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Application of Fine Bubbles in Biofloc Aquaculture: Towards Environmental Sustainability

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Abstract: ***Biofloc Technology (BFT) is specifically designed to tackle critical challenges in aquaculture, including the reduction of excessive water usage, minimizing effluent discharge, optimizing nutrient utilization from feed, and strengthening overall biosecurity on farms. This innovative approach utilizes clusters of bacteria, algae, or protozoa within a matrix rich in particulate organic matter to enhance water quality, improve waste management, and control diseases. Given the system loading rates, there is a heightened need for elevated dissolved oxygen levels and optimal flow rates. Acknowledging the limitations of traditional aeration systems, this review hypothesizes employing fine bubbles as a panacea. The article, therefore, condenses information on fine bubble impacts in biofloc with a special focus on faster biofloc establishment, favorable microbial diversity, improved respiratory health, accelerated growth rates, optimized metabolism, improved feed conversion ratios, reducing costs, and enhanced overall aquatic health. The suitability of fine bubbles in diverse aquaculture environments is also explored with highlights on areas for further research to optimize and scale up fine bubble-fueled biofloc as an environmentally friendly aquaculture.***

Keywords: ***Environmental Footprint; Microbial Diversity; Nanobubbles; Nutrient Recycling; Sustainable Aquaculture.***

I. INTRODUCTION

In the dynamic landscape of aquaculture, the pursuit of innovative and sustainable practices stands as an imperative response to the escalating challenges facing the industry. There has been a growing focus on environmental concerns and the concurrent adoption of measures aimed at minimizing the environmental footprint of aquaculture practices. Environmental issues mainly arise from generating large amounts of organic waste products that emanate from surplus organic matter in the culturing system [1]. Waste organic matter results from feed remains and fecal matter excreted by cultured organisms. Another environmental concern has been the use of chemicals inclusive of antibiotics which are known to cause chemical pollution [2].

Hence, a novel substitute for the conventional aquaculture approach known as biofloc technology (BFT) was introduced to rectify the challenges outlined. BFT is an advanced aquaculture system that aims to decrease excessive water consumption, reduce effluent discharge, optimize the utilization of feed nutrients, and enhance overall farm biosecurity.

It employs bacterial, algal, or protozoal clusters within a matrix containing particulate organic matter to enhance water quality, waste management, and disease control [3]. The matrix which is referred to as a biofloc is consumed by cultured organisms. The BFT is deemed environmentally friendly as it eliminates the need for water exchange in aquaculture [4].

Additionally, BFT is heavily reliant on continuous aeration to maintain a healthy and desirable biofloc system where the total respiration budget is between 5 to 8 mg O2/L per hour of which 2 to 2.5 mg O2/L per hour is for biofloc respiration alone [5, 6]. The evolution of aeration technologies in bioflocs systems has witnessed significant strides, each advancement aimed at augmenting operational efficiency and mitigating environmental impacts. However, as we navigate the realms of advanced aeration, the emergence of fine bubbles warrants a venture into uncharted territories teeming with scientific intrigue, ecological implications, and transformative potential beyond conventional realms.

Therefore, the need for this critical review is propelled by a compelling justification grounded in the multidimensional benefits and opportunities that fine bubbles bring to the forefront of BFT. As conventional aeration methods reach a peak, this review asserts that an in-depth exploration of fine bubble technology represents not merely an incremental refinement but an essential paradigm shift towards better and more efficient techniques. The timeliness and significance of this review is grounded on unexplored ecological dynamics of fine bubbles research progress on biofloc technology. This resonates well with the high precision and efficacy in oxygenation by fine bubble aeration compared to conventional aeration technologies, adaptability across aquaculture environment, synergy with sustainable practices, economic viability leading to industry adoption, and stimulating curiosity for further research. This review aspires to offer not just a snapshot of the status quo but appeals to a vision for the future with more environmentally friendly aquaculture technology.

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II. OVERVIEW OF AERATION IN BIOFLOC

Advanced aeration requirement in BFT is due to the need for high levels of dissolved oxygen levels to support the oxygen demand of 5 to 8 mg O2/L per hour to sustain the system. Aerators are thus installed for this cause. In the absence of sound aeration due to power failure or otherwise, the response time in terms of losing the biofloc is estimated to occur within an hour [6]. Lara, Krummenauer [5] recognize that biofloc aeration aims to provide oxygen beyond the inherent constraints in sustaining elevated stocking densities with high productivity, even distribution of dissolved oxygen in the water column, and to thoroughly oxygenate sediment coverage. Of late, there has been recognition of aeration influencing the aggregation and breakage of biofloc [7]. Fig. 1 shows a hypothetical oxygen budget in a biofloc. From Fig. 1, the biofloc requires dissolved oxygen [DO] to meet aerobic microbial respiration [M], heterotrophic respiration [H], and oxygen demand for cultured organisms [F]. The [DO] is mainly supplied by Aeration [A] from which a fraction dissolving in water is influenced by temperature according to Henry's Law and Van't Hoff Factor to give an equation $C=k \cdot PO2 \cdot e^{-(RTE)}$ where C is the concentration of dissolved oxygen in water, k is Henry's Law constant (solubility coefficient), PO_2 is the partial pressure of oxygen in the air, E is the activation energy for oxygen dissolution, R is the ideal gas constant, and T is the absolute temperature. For a stable biofloc Equation 1 must be satisfied;

$$C=k * PO2 * e^{-(RTE)}) \approx A = DO = H + M + C \text{ ---- } (1)$$

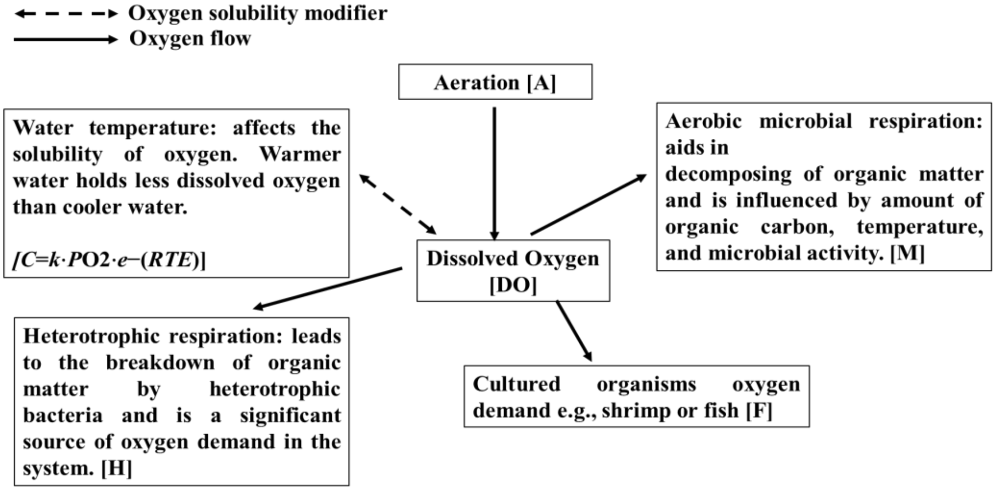

Fig. 1: Oxygen budget in a biofloc

Equation 1 means that A, DO, and $C=k \cdot PO2 \cdot e^{-(RTE)}$ should always be at least 5 to 8 mg O2/L to maintain a steady state in the biofloc, [4-6]. Currently, conventional aerators are dominating the BFT to optimize parameter A [8]. From conventional techniques of aeration, an evolution towards advanced aeration techniques has been observed in BFT. The conventional techniques for aeration in biofloc are summarized in Table 1 while the aeration capabilities of these aeration techniques are shown in Table 2. Table 1 also outlines the specific purposes for the different conventional techniques as used in bioflocs which includes resuspending sludge and ensuring floc stability apart from the principal role of aeration.

Table 2 on the other hand shows that different conventional techniques have different SOTE and SOTR values with paddle wheels showing better SOTR values hence their popularity in bioflocs and other aquaculture establishments.

Table 1: Conventional Aeration Systems in Biofloc

Aeration Type	Purpose	References
Propeller aspirator pump	Aeration and resuspending sludge	[5,9]
Paddlewheel aerators	Aeration and re-suspending sludge	[6]
Vertical pump	Aeration	[5,9]
Diffusion air blower	Aeration and floc stability	[5,9,10]

Table 2: Aeration Characteristics of Selected Aerators Used in Aquaculture

Aeration Device	SOTE^a (%)	SOTR^b (kg/h)	References
Paddle Wheel	14- 18^1	2.5 – 23.2^2	^{1}[11] ^{2}[12]
Propeller Aspirator	14- 18^1	0.1 – 24.4^2	
Vertical Pump	No information	0.3 – 10.9^2	
Diffused Air	10-16^1	0.6 – 3.9^2	

[a] Standard Oxygen Transfer Efficiency
[b] Standard Oxygen Transfer Rate

Though conventional aeration techniques have managed to drive BFT to date, serious shortcomings have been observed. These challenges include; limited efficiency in aggregating bioflocs, the need for selecting and positioning of aerators, and creating turbulent conditions in small tanks or raceways. Traditional bubble diffusers face limitations in efficiently aggregating and sustaining bioflocs. The larger size of bubbles generated by conventional diffusers does not favor microorganism interactions thus affecting the formation and stability of bioflocs [13]. The turbulence produced by conventional aeration units affects the aggregation and breakage of bioflocs [10]. This inefficiency can impact the nutrient cycling capacity of the system and potentially compromise water quality.

The implication of this would be inadequate biofloc aggregation leading to decreased effectiveness in nutrient conversion and waste remediation. This challenge emphasizes the need for aeration systems that can effectively and efficiently integrate with biofloc dynamics, ensuring optimal particle formation and stability.

Choosing the right type of aerator and determining its optimal placement in biofloc systems can be a daunting task. In conventional aeration methods, incorrect selection or improper positioning of aerators may result in uneven oxygen distribution, leading to suboptimal conditions (anoxic zones) in certain areas of the culture environment. The implication of this is inefficient oxygen dispersion that can create localized areas with insufficient oxygen levels, potentially impacting the health and growth of cultured species. Selecting suitable aerators that ensure a uniform random distribution of air bubbles is therefore key in solving this jigsaw puzzle and this points to using fine bubbles.

Generating and maintaining turbulence in relatively small tanks or raceways has shown to become a challenge, particularly in terms of feed distribution and the behavior of bioflocs plus cultured animals [10]. Overly turbulent conditions can hinder the ability of fish or shrimp to locate and consume feed due to turbulence-associated turbidity. This can lead to uneven growth, reduced feed conversion efficiency, and potential stress on the cultured organisms. Striking the right balance between turbulence for effective aeration and avoiding hindrance to feeding behaviors is a critical consideration. To address these challenges and unlock other potential benefits, advanced aeration such as fine bubble technologies is required.

III. FINE BUBBLE FUNDAMENTALS AND CHARACTERISTICS

Exploration and characterization of fine bubbles have widely been done by different researchers. The International Organization for Standardization (ISO) defines fine bubbles as cavity enclosures with a volumetric diameter smaller than 100 µm [14]. Two distinct classes of fine bubbles have been drawn thus, nanobubbles and microbubbles. Nanobubbles, often called ultrafine bubbles, are enclosed voids with a volumetric diameter of not more than 1 µm. Microbubbles are encapsulated cavities with a volume equivalent diameter of at least 1 µm but less than 100 µm. Bubble with a volume diameter of more than 100 µm are generally referred to as macro bubbles and are not part of fine bubbles.

Fine bubbles are produced in a process known as cavitation [15]. Cavitation reduces pressure in a liquid below a certain critical value by applying an acoustic field and pressure variation in the flowing fluid. The produced fine bubbles are measured by different means, including laser diffraction particle size analyzer [16], atomic force microscope [17], and image analysis[18].

Fine bubbles exhibit unique properties, which are the basis for their wide applications. One of the unique properties is the fine bubble's ability to stay longer in the liquid because of their lower buoyancy [19]. This is especially true for nanobubbles, unlike microbubbles which have a shorter life span. Foudas, Kosheleva [20] indicated that microbubbles have a lifespan measured in seconds while Nanobubbles have demonstrated the ability to persist for weeks or even months. This extended duration in the liquid allows for increased contact with water, promoting more effective oxygen transfer. Thus, a high standard oxygen transfer rate of up to 72 has been reported [21]. The improved oxygen transfer is critical for supporting the respiratory needs of cultured organisms and the biofloc. The longer stay of fine bubbles enhances dissolved oxygen levels, contributing to better overall water quality in biofloc systems. Long residence time could be key in reducing the risk of stock and biofloc loss due to abrupt aeration failure in fine bubble aerated systems because the reserved oxygen in the fine bubbles could continue supplying oxygen. Subhan, Iskandar [22] reported a reserve oxygen potential (ROP) of 2.95 ppm when fine bubbles of 518.5 – 607.6 nm were used in aeration. Fine bubble oxygen transfer characteristics are shown in **Table 3.**

Table 3: Aeration Characteristics of Fine Bubbles.

Aeration Device	SOTE (%)	SOTR (kg/h)	References
Fine bubbles (air)	30-35.4	2.18-20	[21]
Fine bubbles (oxygen)	10- 72.1	10-22.02	

Another unique property is that fine bubbles have a high internal pressure due to their smaller size and corresponding high internal pressure [19, 23]. Internal pressure is inversely related to the size of the bubbles. The high internal pressure promotes effective gas exchange between the fine bubbles and the surrounding water depending on the gas that is in the bubble. Oxygen fine bubbles in this case would entail enhanced oxygen dissolution contributing to elevated levels of dissolved oxygen in the water column, supporting the respiratory needs of cultured organisms, and fostering optimal conditions for biofloc formation. Fayolle, Cockx [24] deduced that a 10% reduction in bubble size results in a 15% increase in the oxygen transfer coefficient while a 10% increase in bubble diameter leads to a decrease in the oxygen transfer coefficient. This finding suggests that optimizing bubble size is crucial for enhancing oxygen transfer in biofloc systems as a reduction in aeration bubble size, within certain limits, appears beneficial for improving the oxygen transfer coefficient. A higher oxygen transfer coefficient may contribute to increased energy efficiency in aeration systems which might result in sustainable and cost-effective operation, especially in biofloc aquaculture where oxygenation is very critical.

Fine bubbles also possess a large surface area within the liquid, which enhances mass transfer efficiency by facilitating extensive contact with the liquid phase [19]. Physical and chemical functions done by the bubbles including adsorption, chemical reactions, and the ability to transfer mass between the liquid-gas interphase, would be enhanced because of the large surface area of the bubble on which gas transfer occurs.

Another property of fine bubbles is the ability to generate free hydroxyl radicals (•OH) when they collapse [25]. The hydroxyl radicals contribute to nutrient cycling by participating in the breakdown of organic matter and may aid in water purification by degrading pollutants.

Finally, in the pH range of 2 to 12, fine bubbles typically exhibit a predominantly negative electrical charge of approximately -20 to -50 mV, and this negative charge is referred to as zeta potential [26]. The zeta-potential is an electrical potential difference between the mobile particles dispersed in the medium and the dispersion layer of the medium, which is stationary and attached to the dispersed particle [27]. The high zeta potential in fine bubbles entails adsorbing nutrients in the bulk and randomly moving them in the biofloc system as the bubbles are constantly moving in Brownian motion. This results in the mass transfer of nutrients.

Based on the outlined properties of fine bubbles and their conventional counterparts, a sharp contrast is observed. An example is mass transport performance within the liquid. Thomas, Ohde [28] investigated the impact of fine bubble and macrobubble aeration on an oxygen-consuming glucose oxidase (GOx) -catalyzed biotransformation aiming for gluconic acid production. The study revealed that fine bubble aerators exhibited significantly superior mass transport performance within the liquid volume-specific flow rate range of 0.017–16.67 min−1 compared to the open pipe macrobubble aeration in a solution. In a β-d-glucose-consuming enzymatic model reaction, the use of fine bubbles resulted in a 32% higher yield after 3.5 hours. Moreover, there was a noteworthy 25-fold increase in gas utility (at a constant kLa of 160 1/h) when compared to macrobubble aeration. The calculated atom economy of the oxygen economy of fine bubbles was enhanced by factors ranging from 38- 41.6 and 38 compared to conventional aeration. These findings underscored the advantages of employing fine bubbles in terms of yield, gas utility, oxygen atom economy, and overall mass transfer performance. Notably, the heightened gas utilization presents significant potential for cost reduction and can be integrated into the optimization of processes constrained by the low solubility of gaseous substrates within biofloc systems.

IV. PERSPECTIVE OF MICROBIAL DYNAMICS IN BIOFLOC SYSTEMS WITH FINE BUBBLE

Fine bubbles have demonstrated to boost the rate at which bioflocs form. In a study conducted by Harun, Mohammad [10] where they compared the effect of aero tubes (Fine bubbles) and air stones, it was shown that the biofloc formation developed 10 days earlier compared to conventional aeration. This faster establishment was shown alongside a constant increase in the subsequent days. It was noted that the water movement and circulation of fine bubbles were more refined in the aero tube aeration system than in the air stone system (conventional aeration). This created a more favorable environment for the attachment and aggregation of biofloc. The uneven size of bubbles produced by the air stone led to irregular water movement, and the intense water agitation disrupted the suspended biofloc, thereby impacting the formation of biofloc. In a similar study, Chen, Zhou [29] demonstrated a 9.37% higher potential for biofilm formation when fine bubbles are employed compared to conventional aeration systems that produce big bubbles and more turbulence. Heightened biofilm formation is a precursor to enhanced biofloc formation.

Fine bubbles show a significant impact on the diversity of microbial communities when compared with conventional aeration methods. One of the profound impacts is shifting the microbial community composition [29, 30]. The prevalence of aerobic chemoheterotroph, aerobic ammonia oxidation, nitrification, aerobic nitrite oxidation, and nitrite respiration with fine bubble aeration exceeds that under conventional aeration by 44.2%, 74.6%, 80.5%, 82.8%, and 103.2%, respectively. Moreover, anaerobic microorganism's abundance was found to be high in conventional aeration systems. This proof shows better aeration with fine bubbles and thus a cause for more optimal conditions in the biofloc due to enhanced cellular respiration and enhanced oxidation of organics, ammonia, and nitrite.

V. RESPIRATORY HEALTH AND GROWTH IN CULTURED SPECIES

Fine bubbles promote respiration health and the growth of aquatic organisms by promoting oxygen dissolution and even distribution in water, increasing metabolic efficiency, reducing fish stress, and improving fish immunity. Except oxygen dissolution which has already been discussed, the other phenomena outlined will be discussed in this section.

A. Respiration-associated Health (Optimized Respiration)

On respiration health, fine bubble aeration is capable of maintaining optimal dissolved concentration that is linked with proper development of fish gills. Wu, Li [31] reported discrepancies in the development of gill tissue with healthy gills reported at a higher dissolved concentration of 6.5 parts per million (PPM) and poor gill structure at a dissolved oxygen level of 2.5 PPM. Apart from proper gill structure, Fine bubble aeration also induces a higher level of red blood at 20,000 - 3,000,000 cells / mm3 in Oreochromis niloticus [32]. The combined effect of proper gill development and an increased number of red blood cells would entail a higher uptake and efficacy in oxygen transfer in aquatic organisms that could fuel high metabolic rates. **Fig. 3** shows optimized respiration health brought about by fine bubble aeration.

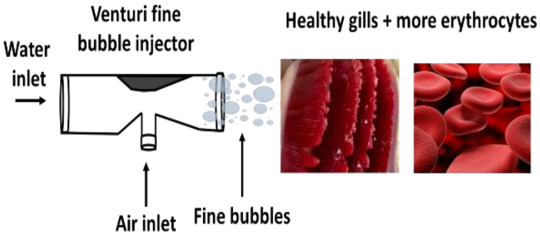

Fig. 2: Illustration of Optimized Respiration Courtesy of Fine Bubbles

B. Growth Rates and Metabolism

Fine bubble aeration shows a huge potential to increase metabolic efficiency in cultured organisms. On metabolism, dissolved oxygen (DO) stands as a primary environmental factor that impacts the development and metabolic processes of fish assuming nutrients required for growth are not limited [31].

Adequate oxygen levels are thus a necessary prerequisite in supporting the metabolic processes of aquatic organisms and promoting better growth rates. Since fine bubbles are excellent at improved oxygenation, they assist in increasing metabolic efficiency and, consequently, enhancing growth rates. Higher specific growth rates of 1.96% in tilapia, and 7.12% in shrimp compared to 1.6% in tilapia and 4.3% in shrimp as reported by Fouda, Elrayes [33] and [9]respectively.

C. Feed Utilization

Indirectly linked to increased metabolic efficiency is the ability of fine bubble aeration to improve Feed Convention Efficiency (FCR). Lim, Ganesan [9] reported high FCR in fine bubble aeration compared to conventional aeration methods. FCR is a measure used in animal agriculture, particularly in aquaculture and livestock farming, to assess the efficiency with which animals convert feed into the desired output, such as body mass or produce. Fine bubble aeration has been attributed to super FCR of up to 0.8 in shrimp compared to conventional aeration deploying large bubbles. The improved FCR means less feed demand which supports the notion of a biofloc and it's also a key towards reducing feed costs which account for 40–75% of production costs in aquaculture [34].

Reduced feed input and a high FCR realization unfold a solution to two impeccable environmental concerns bordering fish farming that is waste generation due to uneaten feed in the system, and contribution to biodiversity loss where fish feed formulation is dependent on fish meal and oils. In the latter, catching fish from the world to formulate fish feed is a threat to aquatic biodiversity translating into a high environmental footprint as the sector increases [35, 36]. Less feed input and high FCR entails less feed remains in the system which would reduce the accumulation of wastes, and this enhances the feasibility of recirculating the water.

D. General Aquatic Organism Health

Fine bubble aeration has been associated with stress reduction in aquatic species. Apart from maintaining optimal oxygen levels, fine bubbles also contribute to the removal of ammonia which is a stressor to fish [22]. The mean acute toxicity values for 32 freshwater species have an average of 2.79 mg NH3/l, while the corresponding value for 17 seawater species is 1.86 mg NH_3/l [37]. Ammonia removal of up to 83.33% due to fine bubble aeration has been demonstrated. The removal is attributed to free scavenger hydroxyl radicals which are formed when fine bubbles collapse. The hydroxyl radicals neutralize ammonia effectively controlling potential fish stress. Effective management of ammonia removal in biofloc systems is crucial, serving as a key element in the nitrogen cycle. Ammonia is mainly generated through the decomposition of organic matter, leftover feed, and the excretion of cultured organisms, including fish or shrimp. Ammonia removal is also attributed to heterotrophs and chemotrophs [38]. These two play a significant role in absorbing ammonia from both feed and fecal waste, serving as a vital pathway for the creation of suspended microbial aggregates referred to as biofloc. Concurrently, chemoautotrophs, exemplified by nitrifying bacteria, facilitate the oxidation of ammonia into nitrite and subsequently into nitrate, fostering favorable conditions for successful aquaculture. Fine bubbles contribute to improved oxygen availability, supporting the aerobic conditions necessary for the efficient functioning of these nitrifying bacteria[39]

Apart from growth enhancement brought by reduced stress and good FCR, Fine bubble aeration has been linked with improved white blood cell (leukocyte) count in fish. Fine bubbles have been shown to increase the number of white blood cells within the normal range of 20,000 - 150,000 cells / mm3 [32]. The rise in white blood cell count suggests a potential stimulation of the immune system. White blood cells play a crucial role in defending the organism against pathogens. In a biofloc system, an enhanced immune response can contribute to the overall health of cultured organisms, such as fish or shrimp.

In summary, the discussion in this section calls for technology and system considerations to optimize fine bubble aeration. The first shot is on bubble size and dissolution rate. A thorough understanding of the regulatory mechanism governing bubble size is crucial for attaining a controllable index in the functions of fine bubbles, such as flotation and gas transfer. [40].

Another aspect is monitoring and controlling the use of fine bubbles to ensure that oxygen levels remain within the optimal range. oxygen saturation reached 136% has been linked to fish trauma and mortality of salmonids a condition referred to as gas bubble disease [41]. Espmark, Hjelde [42] reported that in salmonids, bubbles were observed on significant parts of the fish's body at exposure levels of 190% and 220%. These bubbles were notably present on the fins, along the lateral line, in the gills, and around the eyes. The identification of gas bubbles was confirmed through visual observations, and histological analysis further supported the diagnosis. Because fine bubbles can supersaturate dissolved oxygen in water, further techniques for optimizing its application are needed.

VI. FINE BUBBLES ACROSS DIVERSE BIOFLOC AQUATIC ENVIRONMENTS

Aquatic ecosystems vary widely in terms of temperature and salinity. Assessing fine bubble performance under different conditions helps in evaluating their environmental impact. While the main purpose of fine bubbles is to enhance aeration, assessing their performance under different conditions is justified to ensure informed decisions based on the specific requirements of the biofloc system.

A. Biofloc Temperature Diversity

Biofloc optimum performance temperatures have been reported to vary but generally, ranges of between 25 to 30˚C have been reported with higher temperatures within the range deriving better growth rates [43-46]. In the same vein, fine bubbles have recently been demonstrated to maintain stability at temperatures of up to 50 °C, with stability loss at 60 °C [47]. In this temperature range, fine bubbles typically exhibit greater surface tension, a property that plays a crucial role in preserving their structural integrity and stability.

This heightened surface tension acts as a protective mechanism, preventing the bubbles from coalescing or merging.

Kobayashi and Ushida [47] reported fluctuations in the number density of fine bubbles within the temperature range of 15–50 °C, but notable changes in the particle size distribution were not observed. The highest number density recorded was between 4.04 × 10^7 to 1.04 × 10^8 mL−1, and this density remained consistent despite increases in temperature with peak number density ranging from 72 to 98 nm. This means that fine bubbles can efficiently exhibit their unique properties in this temperature range. Thus, in biofloc systems, fine bubble application has profound feasibility even beyond the maximum optimal temperature range of 30˚C.

B. Biofloc Salinity Condition Diversity

The level of salinity is a key factor in aquaculture, directly impacting the prosperity and long-term viability of aquatic farming methods. Different species of aquatic organisms have specific salinity tolerance ranges. Matching the salinity level to the species being cultured is vital for successful production in bioflocs. Reported salinities in bioflocs vary with a reported maximum of 32 ppt [43, 48-53]. Reported salinity level variations are shown in Fig. 4.

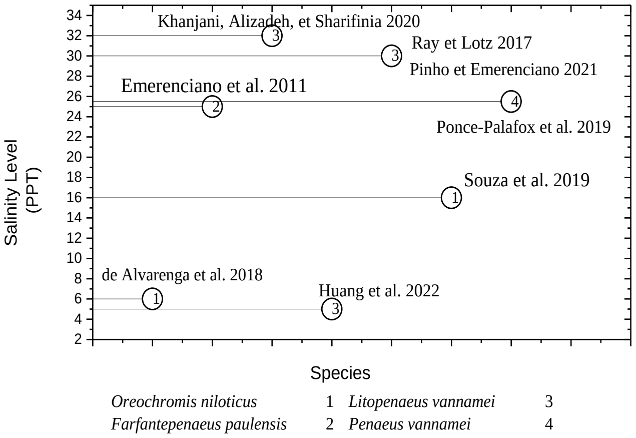

Fig. 3: Salinity Levels for Different Species in Biofloc Systems

From **Fig. 4**, it can be noted that the maximum operational salinity levels in the biofloc culture can be as high as 32 parts per thousand (PPT). This means that fine bubbles need to prove their ability to be stable and effective across these salinity levels to maintain relevance. Research conducted thus far indicates that as salinity rises, there is an enhancement in bubble stability and oxygen transfer efficiency compared to tap water [54]. This improvement is attributed to the suppression of bubble coalescence due to the presence of salts. This makes fine bubbles feasible across diverse biofloc salinity environments.

VII. SYNERGIES WITH SUSTAINABLE PRACTICES

Integrating fine bubble technology with biofloc systems could enhance the stability and performance of the biofloc environment, leading to improved water quality and increased microbial activity as discussed. Enhanced microbial activities and good water quality plus better FCR would in turn reduce feed input and wastage hence reducing production costs and organic effluent generation as discussed. Moreover, enhanced auto tropism in biofloc courtesy of fine bubbles would help to push the limits in aquaculture production because of dwindling pelagic fish catches used to make fish feeds[35].

Additionally, fine bubble application can also help to eliminate the use of antibiotics in the biofloc. widespread and unrestricted use of prophylactic antibiotics in aquaculture led to a proliferation of Anti-bacterial resistant genes which pose a threat to human health[55]. Biofloc however takes a different approach to solve this by relying on probiotics such as *Bacillus subtilis y, Lactobacillus sp* to control pathogens successfully and environmentally friendly [56]. In terms of the role of fine bubbles, the probiotics employed exert an extra load that requires more oxygen, which would be supplied by the fine bubbles.

Fine bubble biofloc operation also enhances nutrient recycling as discussed. It thus helps in water resource conservation due to the limited need for water exchange as conditions in the biofloc tanks are mostly at the optimum conditions, especially with fine bubble aeration. On the reduce, reuse, and recycle paradigm, fine bubbles in bioflocs role can be summarized in Table 4.

Table 4: Role of Fine Bubbles in Biofloc Towards Environmental Sustainability

Paradigm	Parameter	Mechanisms	References
Reduce	Biodiversity loss	Promotes autotrophism hence less fish meal demand and thus reduced demand for a fish caught from the wild.	[10]
	Demand for antibiotics	Reduces fish stress, supports probiotics application, and promotes the production of more white blood cells	[22, 32, 56]
	System failure risk	High oxygen transfer rate and high oxygen reserved potential.	[22]
	Environmental Footprint	Enhanced fine bubble aeration and hydroxyl radicals reduce waste accumulation and discharge.	[25, 37]
Reuse	Water	Promotes optimal water conditions in the biofloc system due to enhanced aeration and production of hydroxyl radicles that oxidize water pollutants making water fit for reuse with minimal exchange.	[25, 38].
Recycle	Nutrients	Promotes nutrient reuse in the system	[3, 10, 27]

The overall picture from Table 4 is that fine bubble application enhances sustainability and environmentally friendly aquaculture if employed in BFT.

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VIII. PROSPECTIVE RESEARCH IN FINE BUBBLE AERATED BIOFLOCS

A. Sensor Technologies and Automated Control Systems for Fine Bubbles in Bioflocs

Incorporating sensor technologies and automated control systems into biofloc systems improve operational efficiency, guarantees ideal environmental conditions, and promotes sustainable and productive aquaculture practices [57]. Utilizing instantaneous data provided by sensors overseeing crucial factors like water quality, dissolved oxygen, and temperature, automated control systems are empowered to make well-informed decisions and exact adjustments. Additionally, the adoption of these technologies aids in promoting sustainable and efficient aquaculture practices through the optimization of resource utilization, reduction of environmental stressors, and the embracing of energy-efficient operations. Bell, Johnston [58] reported energy savings of up to 60% in wastewater treatment aeration automation. On the automation of biofloc parameters, many authors have embraced the Internet of Things (IoT) based models and sensors for monitoring environmental parameters [57]. Moreover, the enhanced prototype of the automated biofloc system exhibited a noteworthy performance improvement, boasting a survival rate of 10% higher and a growth rate of 3.2% superior to the control with no automation [57].

However, despite the benefits of automated aeration and the availability of technology as outlined, no research has been done on applying automation technology to fine bubble-aerated biofloc systems. Automated fine bubble aeration in biofloc would bring extra benefits including reducing the risk of gas bubble disease due to supersaturation apart from reducing operational costs and the other conventional benefits such as remote control using an IoT mobile platform.

B. Innovations in Fine Bubble Generation System Design

Fine bubble full efficacy in biofloc to suit different species and floc performance still requires filling some technical gaps to be fully adopted. One such challenge arises in the production of stable and commercial scale fine bubbles as the current production techniques are mainly laboratory specialized equipment [59]. The challenge on producing stable fine bubbles on a large commercial scale has several implications on cost, accessibility, technological barriers, environmental impact, scaling-up issues, and market adoption.

On cost Implications, the use of specialized equipment for generating fine bubbles can lead to significant production costs. This may make the overall process economically less viable, potentially affecting the competitiveness of products or processes that rely on stable fine bubbles. On accessibility, the need for specialized equipment may limit the accessibility of fine bubble technology to certain industries or applications. Small or resource-constrained businesses may find it challenging to invest in and adopt these technologies, restricting the widespread use of fine bubbles. On technological barriers, the requirement for specialized equipment may create technological barriers, hindering the development and adoption of fine bubble technology. This, in turn, could slow down innovation in industries that could benefit from the unique properties of fine bubbles. On environmental impact, the energy and resource-intensive nature of some techniques for generating fine bubbles may have environmental implications. If the production process involves significant energy consumption and that energy is not produced from environmentally friendly means, it could impact the overall sustainability of the technology. On scaling up issues, transitioning from small-scale laboratory production to large-scale commercial production poses its own set of challenges. Scaling up the production of stable fine bubbles may introduce new complexities, affecting the consistency and quality of the bubbles. Finally, on market adoption, the high costs associated with current production techniques may slow down the adoption of fine bubble applications in the market. Industries and businesses may be hesitant to invest in technologies that have high upfront costs, even if the long-term benefits are significant. This is signified by further costs incurred during the operation and maintenance of such equipment.

Another obstacle herein is limited regulatory mechanism for appropriate bubble size for achieving a manageable index in functions, including floatation and gas transfer index [40]. The lack of a clear grasp on the regulatory mechanisms for bubble size in biofloc systems can impinge on efficiency, sustainability, and successful integration. Major concerns would be on oxygen transfer efficiency, microbial community dynamics, biofloc aggregation and settling, energy consumption, pathogen control, and finally, productivity and biomass yields.

On efficient oxygen transfer, the size of bubbles directly impacts oxygen transfer efficiency as discussed. Without a comprehensive understanding of regulatory mechanisms, achieving the optimal bubble size becomes challenging, potentially leading to suboptimal dissolved oxygen levels and hence running a high risk of compromising system vitality. In microbial community dynamics, bubble size influences the distribution of oxygen, shaping the spatial and temporal dynamics of microbial communities. The absence of control over bubble size introduces variations in microbial activity, disrupting the delicate balance and compromising overall biofloc system performance. On biofloc aggregation and settling, Ineffective bubble size control may disrupt settling dynamics, leading to turbid water and diminished

treatment efficiency. On energy consumption, inefficient bubble generation, stemming from a lack of regulatory understanding, may escalate energy consumption. This poses challenges to the economic viability and environmental sustainability of biofloc technologies. On pathogen control, inadequate bubble size control compromises the system's ability to suppress pathogens, increasing the risk of disease outbreaks. This is so because optimal oxygenation which is contingent on bubble size, is crucial for pathogen control as discussed in earlier sections. Consequently, all these factors would lead to altering productivity and biomass yields. Therefore, research in the field should aim at producing bubbles that will bring more efficacy to the biofloc.

There is also a need for the integration of computational modeling to simulate and optimize fine bubble behavior relative to desired conditions in the biofloc. This can lead to generating data that can ease automation and remote monitoring of fine bubbles in the biofloc.

IX. ECONOMIC VIABILITY AND INDUSTRY ADOPTION OF FINE BUBBLE BIOFLOCS

Examining the economic factors associated with the integration of fine bubble technology into biofloc systems is crucial for fostering sustainable growth in aquaculture enterprises. The efficacy of fine bubble aeration systems in optimizing oxygen transfer and creating a conducive environment for biofloc proliferation underscores their potential to enhance operational efficiency. The resulting advancements in growth and survival rates among aquatic organisms directly influence the financial outcomes, translating to heightened yields and increased profitability over an extended period. Additionally, the judicious use of nutrients within biofloc systems, facilitated by fine bubble technology, not only promotes cost-effective production but also aligns with sustainable practices, addressing both the economic and environmental facets of aquaculture.

Aquacultural enterprises that embrace cutting-edge technologies position themselves advantageously to meet the changing preferences of environmentally-conscious consumers. On the cost-benefit ratio, energy efficiency, and long-term economic implications of fine bubbles, data is limited on its use in biofloc and aquaculture. Published data however from related sectors such as wastewater treatment indicates that fine-bubble aeration systems remain the more efficient and cost-effective alternative for aeration when applied despite high initial costs [60].

FBT scalability for widespread adoption in biofloc might be constrained by associated costs, technical knowledge gaps, and the altitude of would-be adopters. Since available data points at optimal operational costs and favorable biofloc performance, this might enhance wide adoption. Continued commercial scalability on the other hand would depend on more research on optimizing FBT in biofloc. Overall, FBT is on a course toward full commercial success to drive environmentally sustainable biofloc aquaculture.

X. SUMMARY AND CONCLUSION

In conclusion, the dynamic landscape of aquaculture is witnessing a pivotal shift towards sustainability, marked by the introduction of biofloc technology (BFT) as a promising alternative to conventional approaches. The findings presented in this exploration reveal the compelling advantages associated with fine bubble technology, ranging from improved biofloc establishment and microbial diversity to enhanced respiratory health, growth rates, and overall aquatic well-being. Moreover, the adaptability of fine bubbles to diverse environmental conditions, including saline and high-temperature settings, signifies a broad applicability that can contribute to operational cost reduction. It is imperative to acknowledge the need for optimization of fine bubble generation, coupled with the integration of cutting-edge technologies such as IoT platforms and sensors as these hold the key to refining and automating this innovative approach. In essence, the synergy between biofloc technology and fine bubble aeration represents a promising paradigm for environmentally conscious aquaculture.

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