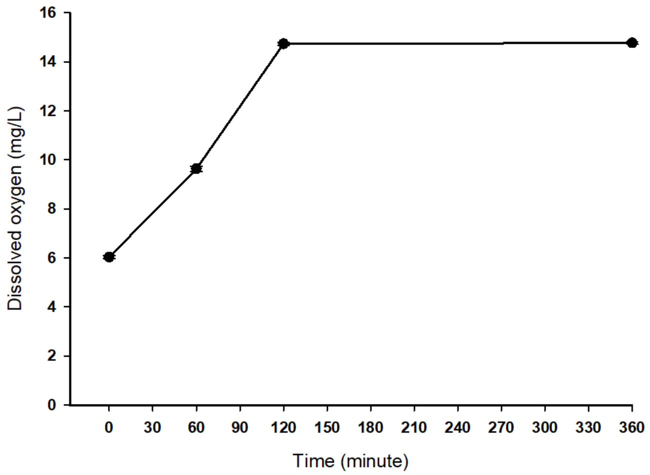

Fig. 8. Dissolved oxygen increasing during ozonation

The breakdown of ozone in water is primarily responsible for the DO levels that are observed to rise during the ozonation process. Ozone contributes to the increase in DO levels in water by breaking down into reactive oxygen species and molecular oxygen. The steady elevation in DO over 360 minutes, from 6.03±0.06 mg/L to 14.77±0.05 mg/L, emphasizes the continuous contribution of ozone and its breakdown, which continuously releases oxygen into the water **(Gray, 2014; Manasfi, 2021)**. The fact that DO levels stabilized after 360 minutes indicates that the system may have established an equilibrium in which the rate of oxygen production from ozone decomposition matched the oxygen consumption rate by oxidative reactions in water.

The increase in dissolved oxygen is especially advantageous in marine aquaculture systems, where high DO levels are critical for aquatic organisms' health and growth. Enhanced oxygen levels may optimize metabolic activities, improve feed conversion efficiency, and minimize stress in cultivated organisms. However, it is crucial to carefully monitor and maintain DO levels since oxygen concentrations that are too high may induce hyperoxia, which leads to oxidative stress and other severe physiological impacts on aquatic species **(Aksakal & Ekinci, 2021; McArley *et al.*, 2021)**.

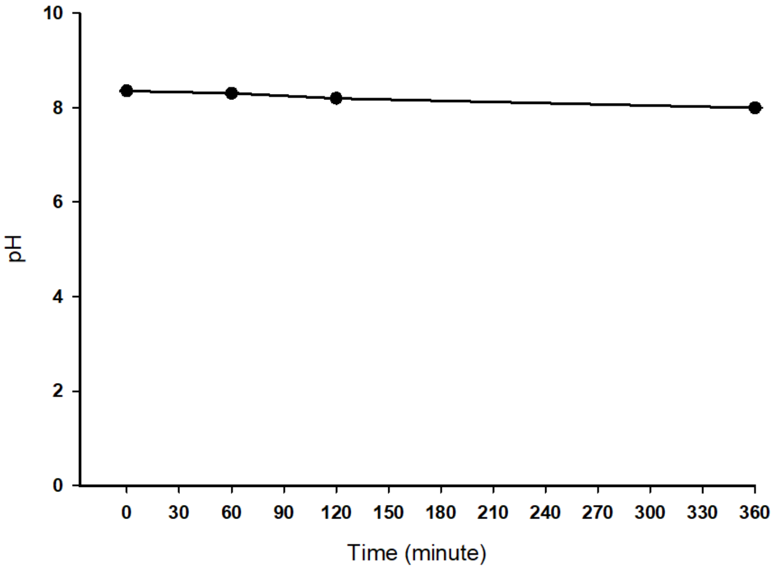

Fig. 9. pH changes during ozonation

In contrast, the gradual reduction in pH during ozonation indicates that ozone has an acidifying effect on seawater. As ozone integrates with various substances in water, it develops acidic byproducts, which contribute to the apparent pH reduction. The cumulative impact of these acid-forming processes is reflected in the pH decline over 360 minutes, which goes from 8.35±0.005 to 7.99±0.005 **(Najm & Krasner, 1995; Von Gunten, 2003; Manasfi, 2021; Wang *et al*., 2022)**. While the pH decrease in this study was modest, it is essential to consider possible consequences for aquaculture systems, where pH stability is critical for maintaining ideal water quality and aquatic organism health.

A reduction in pH can impact various physiological processes in marine animals, including respiration, osmoregulation, and calcification. For example, decreasing pH levels may affect the availability of calcium carbonate, which is necessary for the development of mollusks' and crustaceans' skeletons and shells. In order to prevent adverse impacts on aquaculture species, it is crucial to ensure that pH values during ozonation remain within a suitable range **(Knutzen, 1981; Abbink *et al*., 2012; Gobler & Baumann, 2016)**. Introducing buffering strategies, including adding alkalinity, may assist in reducing ozone's acidifying effects and preserving pH stability.

CONCLUSION

This investigation demonstrates valuable information about the impact of ozone exposure on seawater, with a particular emphasis on bromate formation, oxidation of nitrate and nitrite, and pH and dissolved oxygen changes. The results indicate that the concentration of ammonia is an essential variable in the delay of bromate development during ozonation, with higher levels of ammonia resulting in more substantial delays. It suggests that controlling ammonia loading rates in marine aquaculture systems might serve as a feasible approach to mitigate bromate formation, which is critical for maintaining water quality and protecting aquatic life. Additionally, the study showed that ozonation is beneficial in decreasing the levels of nitrite and nitrate in seawater. The results highlight the prospective benefits of ozonation as a nitrogen control tool in marine aquaculture systems, primarily when utilized in combination with other treatment methods.

Furthermore, the significant improvement in dissolved oxygen levels found during the process of ozonation suggests the potential advantages of ozone for enhancing the availability of oxygen in aquatic environments, which could improve the metabolic requirements of aquatic organisms and enhance the overall efficiency of the system. On the contrary, the pH reduction observed during ozonation indicates that ozone exerts an acidifying effect. Therefore, buffering protocols are required to keep the pH stable and avoid detrimental effects on cultivated species.

Nevertheless, it is crucial to acknowledge that the experimental environments in this study were controlled. On the other hand, actual seawater ecosystems may include additional challenges, such as fluctuating levels of organic matter along with other nitrogen compounds, which might potentially impact the generation of bromate. Future research should focus on exploring the prolonged impacts of ammonia and other nitrogen compounds on the development of bromate in different seawater environments. This investigation should involve variables such as the availability of natural organic matter, as well as variations in temperature and pH levels. Furthermore, an ecotoxicological study on the effects of ammonia injection on fish and aquatic organisms is required to better comprehend the long-term ecological implications. This study would provide essential insights into the potential risk correlated to ammonia deployment, ensuring that recommended treatment procedures are environmentally viable and safe for aquatic ecosystems.

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