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Multivariate Water Quality Patterns as a Proxy for Environmental Performance in Tropical Pond-Based Aquaculture Systems

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Abstract

Water quality plays a central role in determining the environmental performance of pond-based tropical aquaculture systems. This study aimed to evaluate the relative environmental performance of different tropical pond-based aquaculture systems by identifying multivariate water quality patterns that allow their discrimination and comparison under commercial production conditions. Four pond-based production systems were evaluated: an aquaponic system (APS), a recirculating aquaculture system (RAS), a conventional earthen pond system (CEP), and an integrated rice–chame system (RCS). Fourteen physico-chemical water quality variables were monitored throughout the production cycle under real commercial conditions using a comparative observational design. Multivariate discriminant analysis was applied to identify the variables with the highest discriminatory power and evaluate the ability of water quality patterns to correctly classify observations among production systems. The results revealed a clear multivariate separation between technologically intensive systems (APS and RAS) and less intensive and integrated systems (CEP and RCS), reflecting distinct water quality structures and environmental functioning. Variables associated with mineralization and nutrient dynamics, including electrical conductivity, dissolved solids, turbidity, phosphates, chlorides, dissolved oxygen, nitrites, and temperature, contributed most strongly to system discrimination. The discriminant functions achieved a high overall correct classification rate, demonstrating the robustness of the multivariate approach. These findings support the use of water quality variables as consistent environmental signatures for distinguishing tropical pond-based aquaculture systems, providing an operational framework for assessing their relative environmental performance. Discriminant analysis emerges as a valuable tool for system characterization and comparative evaluation, supporting environmentally informed management and optimization of chame aquaculture under tropical conditions. Although water quality represents a robust integrative indicator, it captures only one dimension of environmental performance, and additional factors such as production efficiency, energy use, and effluent characterization should be incorporated in future studies to achieve a comprehensive sustainability assessment.

Keywords: tropical aquaculture; pond-based systems; *Dormitator latifrons*; environmental performance; water quality; multivariate analysis

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1. Introduction

Tropical aquaculture has become an emerging activity worldwide, with a clear predominance of pond-based systems, both in terms of production volume and number of producers [1–3]. These systems contribute substantially to food sovereignty and rural income generation in developing countries and vulnerable rural communities [4,5]. However, their expansion and intensification have revealed structural tensions between increasing productivity and maintaining environmental performance, particularly in low-resource contexts with limited access to advanced technologies [6,7].

In aquaculture, environmental performance is closely linked to water quality dynamics due to the intensive use of water resources, the interaction between water and sediments, and the accumulation of nutrients and organic matter associated with feed inputs and biomass [6–9]. In tropical systems, these processes are intensified by climatic conditions that promote high metabolic rates and rapid chemical transformations, making water quality management a key challenge [6,7]. Water quality constitutes a functional integrator of the environmental performance of pond-based aquaculture systems as it simultaneously reflects the interaction between system design, management practices, organic loading, and the physical, chemical, and biological processes that regulate system functioning [10]. Unlike partial indicators, water quality directly responds to matter and energy fluxes associated with aquaculture production, synthesizing multiple dimensions of the environmental performance of the system [8,11,12]. From this perspective, environmental performance can be understood as the capacity of aquaculture systems to maintain adequate and stable water quality while managing waste without generating negative environmental impacts within the system or the surrounding ecosystem [6,8,9].

Key water quality parameters, such as dissolved oxygen, pH, temperature, alkalinity, conductivity, and inorganic nitrogen forms, are embedded in interaction networks governed by interconnected biogeochemical and biological processes [8,12]. In tropical systems, these interactions are particularly pronounced due to high temperatures and elevated metabolic activity, resulting in strong temporal and spatial variability in water quality parameters [10,13,14].

Water quality acts as an integrative indicator of environmental performance in pond-based aquaculture systems as it reflects the combined effects of system design, management practices, and underlying biogeochemical processes [15–17]. However, water quality parameters are typically evaluated individually using threshold-based approaches, despite their strong interdependence and joint response to management practices. This limitation becomes particularly relevant under real commercial conditions, where temporal variability and multicollinearity complicate interpretation [18,19].

Multivariate analysis provides a suitable framework for integrating multiple interdependent variables, allowing the identification of emergent patterns and functional gradients in complex systems [20]. In aquaculture, this approach has proven effective for discriminating production systems and synthesizing complex environmental information beyond traditional univariate analyses [19–21].

Tropical aquaculture systems provide a particularly suitable framework for evaluating environmental performance through multivariate water quality patterns, because of the coexistence of diverse production designs, intensification levels, and technological inputs under comparable environmental conditions [3,6,22]. Pond-based systems range from conventional low-technology schemes to more intensive and integrated systems, including recirculating aquaculture systems, aquaponics, and integrated production models, reflecting different relationships between technological control, resource use, and ecological functioning [1,4,23]. The use of native species tolerant to environmental variability, such as *Dormitator latifrons*, further supports the interpretation of system-level patterns by minimizing species-specific effects [24–26]. From this perspective, water quality can be understood as a practical and integrative proxy of environmental performance, reflecting the combined effects of system design, management practices, and ecological processes operating within aquaculture systems.

Despite these advances, studies integrating multiple physicochemical parameters under real commercial production conditions remain scarce in tropical pond aquaculture. To address this gap, the present study develops an integrative multivariate framework to identify reproducible water quality patterns as indicators of environmental performance across different tropical pond-based aquaculture systems. Accordingly, the objective of this study was to evaluate the environmental performance of different tropical pond-based aquaculture systems based on multivariate water quality patterns under real production conditions. This study contributes to the field by (i) applying a multivariate framework to characterize water quality patterns under real commercial conditions, (ii) identifying key physicochemical variables driving system differentiation, and (iii) providing an operational approach for the comparative assessment of environmental performance across tropical pond-based aquaculture systems.

2. Materials and Methods

2.1. Study Area and Experimental Design

This study was conducted in Manabí Province, Ecuador, a region characterized by a tropical climate with a mean annual temperature of approximately 25 °C, annual rainfall ranging between 838.7 and 2400 mm, and relative humidity values of 78% to 82% [27]. These conditions directly influence water quality dynamics in pond-based aquaculture systems by accelerating biogeochemical processes and increasing temporal variability in key physicochemical parameters.

Four production systems culturing *Dormitator latifrons* (chame) were evaluated to assess physicochemical water quality: (i) an aquaponic system (APS) implemented at the agricultural facilities of ESPAM-MFL, located in Bolívar Canton (UTM Zone 17S, WGS84; EPSG:32717: 590,589.90 m E, 9,908,726.07 m N); (ii) a recirculating aquaculture system (RAS) established in the agro-industrial area of ESPAM-MFL (UTM Zone 17S, WGS84; EPSG:32717: 590,544.52 m E, 9,908,698.78 m N); (iii) a conventional earthen pond system (CEP) located in the Bachillero–Tosagua area (UTM Zone 17S, WGS84; EPSG:32717: 586,168.84 m E, 9,915,021.26 m N); and (iv) an integrated rice–chame system (RCS) situated at the site known as "El Corozo", Calceta, in Bolívar Canton (UTM Zone 17S, WGS84; EPSG:32717: 591,893.85 m E, 9,905,909.84 m N) (Figure 1).

The study followed a comparative observational design aimed at evaluating pond-based aquaculture systems under real production conditions rather than controlled experimental settings. This approach allows the assessment of environmental variability associated with management practices and operational contexts, providing a realistic representation of system functioning.

The evaluated systems represented a gradient of intensification and technological input, enabling the comparison of environmental performance across different production models. Observational data collected throughout the production cycle allowed the identification of consistent multivariate water quality patterns reflecting system-specific dynamics. The basic unit of analysis was each individual water sample; however, the dataset had a hierarchical structure, with samples nested within sampling events, ponds, and production systems. Given the observational nature of the study and the objective of characterizing system-level water quality patterns under real commercial conditions, individual samples were treated as repeated observations contributing to the overall multivariate structure of each system rather than as fully independent experimental units.

Accordingly, the analytical approach focused on pattern recognition and system discrimination rather than on inference based on strictly independent replicates. This approach is consistent with previous studies that evaluated functional differentiation among systems based on multivariate analyses of multiple internal observations, allowing the identification of emergent patterns and system-level differentiation rather than inference based on strictly independent experimental units [7,20,21].

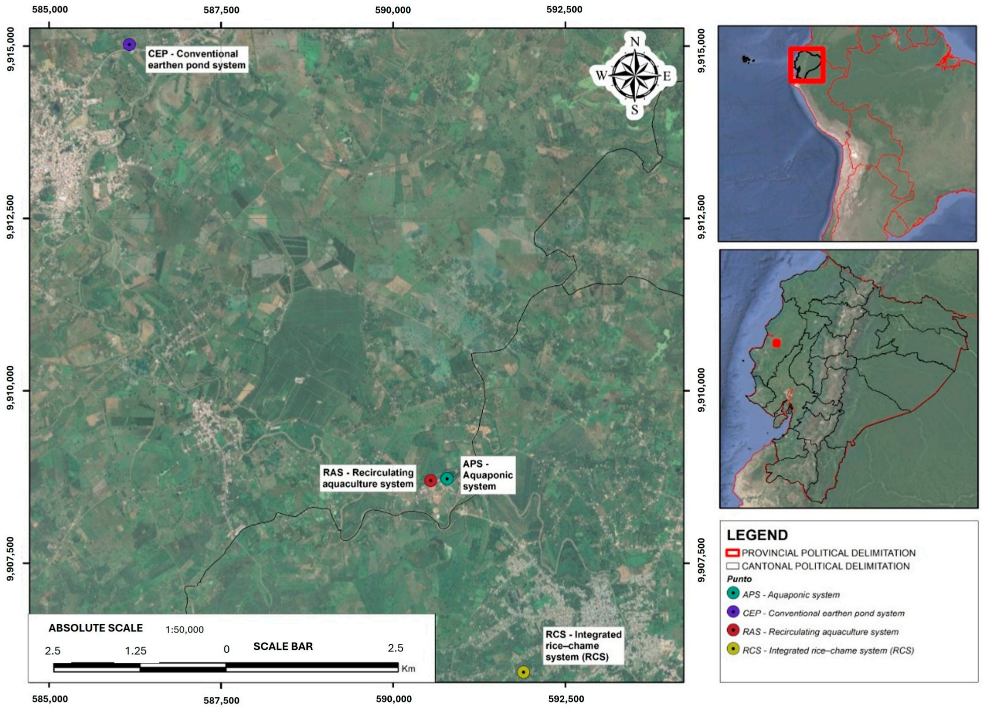

Figure 1. Geographic location of the four aquaculture systems considered in this study.

2.2. Production Systems and Animal Management

All experimental systems cultured chame (*Dormitator latifrons*), a native species widely used by rural communities in the study area, thereby reflecting the real operational and commercial conditions of each production modality [28]. Stocking densities ranged between 10 and 15 chame fingerlings m^{-3} in all ponds and tanks, and fish were reared during the production period from April to October 2024.

Fish were fed once daily with commercial feed, with rations adjusted weekly according to estimated biomass [29]. During the grow-out phase, a diet containing 22% crude protein was used, whereas a feed with 35% crude protein was supplied during the fattening phase. These protein levels are commonly applied in the culture of native and omnivorous tropical fish species in pond-based systems. In the conventional earthen pond system (CEP), feeding was conducted manually and evenly distributed, following the producer's usual practices, due to the pond size and operational constraints inherent to this type of system [24,26,30].

The aquaponic system (APS) consisted of 12 in-ground ponds lined with geomembrane, each with an approximate capacity of 1 m^3. The ponds were connected to a nutrient film technique (NFT) hydroponic module through a gravity-driven recirculation system assisted by a 1000 L·h^{-1} commercial water pump (Figure 2a). This configuration is consistent with previously described small-scale tropical aquaponic pond systems, in which water quality represents the functional core of fish–plant integration [31,32]. The cultivated plant species were lettuce (*Lactuca sativa*) and basil (*Ocimum basilicum*), both compatible with aquaculture production [32,33].

Figure 2. Ponds of the four chame (*Dormitator latifrons*) production systems evaluated: (**a**) aquaponic system (APS), (**b**) recirculating aquaculture system (RAS), (**c**) conventional earthen pond system (CEP), and (**d**) integrated rice–chame system (RCS). The figure illustrates the structural configuration, water flow, and main components of each system, including filtration units, plant integration (in APS), and water exchange dynamics. These systems represent different levels of intensification and technological input under real production conditions.

The recirculating aquaculture system (RAS) was consisted of 12 geomembrane-lined ponds with an approximate volume of 0.9 m^3 each (Figure 2b). Water treatment was conducted using a gravel and activated carbon filter, with a recirculation flow rate of 600 $L \cdot h^{-1}$ and an estimated hydraulic retention time of 1.7 h. Unlike the aquaponic system (APS), which integrates plant production as a biological nutrient removal component, the RAS operates as a closed recirculating system based exclusively on physical and microbial filtration processes without plant integration. The system configuration was consistent with standard small-scale RAS designs [34,35]. The conventional earthen pond system (CEP) was developed in two earthen ponds of 216 and 189 m^2, respectively, supplied with groundwater and oxygenated through gravity-driven water inflow via piping (Figure 2c), following common practices for tropical pond aquaculture [8,10].

The integrated rice–chame system (RCS) was implemented in a rectangular pond with an approximate capacity of 27 m^3. The pond was excavated and compacted, lined with geomembrane, and reinforced with a surface clay layer (Figure 2d). This system followed integrated rice–fish production principles previously described for tropical agro-aquatic systems [4,36,37].

All systems were operated under standard commercial management practices specific to each production model. This included routine feeding schedules, water exchange or recirculation regimes, and system-specific management strategies such as plant integration in aquaponic systems or water reuse in integrated systems. Management practices were maintained consistently within each system throughout the production cycle to reflect real operational conditions.

2.3. Water Sampling and Quality Parameters

Water quality monitoring was conducted twice per week during the morning and afternoon periods. Five water samples were collected per sampling event in each aquaculture system, following a predefined spatial sampling scheme, and subsequently analyzed in the laboratory. The monitored parameters are listed in Table 1 and were measured following procedures described in Standard Methods for the Examination of Water and Wastewater [38]. The full set of analyzed variables included pH, temperature, turbidity, salinity, alkalinity, dissolved oxygen, color, nitrites, phosphates, ammonium, total dissolved solids, total hardness, electrical conductivity, and chlorides.

Table 1. Physicochemical water quality parameters and analytical methods applied.

Parameter	Analytical Method [38]
pH	Potentiometry
Total dissolved solids (mg L^{-1})	Conductimetry
Temperature (°C)	Temperature probe
Dissolved oxygen (mg L^{-1})	Oximetry
Salinity (mg L^{-1})	Conductimetry
Electrical conductivity (mS cm^{-1})	Conductimetry
Turbidity (NTU)	Turbidimetry
Chlorides (mg L^{-1})	Spectrophotometry
Alkalinity (mg L^{-1})	Volumetric titration
Color (UPC)	Spectrophotometry
Nitrites (mg L^{-1})	Spectrophotometry
Phosphates (mg L^{-1})	Spectrophotometry
Ammonium (mg L^{-1})	Spectrophotometry
Total hardness (mg L^{-1})	Volumetric titration

Samples were systematically collected at fixed points within each pond or tank following an "English flag" spatial sampling scheme, widely used in aquatic system studies to capture horizontal variability and minimize biases associated with spatial heterogeneity within water bodies [10,12].

A total of 3544 water samples were collected at an approximate depth of 5 cm throughout the production cycle (April to October 2024), covering different production stages. Samples were processed, preserved, and transported according to the procedure described by Mera Velez and Vélez Espinosa [39]. Sample analyses were conducted at the Environmental Chemistry and Soils Laboratory of the Higher Polytechnic School of Agriculture of Manabí Manuel Félix López (ESPAM-MFL). Physical water parameters, including pH, temperature, total dissolved solids, and electrical conductivity, as well as dissolved oxygen, were measured in situ using a portable multiparameter probe and an oximeter (Hanna Instruments, Woonsocket, RI, USA). The remaining water quality parameters were determined following standardized laboratory methods detailed in Table 1.

2.4. Statistical Analysis

Prior to statistical analysis, data were examined for normality and homogeneity of variance. Water quality parameters were analyzed using descriptive and inferential statistical methods. Differences among production systems were assessed using one-way analysis of variance (ANOVA), with statistical significance set at $p < 0.05$. When significant effects were detected, mean values were compared using Tukey's Honest Significant Difference (HSD) post hoc test.

For chloride and phosphate concentrations, comparisons among APS, RAS, and RCS were performed using one-way ANOVA, as these parameters were only measured in these three systems due to the hydrological dynamics and biogeochemical characteristics of open pond systems with water exchange. When significant differences were detected, Tukey's HSD test was applied. This approach ensured methodological consistency across all analyzed variables. Pearson's correlation coefficients were calculated to evaluate the relationships among water quality parameters.

Multivariate discriminant analysis was performed to identify patterns of variation among production systems. Prior to the analysis, the assumption of homogeneity of covariance matrices was assessed using Box's M test. Variable selection was based on statistical criteria including Wilks' Lambda, Snedecor's F statistic, and tolerance values to avoid redundancy and multicollinearity. Variables with low tolerance (Tolerance = 1 − R^2) were carefully evaluated to minimize redundancy in the model. The discriminant functions were derived from standardized coefficients, allowing the identification of the relative contribution of each variable to group separation. The discriminant analysis was conducted using 3543 complete observations, as one case with incomplete information was excluded from the classification procedure. The discriminant analysis included the classification matrix, Mahalanobis distances to assess group separation, and canonical scatterplots to visualize the spatial distribution of water samples. Aquaculture system type (APS, RAS, CEP and RCS) was used as the grouping variable, and a direct variable entry method was applied with a significance threshold of $p < 0.05$. Model performance was assessed through cross-validation using the leave-one-out (LOOCV) method, providing an estimate of classification accuracy and robustness. The consistency of discriminant analysis outputs was verified across main results and Supplementary Materials to ensure transparency and reproducibility.

A list of abbreviations used throughout the manuscript is provided in Table 2. All statistical analyses were performed using Statistica 12.0 software for Windows (StatSoft Inc., Tulsa, OK, USA).

Table 2. Abbreviations used in the manuscript.

Abbreviation	Definition
APS	Aquaponic System
RAS	Recirculating Aquaculture System
CEP	Conventional Earthen Pond
RCS	Rice–Chame System
TDS	Total Dissolved Solids
DO	Dissolved Oxygen
LOOCV	Leave-One-Out Cross-Validation
ANOVA	Analysis of Variance
HSD	Honest Significant Difference

3. Results

3.1. Water Quality Patterns

All variables showed statistically significant differences among pond-based aquaculture systems (ANOVA, $p < 0.001$), particularly in electrical conductivity, total dissolved solids, and nutrient concentrations. More intensive systems (APS and RAS) exhibited lower values of conductivity and dissolved solids, whereas integrated and conventional systems (RCS and CEP) showed higher values and greater variability ($p < 0.001$) (Table 3). These differences highlight the contrasting environmental dynamics between intensive and integrated systems, reflecting distinct patterns of nutrient accumulation and water renewal. The APS and RAS exhibited significantly higher pH values and lower thermal variability compared with the CEP and RCS. In contrast, dissolved oxygen concentrations were significantly lower in APS and RAS, whereas the highest values were recorded in RCS and CEP.

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Table 3. Physicochemical water quality parameters measured in ponds from four aquaculture systems in Ecuador (mean ± SD and coefficient of variation).

Parameters	**Aquaculture Systems** [1] **APS (*n* = 1152)**	**RAS (*n* = 1152)**	**CEP (*n* = 840)**	**RCS (*n* = 400)**
pH	8.02 ± 0.01 (2.33) [b]	8.14 ± 0.01 (2.39) [a]	7.55 ± 0.01 (4.52) [d]	7.97 ± 0.01 (3.58) [c]
Total dissolved solids, mg/L	522.42 ± 2.54 (16.50) [c]	529.01 ± 2.44 (15.63) [c]	1928.42 ± 4.74 (7.12) [a]	808.13 ± 2.78 (6.87) [b]
Temperature, °C	27.07 ± 0.02 (2.44) [c]	26.35 ± 0.02 (3.12) [d]	28.99 ± 0.06 (5.61) [a]	28.08 ± 0.08 (5.41) [b]
Dissolved oxygen, mg/L	3.88 ± 0.01 (12.02) [d]	4.06 ± 0.02 (12.81) [c]	5.79 ± 0.09 (44.18) [b]	8.12 ± 0.08 (19.25) [a]
Salinity, ppm	644.25 ± 3.40 (17.91) [c]	638.07 ± 3.35 (17.81) [c]	2391.06 ± 4.65 (5.64) [a]	982.11 ± 2.81 (5.73) [b]
Electrical conductivity, mS/cm	1.00 ± 0.01 (17.91) [c]	0.99 ± 0.01 (17.79) [c]	3.74 ± 0.01 (5.71) [a]	1.52 ± 0.00 (5.73) [b]
Turbidity, NTU	10.89 ± 0.26 (82.46) [b]	4.22 ± 0.09 (70.42) [d]	6.38 ± 0.11 (51.79) [c]	20.34 ± 0.62 (61.19) [a]
Chlorides, mg/L	39.94 ± 0.95 (80.71) [c]	48.25 ± 0.62 (43.55) [b]	n.m.	107.33 ± 0.91 (17.05) [a]
Alkalinity, mg/L	65.71 ± 0.48 (24.69) [c]	79.96 ± 3.11 (132.21) [c]	163.37 ± 4.57 (81.05) [b]	797.00 ± 25.56 (64.14) [a]
Colour, Pt/Co	202.54 ± 2.83 (47.48) [a]	83.80 ± 1.70 (68.72) [b]	85.86 ± 1.57 (52.85) [b]	71.65 ± 4.20 (117.10) [c]
Nitrites, mg/L	1.15 ± 0.04 (130.15) [a]	0.13 ± 0.00 (54.66) [b]	0.82 ± 0.16 (560.40) [b]	0.03 ± 0.00 (31.41) [c]
Phosphates, mg/L	12.56 ± 0.14 (38.05) [a]	8.73 ± 0.02 (9.69) [b]	n.m.	2.00 ± 0.04 (44.90) [c]
Ammonium, mg/L	2.08 ± 0.06 (94.24) [b]	0.59 ± 0.01 (45.75) [d]	2.49 ± 0.06 (70.77) [a]	1.32 ± 0.03 (40.70) [c]
Total hardness, mg/L	521.37 ± 3.26 (21.22) [b]	488.43 ± 4.40 (30.58) [c]	1663.39 ± 13.31 (23.18) [a]	375.89 ± 8.95 (47.63) [d]

[1] APS = Aquaponic System; RAS = Recirculation System; CEP = Conventional System; RCS = Integrated Rice–Chame System; a, b, c, d superscript letters indicate significant differences among species ($p < 0.05$); n.m. = not measured in the conventional earthen pond system (CEP).

Regarding ionic water load, the CEP presented the highest concentrations of total dissolved solids, salinity, and electrical conductivity, followed by RCS, whereas APS and RAS showed significantly lower and statistically similar values. Turbidity differed significantly among systems, with higher values observed in APS and RCS and the lowest turbidity levels recorded in the RAS.

Regarding inorganic nutrients, APS showed the highest concentrations of nitrites, phosphates, and ammonium, whereas RAS maintained the lowest levels of nitrogenous compounds. Finally, total alkalinity and total hardness were significantly higher in the CEP and RCS, clearly differentiating them from APS and RAS ($p < 0.001$). These differences were accompanied by a greater dispersion of values associated with these parameters. Overall, high intra-system variability was observed for most of the water quality variables evaluated.

Correlation analysis among water quality variables revealed a marked mineralization gradient (Table S1). Total dissolved solids (TDS), electrical conductivity, and salinity showed very strong positive correlations with each other ($r \geq 0.98$), as well as with total hardness, indicating that these variables are governed by common physicochemical control associated with dissolved salt and mineral concentrations. In contrast, pH exhibited moderate to strong negative correlations with these variables (r ranging from -0.59 to -0.68). Water temperature showed a moderate relationship with dissolved oxygen, reflecting the expected thermal effects on oxygen solubility. Inorganic nutrients (nitrites and ammonium) did not show significant ($p > 0.05$) correlations with most of the parameters analyzed.

3.2. Discriminant Analysis of Water Quality Parameters

The assumption of homogeneity of covariance matrices was assessed using Box's M test, supporting the validity of the discriminant analysis. The discriminant analysis generated three canonical functions, with the first function explaining 88.47% of the discriminant variance and the second function explaining 5.21%. Together, these two functions accounted for 93.68% of the total variance, indicating that most of the group separation was captured by the first two canonical roots. The first canonical function was primarily defined by total dissolved solids, nitrites, electrical conductivity, salinity, and temperature, indicating a gradient associated with mineralization and dissolved load. The second canonical function was mainly associated with electrical conductivity, color, phosphates, nitrites, and dissolved oxygen, reflecting a gradient related to nutrient dynamics and oxygen conditions.

Discriminant analysis revealed a strong and consistent separation among the four pond-based aquaculture systems based on their physicochemical water quality profiles, achieving cross-validated classification accuracy of 94.64%. These results confirm the existence of reproducible system-specific water quality signatures associated with differences in environmental performance. All variables included in the model contributed significantly ($p < 0.001$) to system discrimination, as indicated by very low Wilks' lambda values and highly significant F-tests (Table 4).

Table 4. Discriminant functions of physicochemical water quality parameters in four pond-based aquaculture systems in Ecuador.

Parameters	Wilks' Lambda	Partial Lambda	F-Remove	*p*-Level	Toler	1-Toler
Electrical conductivity	0.00	0.99	9.99	<0.001	0.01	0.99
Alkalinity	0.00	0.77	354.19	<0.001	0.87	0.13
Phosphates	0.00	0.83	241.20	<0.001	0.92	0.08
Chlorides	0.00	0.78	328.78	<0.001	0.90	0.10
Colour	0.00	0.76	369.63	<0.001	0.74	0.26
Total dissolved solids	0.00	0.68	564.08	<0.001	0.48	0.52
Dissolved oxygen	0.00	0.87	179.33	<0.001	0.79	0.21
Nitrites	0.00	0.82	253.04	<0.001	0.52	0.48
Turbidity	0.00	0.85	199.39	<0.001	0.78	0.22
Temperature	0.00	0.82	254.61	<0.001	0.87	0.13
pH	0.00	0.88	159.13	<0.001	0.89	0.11
Ammonium	0.00	0.94	78.73	<0.001	0.85	0.15
Total hardness	0.00	0.97	36.62	<0.001	0.80	0.20
Salinity	0.00	0.99	6.67	<0.001	0.01	0.99

Among the analyzed variables, total dissolved solids, colour, chlorides, turbidity, phosphates, nitrites, and temperature exhibited the highest discriminant power, as indicated by their high F-remove values, reflecting their strong contribution to differentiating water quality patterns among pond-based aquaculture systems. Dissolved oxygen and pH showed intermediate contributions to group separation. In contrast, variables such as, ammonium, total hardness, electrical conductivity, and salinity showed comparatively lower discriminant contributions, although they remained statistically significant. Tolerance analysis revealed collinearity among electrical conductivity, salinity, and total dissolved solids, which is consistent with their shared physicochemical control and association with water mineralization processes.

The classification matrix, based on 3543 complete observations, indicated a high overall correct classification rate (94.64%), confirming the robustness of the discriminant model (Table 5). The integrated rice–chame system (RCS) achieved 100% correct classification, whereas the conventional earthen pond system (CEP) reached 99.88%, indicating highly consistent physicochemical signatures for these systems. The aquaponic (APS) and recirculating aquaculture systems (RAS) also showed high classification accuracy, with only minor misclassifications between these two systems.

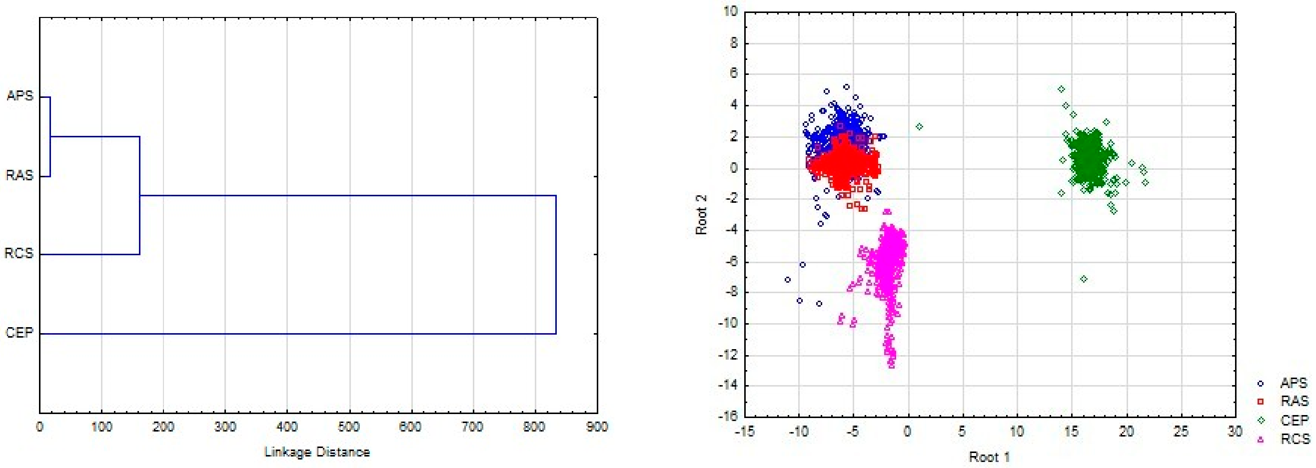
Table 5. Classification matrix of physicochemical water quality parameters for four pond-based aquaculture systems in Ecuador.

System [1]	Percent	APS	RAS	CEP	RCS
APS	84.81	977	171	0	4
RAS	98.78	14	1138	0	0
CEP	99.88	1	0	838	0
RCS	100.00	0	0	0	400
Total	94.64	992	1309	838	404

[1] APS = Aquaponic system; RAS = Recirculation system; CEP = Conventional system; RCS = Integrated rice–chame system. The classification matrix was based on 3543 complete observations; one observation from CEP was excluded due to incomplete data in the discriminant analysis.

All discriminant analysis outputs, including eigenvalues, canonical correlations, and classification results, were cross-checked to ensure internal consistency across tables, figures, and Supplementary Materials. Overall, the discriminant functions supported a strong capacity to distinguish pond-based aquaculture systems based on integrated water quality patterns, supporting the use of multivariate approaches to evaluate differences in environmental performance among production models.

Cluster analysis revealed two main groups among the evaluated pond-based aquaculture systems. The conventional earthen pond system (CEP) was clearly separated at a high linkage distance, indicating a markedly distinct multivariate water quality profile. In contrast, the aquaponic system (APS) and the recirculating aquaculture system (RAS) clustered together at a very low linkage distance, reflecting their high degree of similarity. The integrated rice–chame system (RCS) joined this cluster at a higher linkage distance, indicating that although it shares certain characteristics with more intensive systems, it maintains distinct features (Figure 3a).



(**a**) (**b**)

Figure 3. (**a**) Cluster analysis based on Mahalanobis distances and (**b**) scatterplot of individual observation scores obtained from the canonical discriminant functions using physicochemical water quality parameters of four pond-based aquaculture systems in Ecuador. APS: aquaponic system; RAS: recirculating aquaculture system; CEP: conventional earthen pond system; RCS: integrated rice–chame system. Each point represents an individual water sample. Colors indicate the different

production systems (APS, RAS, CEP, and RCS). The axes correspond to the first and second canonical functions. The separation among groups reflects differences in multivariate water quality patterns among systems.

Canonical discriminant analysis further confirmed a clear separation among pond-based aquaculture systems. The conventional earthen pond system (CEP) was completely segregated along the first canonical root, indicating a markedly different physicochemical profile. The integrated rice–chame system (RCS) formed a distinct cluster primarily separated along the second canonical root, highlighting its unique characteristics relative to APS and RAS, which exhibited partial overlap in the canonical space (Figure 3b).

4. Discussion

4.1. Water Quality Patterns and Intensification Gradient in Tropical Pond-Based Systems

The combined application of variance and discriminant analysis confirmed the existence of structural differences among tropical pond-based aquaculture systems, expressed through consistent and system-specific water quality patterns. While one-way ANOVA and post hoc tests revealed significant differences in most individual physicochemical parameters, discriminant analysis integrated this multivariate information and supported that each pond-based aquaculture system exhibited a characteristic physicochemical signature associated with its design and management practices. These findings indicated that water quality patterns can function as system-level descriptors of environmental performance more efficiently than isolated or univariate measurements.

The high classification accuracy of the discriminant model indicates that observed differences were not driven by isolated fluctuations in single variables but rather by relatively stable functional configurations determined by interactions among water use, organic loading, chemical processes, and management strategies. In this context, water quality acts as an integrative indicator synthesizing multiple dimensions of environmental system functioning, including resource-use efficiency, nutrient assimilation capacity, and control of potential environmental impacts [8,9,12].

The use of water quality as an indicator of environmental performance in aquaculture is widely supported in the literature, as it is directly linked to both the welfare of cultured organisms and the ecological stability of the pond-based aquaculture system [4,6,7]. The multivariate patterns identified here provide an operational framework for comparative environmental performance assessment in tropical pond systems under commercial conditions.

The identified water quality patterns reflect a clear gradient of production intensification and environmental control among the evaluated pond-based aquaculture systems. Conventional earthen pond systems (CEP) and integrated rice–chame systems (RCS) largely rely on natural ecological processes and strong water–sediment interactions, whereas more technologically intensive systems, such as aquaponics (APS) and recirculating aquaculture systems (RAS), incorporate hydraulic and biological control mechanisms aimed at stabilizing physicochemical water conditions.

In lower-intensification systems (CEP and RCS), water quality was primarily driven by the natural dynamics of the aquatic ecosystem, resulting in greater temporal and spatial variability and increased accumulation of dissolved salts and nutrients. These patterns have been widely described for extensive and semi-intensive tropical systems [8,10,11]. Nevertheless, such pond-based aquaculture systems often exhibit high buffering capacity and a degree of resilience derived from their integration with local ecological processes [4].

In contrast, APS and RAS exhibited a higher degree of technical control over the aquatic environment through recirculation, filtration, and aeration. This enhanced control reduces the accumulation of solids and nitrogenous compounds but increases dependence on operational management, biofilter efficiency, and the balance between organic loading and treatment capacity. When these elements are not properly adjusted, functional limitations may arise despite the technological sophistication of pond-based aquaculture systems [40–42].

Discriminant analysis positioned APS and RAS in close proximity within the multivariate space, reflecting structural similarities associated with recirculation and hydraulic control, whereas CEP and RCS were clearly differentiated from each other and from the technologically intensive systems. This pattern indicates that, in addition to the level of intensification, the type of productive integration and the degree of interaction with the sediment play a key role in shaping water quality patterns [11,12]. From a sustainability perspective, these results highlight trade-offs between environmental control, technological dependence, resource use, and system resilience [5,6]. Rather than indicating the superiority of a specific model, the patterns illustrate how different configurations redistribute environmental pressures within the pond-based aquaculture system.

From a multivariate perspective, the observed patterns result from the combined and interdependent effects of multiple physicochemical variables rather than isolated parameter responses. In pond-based aquaculture systems, variables such as dissolved solids, nutrient concentrations, and oxygen dynamics are functionally linked through biogeochemical processes, including organic matter decomposition, nutrient cycling, and microbial activity. Therefore, the discriminant functions do not represent single-variable effects but integrated gradients reflecting system-level processes, where the relative contribution of each variable emerges from their combined interactions within the production environment.

From a conceptual standpoint, these interactions can be simplified through functional relationships among key variables. For example, dissolved oxygen dynamics can be expressed as: DO = f (T, BOD), where DO represents dissolved oxygen concentration, T is water temperature, and BOD represents biological oxygen demand associated with organic matter decomposition and microbial activity. Similarly, nutrient dynamics within pond-based aquaculture systems can be approximated as: $N_{\text{total}} = N_{\text{input}} - N_{\text{assimilation}} - N_{\text{loss}}$, where N_{input} corresponds to nutrient loading (e.g., feed and excretion), $N_{\text{assimilation}}$ represents biological uptake by microorganisms or plants, and N_{loss} includes processes such as sedimentation, volatilization, and denitrification. These simplified relationships support the interpretation of discriminant functions as integrative expressions of underlying system processes.

The differences observed among production systems result from the combined action of physical, chemical, and biological processes rather than from the isolated influence of individual parameters. In this study, three key processes were identified as determinants of the observed multivariate patterns: (i) thermal and dissolved oxygen regulation, (ii) mineralization and ionic balance, and (iii) nutrient transformation and fate.

Water temperature and dissolved oxygen, which are closely interrelated, directly influence fish metabolism and the rates of biogeochemical processes. In open and semi-natural systems (CEP and RCS), greater exposure to solar radiation promoted higher thermal variability and, indirectly, a wider range of dissolved oxygen concentrations, which are associated with photosynthesis and respiration processes [8,13]. In contrast, APS and RAS exhibited greater thermal stability but lower mean dissolved oxygen concentrations, associated with high biological demand resulting from recirculation and nitrification processes [41,43].

The mineralization gradient constituted one of the main axes of differentiation among pond-based aquaculture systems. In CEP and RCS, the accumulation of dissolved salts and minerals was associated with prolonged water–sediment contact and limited water renewal, increasing system buffering capacity and overall mineralization levels [10,11]. Conversely, in APS and RAS, pond impermeabilization and hydraulic control reduced direct substrate influence, resulting in lower and more homogeneous mineralization values, although still dependent on inflow water quality and management practices [34,42].

Nutrient dynamics reflected the balance among excretion, organic matter mineralization, nitrification, and biological assimilation. Low ammonium and nitrite concentrations in RAS indicate efficient biofilter-driven nitrification [43], whereas in CEP nutrient accumulation was associated with organic matter mineralization within sediments under conditions of limited water exchange [8,11]. In APS, elevated inorganic nutrient concentrations indicate limitations in nitrogen conversion and export processes, whereas in RCS, reduced nitrite levels highlight the role of crop cultivation as an active nutrient sink [33,36,44]. These differentiated nutrient pathways reinforce the interpretation of water quality as a functional expression of pond-based aquaculture system metabolism.

The integrated and semi-closed systems evaluated in this study exhibited distinct water quality patterns that reflect their specific environmental functioning and intermediate position along the intensification gradient. The integrated rice–chame system showed a physicochemical profile clearly differentiated from conventional earthen ponds, as confirmed by discriminant analysis, highlighting the functional role of rice cultivation as an active component in regulating the aquatic system. Nutrient assimilation by plant biomass and the influence of the rhizosphere on microbial processes contributed to modifying nutrient availability and buffering nutrient accumulation [4,36].

Aquaponic systems exhibited partial nutrient removal but also elevated turbidity and nutrient coexistence, indicating that integration efficiency strongly depends on hydraulic balance, biofilm performance, and plant uptake capacity [31,33,44]. These findings indicate that integration alone does not automatically enhance environmental performance; its effectiveness depends on the degree of functional coupling among biological components.

From a regulatory perspective, water quality in aquaculture systems is commonly evaluated against national and international environmental standards that define acceptable limits for physicochemical parameters and effluent discharge. In Ecuador, the Unified Text of Secondary Environmental Legislation (TULSMA) establishes reference thresholds for water quality and discharge into natural water bodies. Although the present study was not designed to directly assess regulatory compliance, the observed ranges of key parameters such as dissolved oxygen, pH, and nutrient concentrations provide a useful basis for comparison with these standards.

The results suggest that water quality conditions varied among systems according to their level of intensification and management practices, which may influence their potential compliance with environmental regulations, particularly in relation to nutrient accumulation and oxygen dynamics. These findings highlight the importance of integrated water quality monitoring as a tool not only for system optimization but also for aligning aquaculture practices with environmental legislation and sustainability frameworks.

4.2. Sustainability Implications, Management Strategies, and Study Limitations

Our findings indicate that the environmental performance of pond-based aquaculture systems is reflected in integrated water quality patterns that capture the combined functioning of the production system. The complementary application of ANOVA and discriminant analysis showed that each production model exhibits a distinct physicochemical signature associated with its design, level of intensification, and management strategies. This result, derived directly from empirical evidence, indicates that water quality constitutes an operational and comparative indicator of environmental performance under real production conditions, consistent with established sustainability concepts in aquaculture [4,6–8].

However, it should be noted that water quality represents only a partial dimension of environmental performance; therefore, results should be interpreted as a proxy of environmental performance rather than a comprehensive sustainability assessment. In this context, the identified multivariate patterns allow inference of trade-offs among environmental control, system stability, resource use, and technological dependence, which are widely recognized in recent sustainability assessments of pond-based aquaculture systems [5].

Based on the results obtained and in agreement with the specialized literature, a set of general management recommendations can be proposed for tropical pond-based aquaculture systems. First, water quality monitoring should adopt integrated approaches that simultaneously consider variables related to oxygen dynamics, temperature, mineralization, and nutrient balance, moving beyond traditional univariate assessments [10,20]. Second, the management of organic loading and the balance between system inputs and assimilation capacity emerge as a critical factor to prevent progressive nutrient accumulation and environmental degradation, particularly in systems with limited water renewal [8,11].

The results further highlight the importance of adapting management strategies to each pond-based aquaculture system, rather than applying generalized solutions with limited effectiveness. Environmental performance depends not only on structural pond-based aquaculture system design but also on coherence among intensification level, technological availability, and the operational capacity of producers, as emphasized in recent frameworks for sustainable aquaculture governance and management [5,6]. Sustainability also emerges from the interaction between pond-based aquaculture system design, management decisions, and local operational constraints [45].

In conventional earthen pond systems (CEP), the observed patterns indicate high mineralization and a strong influence of water–sediment interactions. In these pond-based aquaculture systems, practices such as strategic water exchange, organic load control, sediment management, and supplemental aeration may contribute to improving water quality stability and reducing the risk of environmental degradation [8,10]. These recommendations are consistent with the results of this study, in which salt and nutrient accumulation was associated with limited environmental control capacity.

In recirculating aquaculture systems (RAS), the low concentrations of nitrogenous compounds observed confirm the efficiency of biofiltration processes, while simultaneously highlighting the high oxygen demand associated with nitrification and microbial respiration. Accordingly, optimization of aeration, regular maintenance of biofilters, and adjustment of pH and alkalinity are key practices to sustain environmental performance in these pond-based aquaculture systems [41–43].

In aquaponic systems (APS), the identified patterns indicant that fish–plant integration does not automatically result in improved water quality. The literature indicates that the success of these systems depends on a precise balance among organic loading, plant assimilation capacity, and microbial efficiency [32,33]. In this sense, the present results point to the need to reinforce mechanical filtration, optimize fish–plant ratios, and maintain physicochemical conditions compatible with the simultaneous requirements of fish, plants, and nitrifying bacteria.

In integrated rice–chame systems (RCS), the clear functional differentiation observed supports the role of rice cultivation as an active nutrient sink and a modulator of system dynamics. Previous studies have highlighted that appropriate management of irrigation, sediment, and cropping calendars is essential to maximize the environmental benefits of these systems without compromising aquaculture productivity [4,32]. The results confirm that such pond-based aquaculture systems can enhance environmental performance, provided that a balanced integration between both productive components is maintained.

These findings contribute to the advancement of sustainability research in aquaculture by emphasizing the value of multivariate approaches over univariate assessments when comparing pond-based aquaculture systems, as they effectively capture structural patterns emerging from interdependent environmental processes. Comparative analyses conducted under real-world commercial conditions provide important insight into operational heterogeneity that may remain undetected in highly standardized experimental settings. Furthermore, the integration of discriminant techniques with other statistical procedures, such as structural equation modeling (SEM), can enhance the robustness and transferability of sustainability indicators across different contexts. This research was conducted under real-world commercial production conditions, which inherently involve variability in management intensity, hydraulic configurations, and operating timeframes across systems. While this design enhances ecological validity and external relevance, it may limit strict experimental comparability. The assessment focused on physicochemical water quality parameters; additional sustainability dimensions, such as production output, energy consumption, effluent characterization, and the relationship between water quality and fish performance, were beyond the scope of the present study. Future research integrating these complementary indicators could provide a more comprehensive multidimensional evaluation of sustainability in tropical pond-based aquaculture systems. In addition, the hierarchical structure of the data (samples nested within ponds and systems) may introduce potential pseudoreplication effects, as individual samples are not fully independent. Therefore, the results should be interpreted primarily in terms of pattern recognition and system-level differentiation rather than strict inferential comparisons. Future studies should incorporate mixed-effects or hierarchical modeling approaches to explicitly account for nested data structures and disentangle system, site, and water-source effects. Although the observational design may limit strict experimental comparability, it enhances the ecological validity of the results and reflects real-world production conditions.

5. Conclusions

Tropical pond-based aquaculture systems exhibit clear structural differences in water quality associated with production design, level of intensification, and management strategies. The combined application of analysis of variance and discriminant analysis allowed the identification of consistent multivariate patterns that characterize each pond-based aquaculture system, supporting the use of water quality as a proxy and operational indicator of environmental performance under real production conditions.

The results highlight that system performance depends on the balance among physical, chemical, and biological processes, particularly those related to mineralization, nutrient dynamics, and oxygen regulation. Conventional and integrated systems were more strongly influenced by natural ecological processes, whereas technologically intensive systems showed greater environmental control but higher dependence on management and operational efficiency.

This study has some limitations, as it focuses on water quality without incorporating other relevant dimensions, such as production yield, energy use, effluent characterization, or the relationships between water quality and fish performance. In addition, the observational design and hierarchical data structure may impose constraints on strict statistical independence. Future research should integrate these components and apply hierarchical analytical approaches to improve system-level assessments and extend the applicability of the proposed framework.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18073309/s1, Table S1. Pearson correlation coefficients among physicochemical parameters in aquaculture pond systems in Ecuador.

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