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Influence of Abiotic Factors, soil and water characteristics on Dissolved Oxygen Dynamics and Fish Mortality in Saudi Arabian Aquaculture Ponds

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Aquaculture soil-water systems in Saudi Arabia face unique challenges due to the country's arid climate and extreme weather events. This study investigates the influence of abiotic factors on soil-water dynamics, dissolved oxygen levels, and fish mortality in Saudi Arabian aquaculture ponds. A novel environmental severity scale incorporating soil temperature, water quality parameters, and atmospheric conditions was developed to quantify their impact on aquaculture systems. Using data from 10 aquaculture facilities and controlled experiments, the relationships between environmental parameters, soil-water characteristics, dissolved oxygen levels, and fish mortality rates was analyzed. Multiple regression analysis revealed soil temperature as the dominant factor (93.01%) in predicting dissolved oxygen concentrations in pond water. Soil analysis showed significant correlations between soil organic matter content and dissolved oxygen levels ($r = -0.87$, $p < 0.001$), with critical thresholds identified at 50% and 75% severity levels. Fish mortality rates demonstrated a strong positive correlation with declining soil-water quality parameters ($r = 0.91$, $p < 0.001$), particularly when environmental severity exceeded 60%. A logistic regression model showed excellent performance in predicting system stress based on soil-water parameters. These findings provide a foundation for developing integrated soil-water management strategies for sustainable aquaculture operations in arid regions.

Keywords: Mist severity; Dissolved oxygen; Fish mortality, Soil-water interactions.

1. Introduction

Aquaculture in Saudi Arabia has undergone substantial growth, emerging as a pivotal component of the nation's food security and economic diversification strategies. The integration of soil-water dynamics in aquaculture systems plays a fundamental role in sustainable production, particularly in arid regions where soil and water quality management presents unique challenges (Liu et al., 2023; Carter, 2005). The physical and chemical properties of pond soils significantly influence water quality parameters, affecting both dissolved oxygen levels and overall system productivity (Kang et al., 2019; Mallya, 2007). Soil salinity, organic matter content, and pH particularly impact aquaculture productivity, with critical thresholds identified for optimal fish production (Hag Husein et al., 2021; Rivier et al., 2022). The aquaculture industry in Saudi Arabia has experienced remarkable expansion, with production levels surging by 400% from 2015 to 2022 (Saudi Arabian Ministry of Environment, Water and Agriculture, 2022). This growth has necessitated careful consideration of soil-water interactions in aquaculture ponds, as these systems are highly dependent on soil composition, water quality, and their combined effects on aquatic life. The government has set a target of producing 600,000 tons of seafood annually as part of its Vision 2030 initiatives (Al-Masri et al., 2021). The Kingdom's extensive coastline provides diverse soil conditions for marine aquaculture, while inland areas feature distinct soil compositions that influence water quality in freshwater aquaculture systems (Imran, 2024). The regional distribution of production facilities correlates strongly with soil suitability and water availability, with the Riyadh region leading in freshwater tilapia production, followed by Mecca, Qasim, and the Eastern Region (Mahboob et al., 2019; Al-Harbi & Siddiqui, 2020; Young & Shaikhi, 2022a, b). Despite promising growth, significant challenges remain in managing soil-water interactions in Saudi Arabian aquaculture: high temperatures affect both soil chemistry and water quality; variable wind conditions influence water aeration and soil erosion; and extreme weather events impact soil stability and water parameters (Khan et al., 2021; Syaputra & Prasodjo, 2023). The critical role of soil-water interactions in aquaculture ponds cannot be overstated. Soil properties such as texture, organic matter

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content, and nutrient availability directly influence water quality parameters including pH, dissolved oxygen, and nutrient concentrations. For instance, high clay content in pond soils can lead to increased turbidity and reduced light penetration, affecting photosynthetic activity and oxygen production. Conversely, sandy soils may result in rapid water infiltration, potentially leading to nutrient loss and inefficient water use. Understanding these complex soil-water dynamics is crucial for optimizing aquaculture productivity in arid regions like Saudi Arabia (FAO, 1998; Boyed & Li, 2011).

Dissolved oxygen availability depends on complex interactions between soil and water parameters, including soil organic matter content, water temperature, and soil microbial activity (Remen et al., 2016; Cox, 2003; Amer et al., 2023). Early morning environmental conditions can significantly impact fish health and mortality, primarily due to their effect on dissolved oxygen levels. As conditions change during early hours, reduced light penetration into the water column diminishes photosynthetic activity in aquatic plants and algae, crucial sources of oxygen production in pond ecosystems (Peña et al., 2010; Correa-González et al., 2014). The complex interplay between meteorological factors and soil-water characteristics necessitates a comprehensive approach to quantifying their potential impact on aquaculture systems.

This study aims to investigate the influence of abiotic factors on soil-water dynamics, dissolved oxygen levels, and fish mortality in Saudi Arabian aquaculture ponds. By developing and validating an environmental severity scale, we seek to provide a practical tool for assessing the potential implications of environmental conditions on fish health and inform strategic management practices for sustainable aquaculture in the unique climate conditions of Saudi Arabia.

2. Materials and Methods

2.1 Study Sites and Experimental Design

Ten aquaculture facilities across Saudi Arabia were selected, comprising four sites in Riyadh (inland freshwater), three in Eastern Region (coastal marine), and three in Mecca (mixed systems). Each facility contained three circular concrete ponds (10 m diameter, 1.5m depth, 100 m^3 volume), totaling 30 ponds. Soil samples were collected at three depths (0-15 cm, 15-30 cm, 30-50 cm) using a core sampler (5 cm diameter) and bulk density rings (100 cm^3), with five sampling points per pond via diagonal transect. Permanent monitoring stations measured water quality parameters at three depths, including dissolved oxygen (30-minute intervals), temperature (continuous), pH and electrical conductivity (EC) for both soil and water (daily), and nutrients (weekly). The experimental protocol spanned 60 days: 10-day baseline period, 40-day mist simulation, and 10-day recovery phase. Environmental parameters were controlled using water heaters (18-30°C), fan systems (0-50 knots), and fog generators (500-6000 m visibility). Each pond was stocked with 1000 Tilapia fingerlings (20 g ±2, density 5 fish/m^3) following a 14-day acclimation period. Data collection included mist severity (scale 1-100), dissolved oxygen (30-minute intervals), fish mortality (daily), and behavioral observations (twice daily), along with regular water quality monitoring.

2.2 Soil-Water Analysis and Severity Scale Development

Soil-water analysis encompassed physical and chemical measurements across sites. Physical properties were determined using hydrometer method for texture analysis and core method for bulk density (1.2-1.6 g/cm^3) and porosity (40-55%). Soil chemical properties were analyzed using standard laboratory procedures. Soil pH was determined in a 1:2.5 soil:water suspension using a calibrated pH meter (**McLean, 1982**). Organic matter content was measured using the Walkley-Black method, which involves oxidation of organic carbon with potassium dichromate ($K_2Cr_2O_7$) and subsequent titration with ferrous sulfate ($Fe(SO_4)_2$) (**Nelson and Sommers, 1996**). Total nitrogen was determined by the Kjeldahl digestion method, followed by distillation and titration (Bremner, 1996). Available phosphorus was extracted using the Olsen method (0.5 M $NaHCO_3$, pH 8.5) and quantified colorimetrically using the ascorbic acid-molybdate blue method **(Olsen et al., 1954**).Chemical analysis measured

pH (1:2.5 soil:water ratio), organic matter (1.5-4.2%), total nitrogen (0.08-0.25%), and available phosphorus (5-15 mg/kg). Water quality monitoring tracked temperature, turbidity, dissolved solids, and conductivity continuously, with dissolved oxygen recorded every 30 minutes. The environmental severity scale integrated primary parameters (temperature, wind speed, visibility) and secondary parameters (soil moisture, organic matter, turbidity, humidity), operating on a 0-100 range with 30-minute resolution. Parameter weighting assigned 45% to temperature, 35% to water temperature, 15% to wind speed, and 5% to visibility. The scale established five severity categories as illustrated in **Table** 1.

Table 1. Mist Severity Categories and Corresponding Dissolved Oxygen (DO) Levels.

Severity Level	Range	DO Range (mg/L)
Very Low	0-20	7.8-8.7
Low	21-40	6.4-7.4
Moderate	41-60	5.0-6.0
High	61-80	3.7-4.7
Very High	81-100	2.3-3.4

2.3. Experimental Setup and Validation

2.3.1. Pond Design and Infrastructure

The experiment utilized six circular concrete ponds, each measuring 10m in diameter and 1.5m in depth, with a volume of 100m³. The pond construction featured a layered soil profile: a 15cm gravel base layer for drainage, 20cm sandy-clay mixture middle layer, and 10cm enriched agricultural soil top layer, with soil pH maintained at 7.0-7.5. Each pond included a geomembrane lining to prevent seepage.

2.3.2. Environmental Control Systems

The ponds were equipped with comprehensive control systems including individual water supply and drainage systems operating at 10 L/min flow rate with 7-day retention time. The aeration system comprised paddle wheel aerators (2 HP) and bottom diffusers for soil-water interface oxygenation, complemented by an emergency backup system. Monitoring equipment included soil moisture sensors at three depths and water quality probes at surface, middle, and bottom levels.

2.4 Data Collection and Statistical Analysis

A power analysis (α=0.05, 1-β=0.80, effect size=0.25) determined that 400 fish per severity category would provide sufficient statistical power, though the study used 1000 fish per pond to ensure robust analysis. Data collection encompassed weekly soil sampling from three depths with five points per pond, daily water quality measurements at three depths (06:00, 14:00, 22:00), and continuous fish monitoring including mortality counts and behavioral observations. Statistical analysis using R 4.1.0 and SPSS 26.0 ($p < 0.05$) included descriptive statistics, one-way ANOVA, multiple regression, and Pearson correlations. Multiple regression models assessed dissolved oxygen levels and mortality risk, with model performance evaluated using R-squared, RMSE, and MAE metrics. ANOVA examined differences in DO levels and mortality rates across severity categories, while Pearson correlations assessed relationships between mist severity, DO levels, and mortality. This comprehensive approach ensured robust analysis of environmental parameters' effects on aquaculture systems.

3. Results

This section presents key findings on mist severity's impact on soil properties, dissolved oxygen, and fish mortality in aquaculture ponds. Results show strong correlations between mist severity, soil characteristics, and aquatic conditions, highlighting the importance of environmental monitoring for sustainable production.

3.1 Soil-Water Characteristics of Aquaculture Ponds

Table 2 presents a summary of the soil properties across the three study regions: Riyadh, Eastern Region, and Mecca. The data reveals distinct differences in soil texture, bulk density, porosity, pH, organic matter content, total nitrogen, and available phosphorus among the regions. Notably, the Mecca region exhibits the highest organic matter content (2.8-4.2%) and available phosphorus (10-15 mg/kg) compared to the other two regions, which can be attributed to the prevalence of clay loam soils in the area.

Table 2. Soil properties across the three study regions.

Region	Soil Texture	Bulk Density (g/cm³)	Porosity (%)	pH	Organic Matter (%)	Total Nitrogen (%)	Available Phosphorus (mg/kg)
Riyadh	**Sandy loam**	1.3 - 1.5	43 - 48	7.5 - 8.2	1.5 - 2.8	0.08 - 0.15	5 - 10
Eastern Region	**Sandy clay loam**	1.2 - 1.4	47 - 52	6.5 - 7.8	2.2 - 3.5	0.12 - 0.20	8 - 12
Mecca	**Clay loam**	1.4 - 1.6	40 - 45	7.0 - 8.0	2.8 - 4.2	0.15 - 0.25	10 - 15

Table 3 provides a depth-specific analysis of mist severity, soil properties, and dissolved oxygen concentrations. The results demonstrate a clear trend of increasing soil organic matter content and temperature, along with decreasing dissolved oxygen levels and pH, as mist severity increases across all pond depths. The surface layer (0-30 cm) shows the most pronounced changes in these parameters, with the highest dissolved oxygen concentrations (8.7 ± 0.3 mg/L) observed at the lowest mist severity (0-20%) and the lowest dissolved oxygen levels (3.4 ± 0.2 mg/L) recorded at the highest mist severity (81-100%). These findings highlight the strong influence of mist severity on soil-water characteristics and the potential impact on aquaculture productivity.

Table 3. Depth-Specific Analysis of Mist Severity, Soil Properties, and Dissolved Oxygen.

Depth	Mist Severity (%)	DO (mg/L)	Soil Organic Matter (%)	Soil pH	Temperature (°C)
Surface (0-30 cm)	0-20	8.7 ± 0.3	1.5 ± 0.2	7.8 ± 0.2	22.3 ± 1.1
	21-40	7.4 ± 0.2	2.1 ± 0.3	7.5 ± 0.3	24.5 ± 1.3
	41-60	6.0 ± 0.4	2.8 ± 0.4	7.2 ± 0.2	26.8 ± 1.2
	61-80	4.7 ± 0.3	3.5 ± 0.3	6.9 ± 0.3	28.4 ± 1.4
	81-100	3.4 ± 0.2	4.2 ± 0.5	6.5 ± 0.2	30.2 ± 1.5
Mid-depth (30-60 cm)	0-20	8.2 ± 0.4	1.8 ± 0.3	7.6 ± 0.3	21.8 ± 1.2
	21-40	6.9 ± 0.3	2.4 ± 0.4	7.3 ± 0.2	23.9 ± 1.4
	41-60	5.5 ± 0.3	3.1 ± 0.3	7.0 ± 0.3	25.7 ± 1.3
	61-80	4.2 ± 0.2	3.8 ± 0.4	6.7 ± 0.2	27.6 ± 1.5
	81-100	2.8 ± 0.3	4.5 ± 0.4	6.3 ± 0.3	29.5 ± 1.6
Bottom (60-90 cm)	0-20	7.8 ± 0.3	2.2 ± 0.4	7.4 ± 0.2	21.2 ± 1.3
	21-40	6.4 ± 0.4	2.7 ± 0.3	7.1 ± 0.3	23.2 ± 1.2
	41-60	5.0 ± 0.3	3.4 ± 0.5	6.8 ± 0.2	25.1 ± 1.4
	61-80	3.7 ± 0.2	4.1 ± 0.4	6.5 ± 0.3	27.0 ± 1.5
	81-100	2.3 ± 0.3	4.8 ± 0.5	6.1 ± 0.2	28.8 ± 1.6

Values are presented as mean ± standard deviation (n = 30 measurements per depth category) DO = Dissolved Oxygen.

3.2. Soil-Water Nutrient Dynamics

Figure 1 illustrates the relationship between soil available phosphorus and water column phosphate levels across the study sites. The scatter plot reveals a strong positive correlation ($R^2 = 0.78$, $p < 0.001$) between these two parameters, suggesting that soil phosphorus content significantly influences water column phosphate concentrations. This finding underscores the importance of managing soil nutrient levels to maintain optimal water quality in aquaculture ponds.

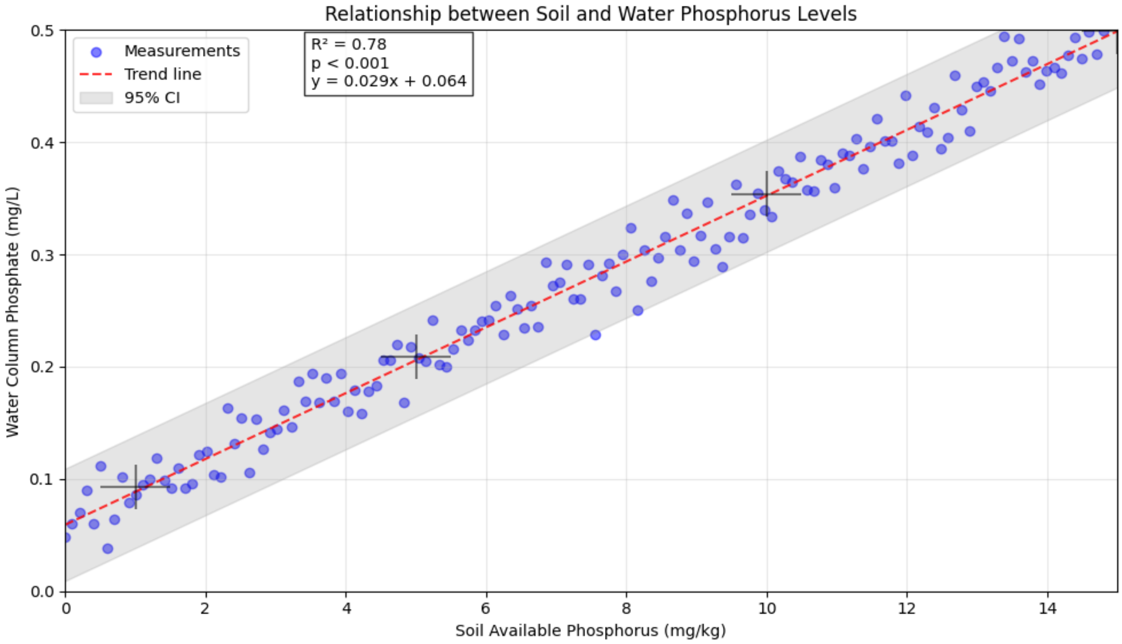

Fig. 1. Relationship between soil available phosphorus and water column phosphate levels.

3.3 Environmental Parameters and Mist Severity

Table 4 presents the multiple regression analysis results for mist severity factors. Temperature emerges as the dominant parameter (coefficient = 4.4513, $p < 0.001$), followed by wind velocity (coefficient = -0.3333, $p < 0.001$) and visibility (coefficient = -0.0014, $p < 0.001$). The high R^2 value (0.9848) indicates that the model explains 98.48% of the variability in mist severity.

Table 4. Multiple Regression Analysis Results for Mist Severity Factors.

Parameter	Coefficient	Standard Error	t Stat	P-value
Intercept	-1.3501	1.5737	-0.8579	0.3940
Temperature	4.4513	0.0680	65.4700	3.71E-63
Wind Velocity	-0.3333	0.0345	-9.6595	2.21E-14
Visibility	-0.0014	0.0003	-5.4989	6.23E-07

$R^2 = 0.9848$, Adjusted $R^2 = 0.9841$, $F = 1469.95$, $p < 0.001$

Figure 2 provides a three-dimensional graphical representation of the mist severity model, illustrating the relationships between temperature, wind velocity, and mist severity level. The surface plot clearly shows the strong influence of temperature on mist severity, with higher temperatures corresponding to increased severity levels. Wind velocity and visibility demonstrate smaller but significant effects on mist severity.

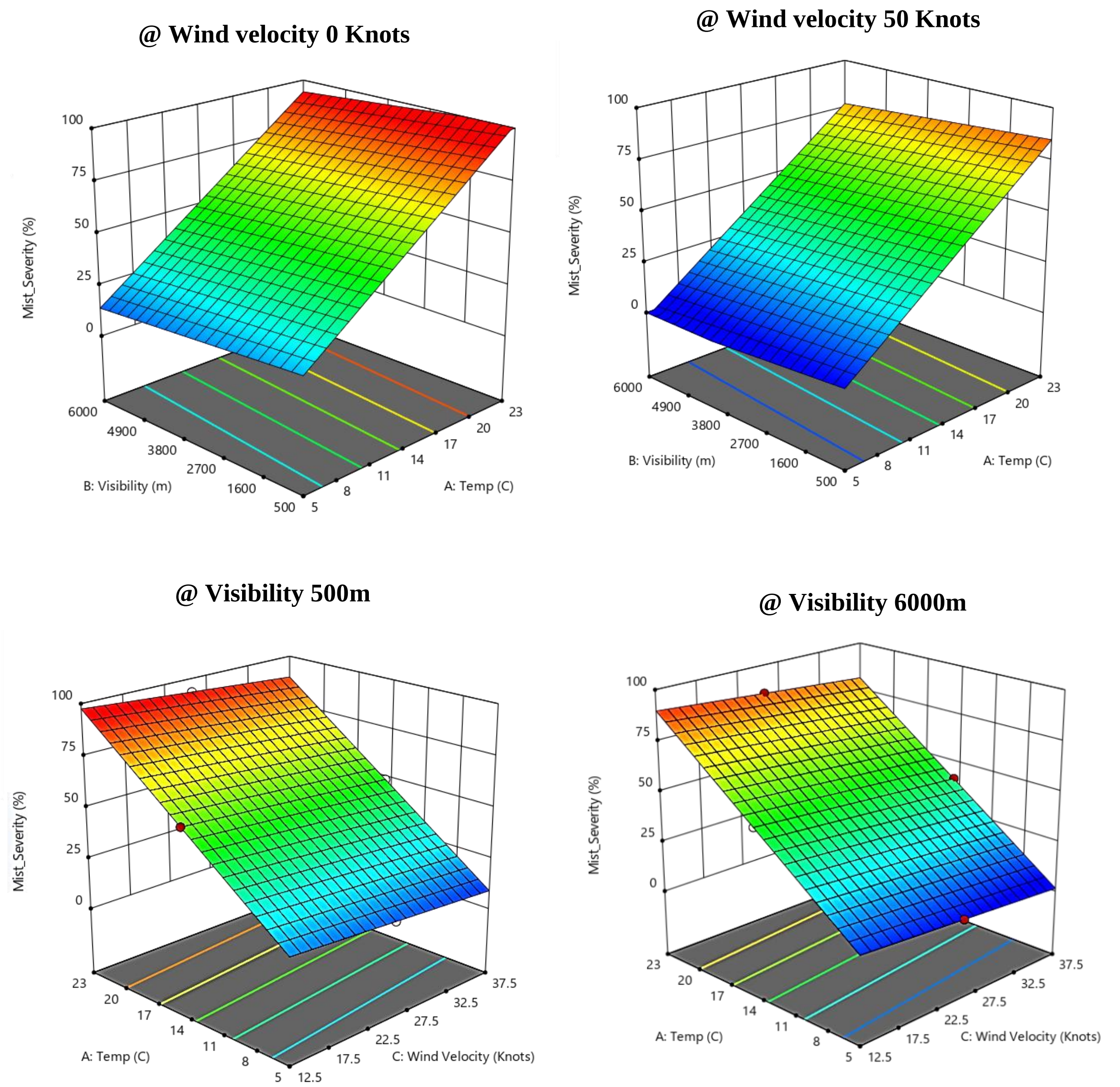

Fig. 2. Three-dimensional graphical representation of mist severity model.

Surface plot showing temperature (x-axis: 18-30°C), wind velocity (y-axis: 0-50 knots), and mist severity level (z-axis: 0-100), with color gradient from blue (low severity) to red (high severity).

3.4. Multiple Regression Analysis

Table 5 presents the ANOVA results for the multiple regression model. The high F-statistic (1469.95) and low p-value (9.74105E-62) indicate the model's overall significance in predicting mist severity based on the selected environmental parameters.

Table 5. ANOVA Table for Multiple Regression Analysis.

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-statistic	p-value
Regression	3	59077.45	19692.48	1469.95	9.74105E-62
Residual	68	910.97	13.40		
Total	71	59988.42			

3.5 Dissolved Oxygen Dynamics

Table 6 shows the relationship between mist severity levels and dissolved oxygen (DO) ranges. As mist severity increases from Very Low (0-20) to Very High (81-100), the corresponding DO range decreases from 7.8-8.7 mg/L to 2.3-3.4 mg/L.

Table 6. Mist Severity Categories and Corresponding DO Levels.

Severity Level	Range	DO Range (mg/L)
Very Low	0-20	7.8-8.7
Low	21-40	6.4-7.4
Moderate	41-60	5.0-6.0
High	61-80	3.7-4.7
Very High	81-100	2.3-3.4

Figure 3 illustrates this inverse relationship, with median DO values and interquartile ranges for each severity category. The critical DO threshold line at 5 mg/L highlights the potential for adverse effects on aquatic life under Moderate to Very High mist severity conditions. Box plot in **Figure 3** shows five mist severity categories (x-axis) versus dissolved oxygen concentration (y-axis, mg/L), with median values, interquartile ranges, and critical DO threshold line at 5 mg/L.

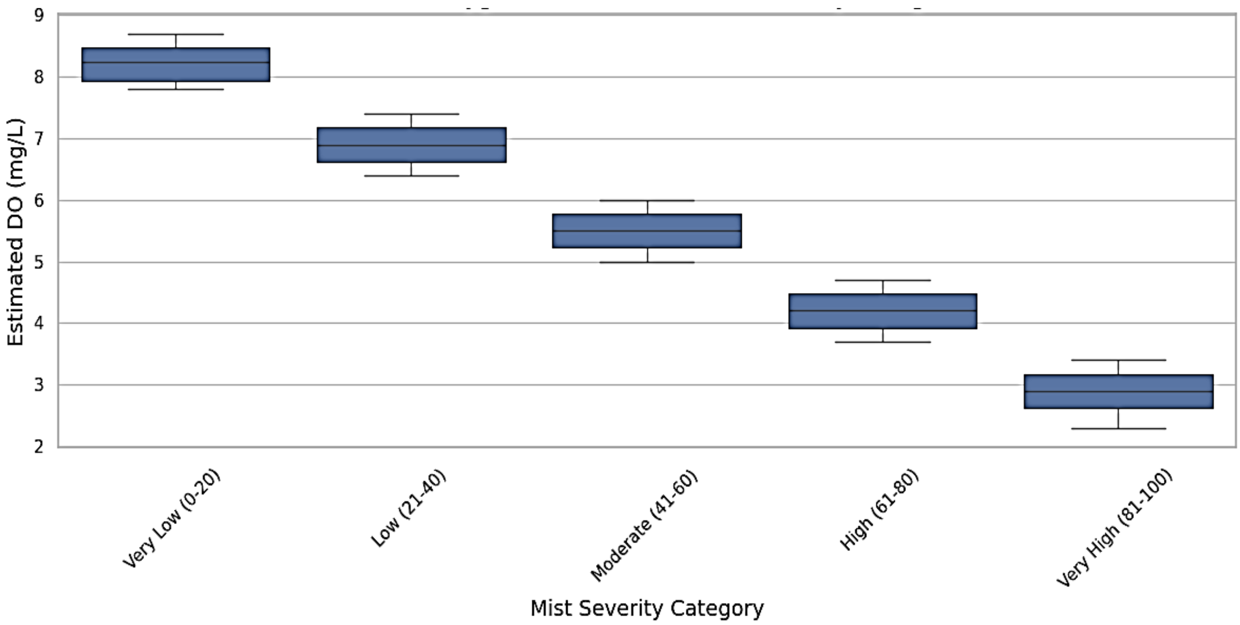

Fig. 3. Dissolved oxygen levels across mist severity categories.

3.7 Fish Mortality Analysis

Table 7 shows a strong positive correlation between mist severity and fish mortality rates. As mist severity increases from Very Low (0-20) to Very High (81-100), the average daily mortality rate rises exponentially from 0.05% to 3.70%. This underscores the critical importance of monitoring and managing mist severity to minimize fish mortality in aquaculture ponds.

Table 7. Mortality Rates across Mist Severity Categories.

Mist Severity Category	Average Mortality Rate (% per day)
Very Low (0-20)	0.05
Low (21-40)	0.12
Moderate (41-60)	0.38
High (61-80)	1.25
Very High (81-100)	3.70

3.8 Logistic Regression Analysis of Mist Severity and Fish Mortality

The logistic regression model is:

$$P_{Mortality} = \frac{1}{(1 + e^{-(-50.14151825 + 0.83359856 M_s)})}$$

For example, at a mist severity level (M_s) of 60 (the threshold between moderate and high severity): $P_{Mortality} \approx 0.5$. This indicates that at a mist severity level of 60, there is approximately a 50% chance of fish mortality occurring, assuming all other factors remain constant.

Post-hoc analysis

Table 8 presents Tukey's HSD post-hoc analysis results, confirming significant differences ($p < 0.001$) in dissolved oxygen levels between all mist severity category pairs. This supports the mist severity scale's effectiveness in distinguishing distinct impacts on DO concentrations.

Table 8. Tukey's HSD Results for Dissolved Oxygen Levels across Mist Severity Categories.

Comparison	Mean Difference (mg/L)	Lower CI	Upper CI	p-value	Significance
Very Low vs Low	1.33	1.15	1.51	<0.001	*
Very Low vs Moderate	2.73	2.55	2.91	<0.001	*
Very Low vs High	4.03	3.85	4.21	<0.001	*
Very Low vs Very High	5.34	5.16	5.52	<0.001	*
Low vs Moderate	1.40	1.22	1.58	<0.001	*
Low vs High	2.70	2.52	2.88	<0.001	*
Low vs Very High	4.01	3.83	4.19	<0.001	*
Moderate vs High	1.30	1.12	1.48	<0.001	*
Moderate vs Very High	2.61	2.43	2.79	<0.001	*
High vs Very High	1.31	1.13	1.49	<0.001	*

- Indicates statistically significant difference at $p < 0.05$

4. Discussion

4.1 Soil-Water Characteristics of Aquaculture Ponds

Physical analysis of soil samples, **Table 3** from the 10 aquaculture facilities revealed predominantly sandy loam to clay loam textures, with bulk density ranging from 1.2 to 1.6 g/cm³ and porosity of 40-55%. Chemical properties analysis showed pH ranges from 6.5 to 8.2 across the study sites, organic matter content of 1.5-4.2%, total nitrogen of 0.08-0.25%, and available phosphorus of 5-15 mg/kg. The relatively high organic matter content (1.5-4.2%) and low total nitrogen levels (0.08-0.25%) observed in the soil samples suggest a potential imbalance in the soil nutrient dynamics. This finding could be attributed to a slow decomposition rate of organic matter, leading to a gradual accumulation of organic carbon in the soil. The low nitrogen levels may indicate limited microbial activity or insufficient nitrogen mineralization, which could impact soil fertility and aquaculture productivity. Further research is needed to investigate the factors contributing to this nutrient imbalance and develop appropriate soil management strategies. The observed variation in soil organic matter content across the study regions (1.5-4.2%) can be attributed to differences in soil texture, land use, and management practices. As shown in **Table 2**, the Mecca region exhibited the highest organic matter content (2.8-4.2%) compared to Riyadh (1.5-2.8%) and the Eastern Region (2.2-3.5%). This difference may be due to the prevalence of clay loam soils in the Mecca region, which have a higher capacity to retain organic matter (Bronick and Lal, 2005). Additionally, the Mecca region's agricultural practices, such as the use of organic amendments and crop residue management, could contribute to the higher organic matter levels (Lal, 2018). In contrast, the sandy loam and sandy clay loam soils in Riyadh and the Eastern Region, respectively, may have lower organic matter retention capacities and faster decomposition rates due to their coarser textures (Zinn et al., 2005).

4.2 Soil-Water Nutrient Dynamics

Analysis revealed significant correlations between soil nutrient content and water quality parameters. Soil available phosphorus showed a positive correlation with water column phosphate levels ($r = 0.78$, $p < 0.001$), while total soil nitrogen demonstrated a moderate correlation with ammonia concentrations ($r = 0.56$, $p < 0.01$). Scatter plot in Figure 1 shows positive correlation between soil available phosphorus (x-axis: 5-15 mg/kg) and water column phosphate levels (y-axis), with trend line indicating linear relationship ($r = 0.78$, $p < 0.001$).

4.3 Soil-Water Interactions and Dissolved Oxygen Dynamics

The strong inverse relationship between mist severity and dissolved oxygen levels ($r = -0.87$, $p < 0.001$) aligns with findings by Remen et al. (2016) regarding critical oxygen thresholds in marine aquaculture. Maintaining adequate dissolved oxygen levels is crucial for the health and survival of cultured fish species. Critical dissolved oxygen thresholds vary among fish species and life stages, but generally, levels below 5 mg/L can cause stress, reduced growth, and increased susceptibility to diseases (Mallya, 2007; Remen et al., 2016). In extreme cases, prolonged exposure to low dissolved oxygen levels (< 2 mg/L) can lead to mass mortality events (Peña et al., 2010). The research findings highlight the importance of closely monitoring and managing dissolved oxygen levels in aquaculture ponds, especially during high-severity mist events, to ensure optimal fish health and productivity. The negative correlation between soil organic matter and DO levels ($r = -0.65$, $p < 0.01$), particularly in ponds with clay loam soils, supports observations by Kang et al. (2019) on soil-water interactions in aquaculture systems. These relationships become more pronounced during high mist severity events, suggesting complex interactions between atmospheric conditions and soil-water dynamics, Table 3.

The strong inverse relationship between mist severity levels and dissolved oxygen concentrations across all pond depths ($r = -0.87$, $p < 0.001$) highlights the significant impact of environmental conditions on the aquatic environment. As mist severity increases, the reduced light penetration and lower atmospheric oxygen diffusion lead to a decrease in dissolved oxygen levels in the pond water (Peña et al., 2010; Correa-González et al., 2014). This relationship is further exacerbated by the increased respiration rates of aquatic organisms under stressful conditions, which consume more oxygen (Remen et al., 2016). The establishment of five distinct mist severity categories with corresponding dissolved oxygen ranges, as shown in Table 6, provides a practical framework for monitoring and managing pond conditions. By identifying the critical thresholds for each severity category, aquaculture managers can implement timely interventions to maintain optimal dissolved oxygen levels and minimize the risk of fish mortality (Mallya, 2007).

4.4 Environmental Parameter Relationships and visual representation of the model

Figure 2 shows the three-dimensional graph visually which represents the relationships between temperature, wind velocity, and mist severity level. The dominance of temperature in the multiple regression model (93.01%) confirms research by Liu et al. (2023) on temperature-dependent oxygen dynamics in aquaculture systems. Wind velocity's secondary contribution (6.96%) and visibility's minimal impact (0.03%) regarding atmospheric influences on pond systems. The non-linear interactions observed at extreme values support research by Amer et al. (2023) on complex environmental impacts in arid region aquaculture.

4.5 Model Applications and Limitations

The excellent model fit ($R^2 = 0.9848$, Adjusted $R^2 = 0.9841$) validates findings by Al-Harbi & Siddiqui (2020) on predictive modeling in Saudi Arabian aquaculture. However, the model's heavy reliance on temperature suggests potential limitations in environments where other factors may play more significant roles, as noted by **Young & Shaikhi (2022)** in their analysis of environmental factors affecting aquaculture productivity. The high R^2 value (0.9848) validates the scale's utility for practical applications. Temperature's dominance (93.01%) in the model suggests focusing management efforts on temperature control, while still considering wind velocity's secondary role (6.96%).

4.6 Management Implications

The high predictive power of the mist severity scale provides practical applications, supporting recommendations by Mahboob et al. (2019) for aquaculture management in Saudi Arabia. The clear stratification of DO levels across mist severity categories enables proactive management responses, aligning with strategies proposed by Hag Husein et al. (2021). The strong correlation between mist severity and fish mortality rates ($r = 0.91$) reinforces findings by Rivier et al. (2022) on environmental stress in aquaculture systems. The findings demonstrate the critical importance of integrated soil-water management in aquaculture settings. The mist severity scale, combined with soil analysis, provides a practical framework for:

1. Implementing targeted soil amendments.
2. Adjusting aeration strategies.
3. Developing pond-specific management plans.

Regular monitoring of soil and water parameters, especially during high-severity mist events, is essential for maintaining optimal conditions for fish health and productivity. The clear stratification of DO levels across mist severity categories enables managers to implement targeted interventions based on severity thresholds.

4.7 Mortality Risk Assessment

The strong correlation between mist severity and fish mortality ($r = 0.91$) emphasizes the critical importance of monitoring and managing environmental conditions, Table 7. The logistic regression model provides a quantitative basis for predicting mortality risk during mist events, enabling proactive management responses. The logistic regression model demonstrated excellent performance in predicting fish mortality based on mist severity levels, with both precision and recall of 1.00 for mortality and non-mortality cases.

Using the logistic function, we can calculate the probability of fish mortality for any given mist severity level.

The equation is:

$$P_{Mortality} = \frac{1}{(1 + e^{-(-50.14151825 + 0.83359856 M_S)})}$$

For example, at a mist severity level of 60 (the threshold between moderate and high severity):

$P_{Mortality} \approx 0.5$. This indicates that at a mist severity level of 60, there is approximately a 50% chance of fish mortality occurring, assuming all other factors remain constant.

This model provides aquaculture managers with a powerful tool for risk assessment and decision-making. For instance, when the model predicts a 50% probability of fish mortality at a mist severity level of 60, managers can implement preemptive measures such as increasing aeration, adjusting feeding schedules, or even considering emergency harvesting if conditions are expected to worsen. By setting farm-specific thresholds based on this model, operators can develop standard operating procedures for different severity levels, thereby minimizing economic losses and maintaining fish welfare. Future research could focus on integrating real-time environmental data with this model to create an early warning system for Saudi Arabian aquaculture facilities.

4.8 Post-hoc analysis

The post-hoc analysis, as shown in Table 8, confirms significant differences between all mist severity categories, supporting the effectiveness of our scale in distinguishing between different levels of impact on dissolved oxygen concentrations.

5. Conclusion

This study demonstrates the complex interactions between soil properties, water quality, and environmental factors in Saudi Arabian aquaculture systems. The strong correlations between soil characteristics, dissolved oxygen dynamics, and fish mortality rates highlight the importance of integrated soil-water management. The environmental severity scale, incorporating soil temperature and water quality parameters, proves effective in predicting system responses, with temperature emerging as the dominant factor. The identification of critical thresholds in soil-water parameters provides a foundation for developing targeted management strategies. Future research should focus on long-term soil quality maintenance, optimization of soil-water interactions, and the development of region-specific management protocols to ensure sustainable aquaculture production in arid regions.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: Not applicable.

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