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Seasonal Changes in Sediment Oxygen Demand Across Intensive and Extensive Aquaculture Ponds

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Abstract: Sediment Oxygen Demand (SOD) is a substantial sink of dissolved oxygen in aquaculture ponds and an important coupling between the benthic organic matter mineralization and water quality, production risk, and ecosystem functioning. In this study, the SOD rate has been quantified in three intensive and three extensive freshwater aquaculture ponds for one year of operation using intact-core incubation method (n = 72 cores), in addition to sediment organic matter content, nitrogen content, acid-volatile sulfide content and water column chlorophyll-a. The SOD rate varied from 0.38 to 2.14 g O_2 m^{-2} d^{-1} and was significantly higher in intensive (annual mean = 1.44 g O_2 m^{-2} d^{-1}) than in extensive (0.69 g O_2 m^{-2} d^{-1}) ponds. The effect of both the pond type and the season was significant, and the SOD in summer was 2.6-2.8 times higher than in winter. SOD responded in an exponential manner depending on the temperature (Q_{10} value of 1.77 in intensive and 1.85 in extensive ponds). SOD was significantly correlated with water temperature, sediment OM, and chlorophyll-a. It is clearly evident that oxygen consumption by the benthos occurs at the time when oxygen concentration in the water column is lowest and hence requires a specific season-based sediment and aeration management approach.

Keywords: Sediment Oxygen Demand; Aquaculture Ponds; Seasonal Variation; Benthic Respiration; Pond Sediment; Water Quality Management.

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I. Introduction

Aquaculture production intensification leads to organic accumulation, nutrient enrichment, and oxygen consumption in pond sediments. Sediment oxygen demand (SOD) is a useful parameter for monitoring benthic respiration and degradation of water quality conditions, especially in aquaculture production systems (Araujo et al., 2025; Tan et al., 2022; Kim et al., 2021). Temperature fluctuations during different seasons impact the process of microbial decomposition and nutrient cycling in the interface of sediments and water (Liu et al., 2022; Hatakeyama et al., 2021; Tang et al., 2023). Variations in stock density, feeding regimes, and sediment nutrients could also lead to differences in oxygen consumption in intensive and extensive ponds (Bai et al., 2023; Jia et al., 2023; Yan et al., 2024). Adequate sediment management, oxygenation and monitoring of dissolved oxygen levels are important for sustaining stable aquatic ecosystems (Zhang et al., 2024; Castillo Alvarez et al., 2024; Tauviqirrahman et al., 2024). Water quality fluctuations through seasons and biological activities within the sediment stress the need for monitoring oxygen demand throughout the culture period (Kang et al., 2024; Ratti & Kunda, 2025; Gadeken & Dorgan, 2024). Hence, this research analyzes the seasonal variations in the SOD and the relationship between it and temperature, sediments and water quality in intensive and extensive ponds.

This study aims to bridge this gap through (i) determination of seasonal SOD in intensive and extensive ponds, (ii) identification of factors linked with SOD, namely sediment and water column characteristics, and (iii) discussion of managerial and ecological implications of the results.

II. Literature Review

Previous studies examined the process of sediment respiration, decomposition of organic material, and nutrient cycling in aquaculture systems (Liu et al., 2022; Tan et al., 2022; Tan et al., 2022; Kim et al., 2021). The accumulation of organic material leads to oxygen consumption by sediments, whereas the variation in seasonal temperatures affects the activities of microorganisms (Hatakeyama et al., 2021; Tang et al., 2023).

Nutrient cycling, nutrient diffusion, and nitrogen transformation by microbes are important for nutrient availability and water quality (Yan et al., 2024; Zhang et al., 2024). Studies have been conducted on sediment-water oxygen distribution to show the significance of oxygen consumption at micro-scale level (Kang et al., 2024). There have been recent studies focused on aeration efficiency, oxygen distribution, and seasonal water quality management in aquaculture ponds (Castillo Alvarez et al., 2024; Tauviqirrahman et al., 2024; Ratti & Kunda, 2025). Daily oxygen variations and the activities of benthic organisms also affect the sediment oxygen demand (Gadeken & Dorgan, 2024). However, little evidence is available about the differences of seasonal SOD between intensive and extensive aquaculture ponds.

III. Materials and Methods

Study Ponds

The research was performed in a commercial fish farm having six earthen ponds – three of which were intensive (I1-I3), and three were extensive (E1-E3). While the intensive ponds were fed using pellets and were aerated through paddle wheels, the extensive ponds were fertilized using organic manure and no aeration was done. Table 1 provides the details about these ponds. The ponds were continuously running for more than five years and were of silty clay bottom soil type.

Table 1: Characteristics of the Study Ponds (Mean of Three Ponds Per Type)

Characteristic	Intensive	Extensive
Pond area (ha)	0.35	1.00
Mean depth (m)	1.5	1.0
Nutrient input	Pelleted feed	Organic manure
Aeration	Paddlewheel, ≈15 kW ha^{-1}	None
Bottom soil texture	Silty clay	Silty clay
Years in operation	> 5	> 5

Sampling and SOD Measurement

Sample collection was carried out once during each season for one full year cycle (winter, spring, summer and autumn). In each pond, three complete sediment cores (acrylic tubes with 7 cm inner diameter and 20 cm height) were obtained using a gravity core, giving a total of 72 cores. Cores were capped with 10 cm of water overlay and transferred in darkness at the in-situ temperature after no more than 4 h since the sample collection. Water was stirred in the incubator to simulate the presence of a diffusive layer. Oxygen concentration was measured every 15 min during 4-6 h using an optical dissolved oxygen sensor, and the incubation period was stopped when oxygen concentration reached less than 60% of the initial concentration. SOD was estimated based on the linear regression of the decline in oxygen concentration after correction for water-only incubations and is expressed as g O_2 m^{-2} d^{-1} (Hatakeyama et al., 2021). Quality control includes calibration of the oxygen sensor before each day of sampling, duplicated water-only controls for each pond and exclusion of non-linear regression incubations ($R^2 < 0.90$). If cores had visible fish, large macrofauna, or disturbed surface layers, then those were replaced. Sampling for pond types was done on the same day each season to control for variations in the weather among types.

Ancillary Variables

Water temperature and bottom-water DO levels were measured during sample collection. Organic matter in the surface sediment (0 to 5 cm) was determined through loss on ignition at 550°C, total nitrogen using Kjeldahl method and acid volatile sulfides (AVS). Water chlorophyll-a was determined through spectrophotometry of acetone extracts.

Statistical Analysis

Differences in SOD activity were determined by using two-way analysis of variance for pond type and season as fixed factors, which was followed by Tukey's test. Correlation between SOD and environmental factors was assessed with Pearson's correlation coefficient. Temperature response curve was defined by SOD=a·e^(bT), where Q_{10}=e^(10b). Significance was accepted as $p<0.05$.

Oxygen Budget Calculation

In order to describe the oxygen load of the benthos as a quantity that can be related to pond management, the areal SOD value was converted to a volumetric oxygen loss per day using mean pond depth (Table 1). The assumption is that the water column is fully mixed and the calculation is meant for comparative purposes only.

IV. Results

Seasonal Variation in SOD

SOD differed significantly by season and pond type (Table 2, figure 1). The highest SOD in summer for intensive ponds was 2.14 ± 0.24 g O_2 m^{-2} d^{-1} while the lowest was 0.82 ± 0.11 g O_2 m^{-2} d^{-1} in winter. Similarly, but at a lower rate, the extensive ponds had 0.38 ± 0.06 g O_2 m^{-2} d^{-1} in winter and 1.05 ± 0.13 g O_2 m^{-2} d^{-1} in summer. Mean annual SOD values were 1.44 g O_2 m^{-2} d^{-1} and 0.69 g O_2 m^{-2} d^{-1} in intensive and extensive ponds respectively giving a ratio of 2.1 that remained constant across seasons (2.0–2.2). The two-way ANOVA indicated significant effects of pond type ($F_{1,64} = 212.4$, $p < 0.001$), season ($F_{3,64} = 96.8$, $p < 0.001$) and interaction of pond type and season ($F_{3,64} = 7.9$, $p < 0.001$).

Table 2: Seasonal Water Temperature and SOD (Mean ± SD, n = 9 Cores Per Pond Type Per Season)

Season	Temp. I (°C)	Temp. E (°C)	SOD intensive	SOD extensive	I/E
Winter	14.2	13.8	0.82 ± 0.11	0.38 ± 0.06	2.2
Spring	22.5	22.0	1.35 ± 0.16	0.62 ± 0.08	2.2
Summer	31.0	30.4	2.14 ± 0.24	1.05 ± 0.13	2.0
Autumn	24.1	23.6	1.46 ± 0.18	0.71 ± 0.09	2.1

SOD in g O_2 m^{-2} d^{-1}; I = intensive, E = extensive.

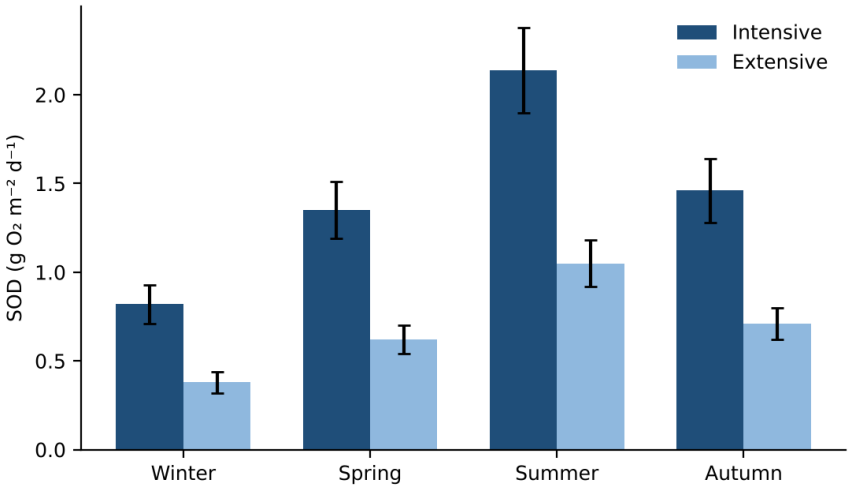


Figure 1: Seasonal Sediment Oxygen Demand in Intensive and Extensive Ponds (Mean ± SD)

As can be seen from figure 1, variability between replicate cores was relatively low: 11-14% in intensive ponds and 12-16% in extensive ponds. The difference between the three ponds in each category was

relatively insignificant compared to the difference between different categories and seasons. This confirms the assumption that the ponds within one category can be considered identical. By applying the Tukey test it was found that in intensive ponds all seasons were statistically different while in extensive ponds spring and autumn differed insignificantly ($p = 0.21$).

Sediment and Water-Column Conditions

Intensive ponds had more organic matter in sediment and total nitrogen content than extensive ponds. They also contained higher levels of AVS (about three times) and about 2.5 times more chlorophyll-a than extensive ponds. Summer oxygen levels in bottom waters of intensive ponds were low (2.9 ± 0.7 mg L^{-1}) compared to those of extensive ponds (4.6 ± 0.9 mg L^{-1}) (table 3).

Table 3: Annual Mean Sediment and Water-Column Variables (Mean ± SD)

Variable	Intensive	Extensive
Sediment organic matter (%)	7.8 ± 0.9	3.6 ± 0.5
Sediment total nitrogen (g kg^{-1})	3.9 ± 0.4	1.8 ± 0.3
Acid-volatile sulfide (mg g^{-1})	0.62 ± 0.10	0.21 ± 0.05
Chlorophyll-a (µg L^{-1})	86 ± 21	34 ± 9
Summer bottom DO (mg L^{-1})	2.9 ± 0.7	4.6 ± 0.9

Temperature Response and Controlling Factors

SOD activity grew exponentially with temperature in the two pond types (Figure 2), with Q10 value of 1.77 for intensive and 1.85 for extensive ponds. SOD activity was found to have positive correlation with temperature, OM and chlorophyll-a of the water and negative correlation with bottom-water DO (Table 4).

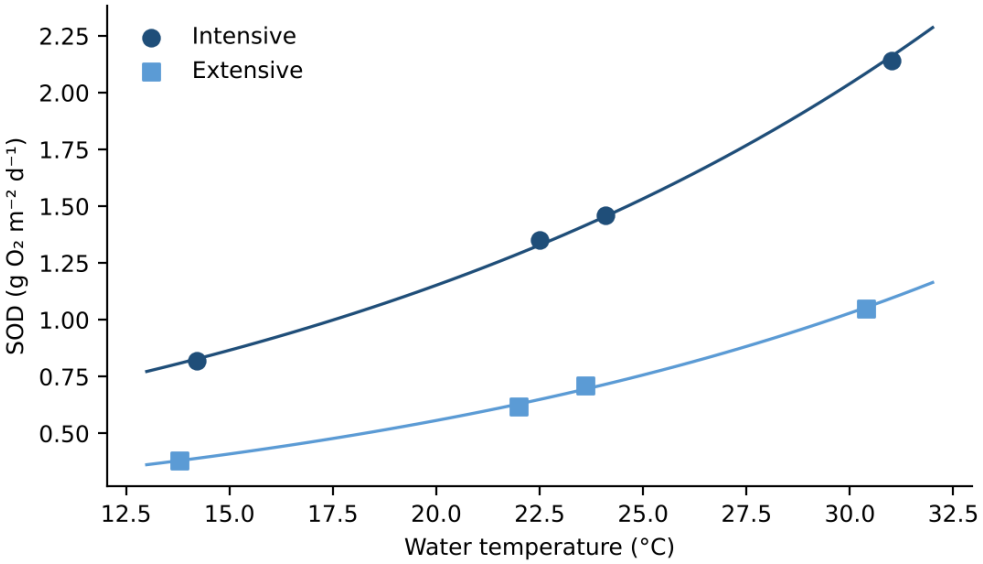


Figure 2: Relationship Between Water Temperature and SOD (Seasonal Means) with Fitted Exponential Curves

The graph in figure 2 shows the correlation between water temperature and sediment oxygen demand (SOD) in both intensive and extensive aquaculture ponds. An exponential relationship was found where SOD increased with increasing temperature in both cases. SOD in intensive ponds increased from 0.82 to 2.14 g O_2 m^{-2} d^{-1}, while in extensive ponds, it increased from 0.38 to 1.05 g O_2 m^{-2} d^{-1}. The temperature sensitivity coefficients (Q_{10}) in intensive and extensive ponds were 1.77 and 1.85, respectively. The results show that there is higher oxygen demand in intensive ponds in association with seasonal warming.

Table 4: Pearson Correlation Coefficients Between SOD and Environmental Variables (n = 72)

Variable	r	p
Water temperature	0.93	< 0.001
Sediment organic matter	0.88	< 0.001
Chlorophyll-a	0.81	< 0.001
Acid-volatile sulfide	0.76	< 0.001
Bottom-water dissolved oxygen	−0.67	< 0.001

Pond-Level Association with Sediment Organic Matter and Volumetric Oxygen Loss

At the pond scale, the mean SOD of a year was positively and linearly correlated with the amount of organic matter in sediments ($r > 0.99$, $n = 6$; figure 3). Since ponds were classified into groups on the basis of their management types, this correlation is basically attributed to the difference between intensive and extensive systems, which had narrow ranges. The conversion of areal SOD to volumetric SOD revealed that the removal of oxygen per unit volume of water due to sediment was estimated between 0.55 to 1.43 mg O_2 L^{-1} d^{-1} for intensive ponds, and 0.38 to 1.05 mg O_2 L^{-1} d^{-1} for extensive ponds (Table 5).

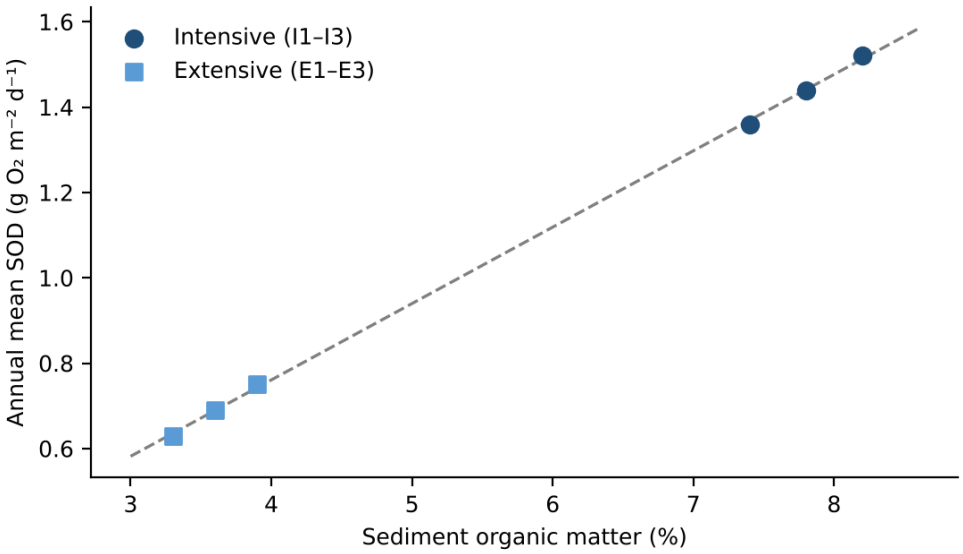


Figure 3: Annual Mean SOD in Relation to Sediment Organic Matter for the Six Study Ponds (Dashed Line: Linear Fit)

Table 5: Volumetric Oxygen Loss to the Sediment (SOD Divided by Mean Pond Depth)

Season	Intensive (mg O_2 L^{-1} d^{-1})	Extensive (mg O_2 L^{-1} d^{-1})
Winter	0.55	0.38
Spring	0.90	0.62
Summer	1.43	1.05
Autumn	0.97	0.71

V. Discussion

Why SOD Differs Between Pond Types and Seasons

The regularity of the two-fold differences between the ponds in terms of their types coincides with the differentiation in the level of organic enrichment. The higher organic content in sediments, the higher level of nitrogen and sulfides in intensive ponds suggest the presence of more amounts of degradable substances

and more reduced substances oxidizable chemically, which is consistent with the high level of mineralization of sediments typical of intensively fed ponds. The statistically significant interaction effect suggests that the more enriched substrate leads to a stronger seasonality, meaning the higher availability of organic substance for respiration with increasing temperature.

Q_{10} of 1.8–1.9 is consistent with the Q_{10} range anticipated from benthic respiration regulated to some extent by diffusion, with biological activity enhancement being constrained by limitations to transfer at the interface. The shallower oxygen penetration under warmer conditions results in higher oxygen transfer rates due to increased oxidation closer to the surface. The inverse relationship with oxygen in bottom water relates to the feedback mechanism that oxygen depletion in water overlying high SOD and lower oxygen content in warm water. The connection of SOD with organic matter at the pond level (Figure 3) and its close correlation with chlorophyll-a (Table 4) suggest two sources of degradable carbon: feed waste and faeces accumulating in the bottom sediments and settling of phytoplankton developing under the condition of high nutrient input into the ponds. Since these sources are increasing in parallel with the intensification, SOD can be considered as an integrated indicator reflecting pond loading rather than a characteristic of bottom sediments alone. High AVS content in intensive ponds implies that chemical oxygen demand occurs due to reoxidation of reduced sulfides, which is maximum in summer.

The range of SOD values found, from 0.4 to 2.1 g O_2 m^{-2} d^{-1}, is comparable to values found for productive lakes and organic sediments, and thus shows that extensive earthen aquaculture ponds have the characteristics of an active benthic system despite their extensive nature. Another important point is the stability of the intensive/extensive ratio throughout the seasons, which can be interpreted as the fact that the degree of management intensity determines the baseline value of benthic oxygen demand, whereas temperature defines its expression during the year.

Management Implications

Considering the average value for summer SOD of 2.14 g O2 m-2 day-1, a water column of 1.5 m depth in an intensive pond will lose 1.4 mg O2 L-1 per day to the bottom sediments, which is quite significant in relation to oxygen that must be produced by photosynthesis and aeration. Hence, management of the ponds must target the warmer months since SOD is at its peak and oxygen solubility is at its lowest in the warmer months. Some of the strategies include control of feed inputs to prevent organic load and aeration of the pond bottom during nighttime and early morning hours and removal or oxidation of the accumulated sludge during the off-season.

As shown in table 5, the volume ratio explains why the depth is important. The deeper the pond becomes, the more diluted the sediments become within the bigger water volume. This counteracts the higher surface oxygen demand that the deeper ponds have, while the shallower ones do not have sufficient buffering capacity in warm periods. It is better to think of the pond depth along with other factors instead of using the pond category alone.

Limitations

The core incubation technique does not involve resuspension or bioturbation by farmed fish or water motion within the pond, which might affect the in situ SOD. Sampling is done only once per season, and data obtained represent only one farm for one year of production.

Seasonal Oxygen-Budget Sensitivity and Depth-Normalized Exposure

The areal SOD rate is a flux of oxygen consumption per unit bottom surface area, while the impact on fish is due to the oxygen consumption in a volume of water. Therefore, the pond depth affects the volume importance of a given bottom flux. The areal SOD rates were converted into the daily oxygen loss volume in table 5 by using average pond depths of 1.5 meters for intensive and 1.0 meter for extensive ponds. Such conversion assumes uniform distribution of the oxygen sink throughout the whole water column. It is a

preliminary estimation rather than the prediction of DO profile measurements because photosynthesis and other oxygen sinks are ignored.

Intensive ponds showed highest sediment-bound oxygen consumption rates during the summer season (1.43 mg O_2 L^{-1} d^{-1}) as compared to that in winter (0.55 mg O_2 L^{-1} d^{-1}). This value in case of extensive ponds was 1.05 mg O_2 L^{-1} d^{-1} for summer season and 0.38 mg O_2 L^{-1} d^{-1} for winter season. Therefore, the difference between the oxygen demand rate during summer and winter seasons in intensive ponds was 0.88 mg O_2 L^{-1} d^{-1} while that in extensive ponds was 0.67 mg O_2 L^{-1} d^{-1}.

As regards the operational planning, what is important is the observation that the peak value of the benthic oxygen demand occurred when the oxygen concentration of bottom water was at its minimum during summer in intensive fish farms. Regarding the annual average ancillary data, summer bottom DO concentration was 2.9 ± 0.7 mg L^{-1} in intensive farms and 4.6 ± 0.9 mg L^{-1} in extensive fish farms. The 1.7 mg L^{-1} difference between the two is observed, and it cannot be considered the sole effect of SOD since there is a difference in feed supply and pond depth.

Management decisions must consider multiple pre-dawn and near-bottom oxygen readings, not one midday reading. If there is vertical stratification, then the average water column reading could hide localized oxygen stress at the sediment level. In this case, the aeration and mixing must be taken into account, along with oxygen levels, temperatures, and fish behavior. The reduction of organic loading through sediment removal or changes to feeding practices can be estimated by field tests, but not from SOD alone (Table 6).

Table 6: Derived Seasonal Changes in Sediment-Related Volumetric Oxygen Loss

Pond type	Winter (mg O_2 L^{-1} d^{-1})	Summer (mg O_2 L^{-1} d^{-1})	Summer − winter	Summer/winter ratio
Intensive	0.55	1.43	0.88	2.60
Extensive	0.38	1.05	0.67	2.76

Interpretation of Sediment Chemistry and Phytoplankton Coupling

The above-mentioned data help to explain the difference that exists between the two pond types. The annual average of organic matter content was 7.8 ± 0.9 % in intensive ponds and 3.6 ± 0.5 % in extensive ponds. In addition, the sediment total nitrogen was equal to 3.9 ± 0.4 g kg^{-1} and 1.8 ± 0.3 g kg^{-1}, respectively. From the above-mentioned data, one may conclude that there is higher organic matter content and higher nitrogen enrichment in the intensive ponds. According to the source study, acid-volatile sulfide (AVS) in intensive ponds was 0.62 ± 0.10 mg g^{-1} while in extensive ponds it was 0.21 ± 0.05 mg g^{-1}. It is important to note that AVS is not an estimation of the chemical fraction of SOD.

Correlation coefficients of 0.88 for sediment organic content, 0.81 for chlorophyll-a, and 0.76 for AVS are consistent with a coupled sediment-water column environment. It is possible that residues from the feeds and the effluents from fish can accumulate at the bottom. On the other hand, organic matter from the growth of algae in a nutrient-filled water body can provide extra organic matter. The exact proportions of these two mechanisms have not been established. Positive correlations must thus be considered as signs of covariation and not necessarily causation.

The most significant reported correlation of SOD was with temperature ($r = 0.93$), however, temperature, seasons, and management were not tested in isolation experimentally. Seasonal increase in temperature increases microbial respiration, affects oxygen solubility, and affects phytoplankton production. These three effects can happen concurrently; therefore, multiple variable causal explanation will need further data or experiment. The Q_{10} value of 1.77 and 1.85 is the calculated temperature coefficient for these two groups of ponds and should not be used as a universal constant.

Another point to note is that of the statistical unit. In this research, the sampled 72 sediment cores taken from six ponds, with several repeat measurements at different times of the year. Each core sample taken in each pond may not represent an independent biological replicate of management intensity. While the current

paper provides the results for a two-way ANOVA and Pearson correlation analysis, further statistical analysis should factor the ponds in as the random variable in a mixed-effects model.

Monitoring Protocol and Management Decision Framework

The sampling frequency in an efficient SOD assessment needs to correlate with the times of heightened oxygen danger. The base sampling is performed under cool conditions to define the reference level for the season, whereas additional sampling under warm conditions will indicate the beginning of high sediment requirements. Oxygen must be sampled near the sediment-water boundary at different times during the day, if possible. The paired sampling of the sediment with regard to the amount of organic matter, nitrogen, and AVS may show the reasons for oxygen demand.

The initial incubation protocol can be considered as a good basis for standardization; cores are kept intact without any surface disruption and transferred quickly to the lab where the incubation is carried out at in situ temperature corrected by the water control. Replicate core analysis and calibration help maintain high quality of results. However, the analysis of the cores in the lab may not reflect the flow in-pond, fish behavior and sediment resuspension.

Thresholds need to be established on a local basis based on fish species' tolerance, water quality criteria, and local oxygen relationships. The current data do not provide a single universal threshold for the critical level of SOD. In this situation, a decision framework could use a combination of growing SOD, reduced pre-dawn DO, and increasing sediment organic content as concurrent warnings. Where multiple warnings occur, managers can assess feed practices, solids accumulation, aeration extent, and pond maintenance scheduling (table 7).

Table 7: Proposed Monitoring Framework for Seasonal Sediment Oxygen Demand

Component	Recommended observation	Purpose / interpretation
Sediment oxygen demand	Replicate intact-core incubations by season	Quantify benthic oxygen flux
Bottom-water DO	Pre-dawn and near-bottom profiles	Identify oxygen stress periods
Water temperature	At each oxygen and SOD measurement	Interpret thermal sensitivity
Organic matter and total N	Surface sediment, repeated consistently	Track substrate enrichment
Acid-volatile sulfide	Surface sediment where feasible	Track reduced sediment conditions
Chlorophyll-a	Paired water-column samples	Track potential settling algal inputs
Aeration and feeding	Daily operational logs	Contextualize management differences
Pond identity and depth	Fixed site metadata	Support repeated-measures analysis

Study Limitations and Priorities for Validation

The paper provides an interesting comparison between the intensive and extensive ponds but is limited to a commercial farm in just one season of the year. The six ponds are not sufficient to capture all of the variations that exist regarding the climatic conditions, texture of the sediments, species of fish used, feeding and water change regimes in the system of aquaculture production. The incubation procedure used in the study eliminates some of the variations in the measurements, but not all of them.

Observational design restricts causal inference. There were several differences between pond types, such as depth, feed input, and aeration, at the same time. Thus, the increased SOD found in intensive ponds should be considered an association with the intensive management system, and not the result of stocking

intensity alone. A further study could involve replicate ponds with similar depth and bottom sediments, as well as feed inputs, biomass production, aeration, and water exchange.

Future research needs to include continuous oxygen sensors for bottom waters, repeated sampling of SOD during each season, and the determination of organic matter accumulation. Hierarchical statistical modeling taking into account cores nested within ponds and seasons repeated within ponds would be useful to determine the degree of error associated with comparisons between treatments. Measurements of sediment oxygen penetration, ammonia and sulfide fluxes from porewaters would assist in determining the biological and chemical contributions to SOD.

In summary, the supplemental analysis supports the primary finding without implying any new field data: seasonal warming was associated with an increase in oxygen demand by the bottom community in both ponds, and the intensive one had a higher total oxygen load. The volume-based calculation demonstrates the importance of pond depth in terms of making areal sediment oxygen dynamics practically meaningful. Thus, monitoring the state of the sediment along with oxygen at the bottom and management practices is crucial.

VI. Conclusions

This research shows that sediment oxygen demand is highly variable based on aquaculture management and seasonal variation in temperature. The SOD of intensive ponds was two times greater than that of extensive ponds, with annual means of 1.44 and 0.69 g O2 m-2 day-1, respectively. There was an increase in SOD by 2.6-2.8 times from winter to summer season, with maximum SOD of 2.14 g O2 m-2 day-1 for intensive ponds and 1.05 g O2 m-2 day-1 for extensive ponds. Temperature-dependent oxygen consumption, indicated by high Q_{10} values of 1.77 and 1.85, presents the impact of seasonally increasing temperature on benthic oxygen consumption. Additionally, the association with sediment organic matter, chlorophyll-a, and temperature indicates the role played by organic enrichment and biota. Seasonal monitoring of oxygen, optimal aeration, controlled feeding, and sediment management, especially during summer season, will be helpful for maintaining water quality and preventing oxygen loss.

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