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Comparative Analysis of Environmental Parameters and Growth Performance of Orange-spotted Grouper (Epinephelus coioides) in RAS, Earthen Ponds, and Natural Habitats: Integrating Water Quality, Soil Chemistry, and Heavy Metal Dynamics

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GROWTH rates in fish and aquaculture systems are impacted by environmental parameters and contaminants. A complete growth model was constructed for Orange-spotted Grouper (Epinephelus coioides) by assimilating water quality and heavy metals toxicity effects in three production systems: recirculating aquaculture systems (RAS), earthen ponds, and natural habitats of the Red Sea. The model involved water quality features (temperature, dissolved oxygen, pH, electrical conductivity), soil (pH, EC, CEC, exchangeable cations), and heavy metals (Hg, Cd, Pb, Cr, Cu, Zn). With regard to validation, the model accuracy was remarkable across growth phases, $R^2 > 0.999$, with phase-wise precision highest with fingerlings (RMSE: 0.53g, MAPE: 1.28%), and juveniles (RMSE: 6.12g, MAPE: 1.41%). Environmental parameters have distinct bases: temperature optimal range 27.5 ± 0.5°C with growth reductions of 45% and 52% at 22.3°C and 31.8°C respectively, dissolved oxygen optimal levels above 6.5 mg/L with growth cessation below 4.8 mg/L. Heavy metal toxicity exhibited element-specific patterns: mercury had the greatest toxicity (CT=0.14 mg/l 70% reduction), followed by cadmium (CT=0.17 mg/l) while zinc demonstrated the lowest (CT=0.80 mg/l 40% reduction). The comparison found that each system had its own particular advantages. Ponds scored lower on energy use and operational expenditures by 61.6% and 14.3% respectively, and also grew faster, achieving a 15-25% higher growth rate along with 16.7% improved FCR. RAS contrarily outperformed with its renewable natural resources. Natural areas gave optimization data for the environment. The model was able to predicted synergistic effects among environmental controls especially the interactions of dissolved metals and pH, temperature and oxygen, as well as soil and water in earthen ponds. These results have important implications for improving aquaculture management systems through system specific environmental regulation to achieve higher productivity levels while reducing the impact on the environment in marine aquaculture systems.

Keywords: Growth modeling; Heavy metal toxicity; Environmental interactions; Aquaculture management; Epinephelus coioides; Water quality parameters; Production systems; Soil-water interactions.

1. Introduction

The aquaculture of orange-spotted grouper (Epinephelus coioides) has an economic value close to $85 million and produces over 12,000 metric tons each year, making it one of the most important components of the marine fisheries in the Red Sea region (Ranjan et al., 2017; Rimmer & Glamuzina, 2019; FAO 2023). Ensuring the quality of the environment, however, remains an ever-lasting struggle (Boyd, 2017; Ybanez & Gonzales, 2023). Apart from their high market value, the species also have excellent growth rates and adaptability to extensive culture systems, which increases their significance towards aquaculture. Special care must be taken with the possibility of heavy metal contamination, but novel approaches utilizing microbial bioremediation strategies offer sustainable solutions. Issues like these pose a challenge towards sustainable husbandry. Most traditional approaches to aquaculture management design, however, treat each parameter as a single entity instead of integrating the intricate surround systems (Sarà et al., 2018). This is becoming a limitation as the scales of operations grow and become more complex, as well as raising further concerns regarding sustainability of the environment and efficiency of production (Frankic & Hershner, 2003; Edwards, 2015).

The advent of recirculating aquaculture systems (RAS) has given rise to new challenges in which maintenance of conditions necessary for the growth of fish populations is blended with treatment of metabolites and contaminants (Olaussen, 2018; Canosa & Bertucci, 2023). It is important to also assess the wider ecology associated with nanomaterials. One needs to evaluate the engineered nanoparticles' worth in soil ecosystem

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health and biodiversity, as mentioned by Gupta et al. (2024), in nanoecology. Assessment of such criteria would be necessary in a long-term sustainability perspective of aquaculture practices involving nanomaterials. Environmental parameters restrict the fish to grow at different developmental stages (Das et al., 2021). In an earthen pond, soil turns out to be the producer of some water quality and nutrient cycling (Boyd, 2017) as relied on soil and water chemistry and biological productivity with parameters such as soil pH, CEC, and exchangeable cations that directly act on system stability and fish growth performance (Yusoff et al., 2024). The feed intake and metabolism are directly associated with temperature. The specific thermal optima for different phases differ for fry (26 – 30 ºC) and adults (25 – 28 ºC) (De et al., 2019; Xavier et al., 2021).

Heavy metal contamination is another aggravating factor since growing concentrations are being reported in coastal locations of the Red Sea (El-Moselhy et al., 2014; El-Metwally et al., 2019; Nour & Garoub, 2024). Metallic forms interact very complexly with water quality parameters being pH-dependent bioavailability (El Nemr et al., 2016; Yusoff et al., 2024) and temperature-dependent toxicity (Saleh, 2021; Al-Mutairi & Yap, 2021). Knowledge gaps in existing quantitative studies on the interactions of parameters across growth stages are still present (Klinger et al., 2017; Raposo, 2024). Although simultaneous isolated effects are well documented, combined simultaneous isolated effects have not yet been understood well, especially when modeling growth responses under diverse conditions (Neill et al., 2004; Yamuna et al., 2023).

This research intended to establish a relatively new complete predictive model that integrates phase-specific growth responses by environmental parameter interaction and heavy metal toxicity effects (Rimmer et al., 2004; Glamuzina & Rimmer, 2022). The main objectives of such study include the quantification of critical threshold and identifying patterns of metal-specific toxicities as well as comparisons between growth performance in natural habitats versus RAS (Badr et al., 2009; Kahal et al., 2018; Lonthair et al., 2020; Read & Fernandes, 2003; Robitzch et al., 2023). According to the guidelines provided by the evidence, such guidelines will establish a sustainable production method balancing maximum performance growth and the environment.

2. Materials and Methods

2.1. Study Species and Production System

The study investigated the growth of Orange-spot Grouper (Epinephelus coioides) among three dissimilar production systems-those of natural marine habitat, recirculating aquaculture systems (RAS), and the earthen fish ponds. Research was conducted along the Saudi Arabian coast of the Red Sea, comprising sites with representations from each production system.

2.1.1. Study Sites and System Characterization

Studies in natural habitats were centered around three coastal sites: northern region near Duba (27°21'N, 35°42'E), central region near Jeddah (21°29'N, 39°11'E), and southern region near Jizan (16°52'N, 42°35'E). These sites represented different coastal marine environments, with depths typical for Orange-spotted Grouper ranging between 5 and 30 meters. The RAS was located in Jeddah and comprised six independent units, each consisting of four circular tanks (5 m diameter x 1.5 m depth with a total filling water volume of 25 m³). Water treatment included multi-stage filtration using drum filters, protein skimmers, moving bed bioreactors followed by UV sterilization and a heavy metal removal system. The earthen pond system comprises twelve 0.5-hectare ponds located in the coastal region near Jeddah (21°27'N, 39°10'E). Ponds were made according to standard engineering specifications presenting a slope of 1:2 and an average depth of 2.0 m. The soil texture was described as sandy loam with an average value of organic matter of 2.3%. Ponds consist of separating water intake and drainage systems: water collected directly from the Red Sea, through the settling reservoir system.

2.1.2. Water and Soil Monitoring

The study monitored two main kinds of parameters-water quality and soil characteristics. Water quality parameters were: physical properties (temperature, dissolved oxygen, electrical conductivity); chemical properties (pH and alkalinity); ionic composition, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}; and heavy metals (Hg, Cd, Pb, Cr, Cu, Zn). For earthen ponds, soil analyses concentrated on chemical properties (pH and electrical conductivity), exchange properties (CEC and exchangeable Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), and organic matter. These parameters were selected for monitoring since they directly relate to fish growth and the stability of a given production system as well as their ability to interact with each other in the aquaculture environment. The Sodium Adsorption Ratio (SAR) was calculated to evaluate the potential for interaction of the soil-water in case of earthen ponds. Environmental monitoring of all production systems was done comprehensively with utmost care and precise instruments and followed standardized analytical procedures. The fundamental water quality parameters were continuously monitored with use of an integrated sensor network. The temperature was recorded every 15 minutes with the use of digital temperature loggers with an accuracy of ±0.1°C, while dissolved oxygen was measured using optical DO probes with automated compensation for the temperature and salinity effects attached to them. Multi-parameter probes, calibrated on a daily basis, simultaneously filled in pH and electrical conductivity accuracies of ±0.01 pH units and ±0.1 mS/cm respectively.

The heavy metal concentrations were measured weekly using inductively coupled plasma mass spectrometry (ICP-MS), with a detection limit of 0.01 mg/L. For the earthen pond system, water chemistry assessments were carried out for the ionic composition and the water quality parameters important for soil-water interactions. Weekly sampled analyses were water samples for major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and main anions (CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}), and the concentrations reported as meq/L. Total alkalinity was determined by titration, and Sodium Adsorption Ratio (SAR) was calculated as:

$SAR = \mathrm{Na^+} / \sqrt{\left((\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}) / 2 \right)}$ (Richards, 1954). Ionic balance was confirmed for all samples to ascertain that the sum of cations equaled the sum of anions, within acceptable analytical error limits. Soil analysis in the earthen ponds was based on a systematic procedure that was aimed at characterizing the physical and chemical properties that enhance water quality and fish production. Composite soil samples were taken from five standard spots in each pond (inlet, centre, two sides, and an outlet) using a core-type auger penetrating a depth of 15 cm. pH was determined from the saturated paste of soils using a 1:2.5 soil:water ratio. Electrical conductivity was determined from the saturated extract of soils, while organic matter was estimated using the modified Walkley-Black method. Cation Exchange Capacity (CEC) was assessed by the ammonium acetate method. The exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were analyzed to obtain the value of Soil SAR and thus assess soil-water interactions taking place. Air-drying, grinding, and sieving through a 2mm sieve were done on each composite sample for further analysis. Quality control measures for soil analysis included duplicate analyses of 10% of samples and the validation of standard reference materials.

The monitoring program implemented stringent quality assurance protocols to monitor quality across any other stages of the analytical processes. Water sampling utilized standard methods of collection, preservation, and analysis, while in-situ measurements for temperature, DO, pH, and conductivity were made at each specific sampling occasion (Boyd & Tucker, 2014). The laboratory analyses included not less than basic quality control measures in every analysis, like duplicate samples, standard solutions, and analytical blanks. The calibration of monitoring equipment was conducted weekly, while maintenance was done on a monthly basis to guarantee credibility in measurement and consistency in data during the study period. Continuous parameters were recorded by automated data logging systems, while occasional manual cross-verification and calibration were carried out on these sets of data. Such a comprehensive monitoring procedure provided a highly credible environmental dataset characterizing the performance of all three production systems and establishing the ground for detailed comparative analysis of the operational performance of these systems and the environment concerning fish growth and development.

2.2. Aquaculture Facilities

The study used an indoor RAS in Jeddah, consisting of six independent units of four circular tanks (5 m diameter, 1.5 m depth, 25 m^3 volume) in parallel configuration. Water treatment consisted of multi-stage filtration: automated drum filters (40 μm), protein skimmers, moving bed bioreactors (850 m^2/m^3), UV sterilization (80 mJ/cm^2), with heavy metal removal via activated carbon and ion-exchange units (<0.01 mg/L detectable limit). Temperature (27±1°C for titanium heat exchangers), dissolved oxygen (above 6.0 mg/L, oxygen injection and air diffusion), pH 7.8-8.2 (controlled by CO_2 degassing and calcium buffering), and salinity (35±1 ppt) have environmental control of the system. Daily water exchange was 300%. Parameters were continuously monitored in a SCADA-based centralized system: temperature (±0.1°C), DO (±0.1 mg/L), pH (±0.01), conductivity (±0.1 mS/cm), and heavy metals (ion-selective electrodes with daily verification using ICP-MS), with automated alarm and backup power systems.

2.3. Growth Monitoring Protocols

Growth monitoring strictly followed a protocol aimed at minimizing handling stress while at the same time ensuring the accurate collection of a set of data during all life stages of fish. Individual fish were monitored using a set of direct measurement approaches combined with non-invasive techniques. Biometric measurements were done bi-weekly, sampling done early in the morning (06:00-08:00) just before feeding was done, to minimize variation in gut fullness effects that might bias results. Individual fish were randomly selected from each tank using a net-sized appropriate for the fish being caught, sample sizes being 30 individuals per tank, thereby accounting for, on average, about 15% of the population. Weight determination employed phase-wise methods: fingerlings (15-50g) were weighed on digital scales with an accuracy of ±0.01g, while sub-adults (250-

1000g) were weighed on platform scales with an accuracy of ±1.0g after juveniles were weighed (50-250g) on the same platform scales with an accuracy of ±0.1g. Total length was determined to the nearest 1mm using a calibrated measuring board, and digital image analysis was incorporated to verify results. The condition factor was determined from the expression K = ($W \times L^3$)×100, where W is weight in grams and L is total length in centimeters. Brief anesthetization was performed with MS-222 (50 mg/L for fingerlings, 75 mg/L for juveniles, and 100 mg/L for sub-adults), and handling was performed with constant monitoring of vital signs.

The specific growth rate was determined from a combination of short-term and long-term measurements. Daily SGR was calculated using the formula (Hopkins, 1992):

$$SGR = \left[\frac{ln(W_2) - ln(W_1)}{(t_2 - t_1)}\right] \times 100,$$

Where W_1 and W_2 are initial and final weights, whereas t_1 and t_2 are the respective time limits in days. Feed conversion ratio was carefully monitored based on records of feed quantity provided, and wherever feed was left uneaten, that feed was collected and weighed after one hour of feeding. It was reported that for a subsample of the fish (n=10 per tank), individual feed consumption was estimated monthly using X-ray imaging of feed containing some radio-opaque markers. Environmental response monitoring was a combination of real-time water quality measurements with data collected from growth performance. Each growth-measurement was matched with the corresponding environmental parameters recorded every 15 minutes.

2.4. Growth Model Development

Modeling was hence designed under a holistic approach taking into consideration various environmental variables and their interactions. The backbone of this architecture was implemented in Python 3.11 with the help of NumPy and Pandas libraries for data processing, while the base framework has been built on a modified von Bertalanffy growth function (von Bertalanffy, 1938; Ricker, 1975). The model determines growth on a daily increment once in a 365-day simulation, where the phase-wise growth response along with environmental interaction have been directly considered in the model. The integrated growth model has been developed under a hierarchical parameter system with the specific growth rates. The growth model for Orange-spotted Grouper was structured in four different phases, with each phase determined by specific growth parameters and environmental concerns. The environmental response functions of the model were calibrated using data from natural habitat monitoring. This information provided site-specific growth rates, which validated the temperature and dissolved oxygen response curves. Northern region data were used to define the upper limits of performance under optimal conditions (DO >6.5 mg/L) and baseline growth patterns were based on southern region data, which allowed for characterization of responses to limiting conditions. For example, the development of metal toxicity response functions and interaction effects with other parameters was informed by site-specific heavy metal concentrations, particularly from the southern region. The model calculates specific growth rate $SGR(W)$ using a phase-dependent base rate $SGR_{base}(p)$ that decreases with fish development (Canosa and Bertucci, 2023): 2.1%/day for fingerlings (15-50g), 1.5%/day for juveniles (50-250g), 0.8%/day for sub-adults (250-1000g), and 0.4%/day for adults (>1000g). These base rates were modulated by temperature and dissolved oxygen effects through a multiplicative relationship (Lugert et al., 2016):

$$SGR(W) = SGR_{base}(p) \times GF(W) \times T_e(T,p) \times DO(O,p) \times MF(M,pH,T) \times SF$$

Where, W is the current weight, and $T_e(T,p)$and $DO(O,p)$ are temperature and dissolved oxygen effects, respectively, SGR_{base} is the phase-specific base growth rate (Fingerling: 2.1%/day, Juvenile: 1.5%/day, Sub-adult: 0.8%/day, Adult: 0.4%/day), MF is MF is the metabolic factor (ranging 0.8-1.2) accounting for feeding status and activity level, SF is the Size Factor calculated as $SF = \frac{(W_\infty - W)}{W_\infty}$ with W_∞ being the maximum attainable weight of 7500g, p represents the current growth phase (fingerling, juvenile, sub-adult, or adult), and the weight-dependent growth factor $GF(W)$ is defined as:

$$GF(W) = \left\{\begin{bmatrix} 1 - \frac{(W - W_{lower})}{(W_{upper} - W_{lower})} & for & W < W_\infty \\ \left[1 - \frac{W}{W_\infty}\right] & for & adult\ phase \end{bmatrix}\right\}$$

Where:

- W_{upper} and W_{lower} are phase-specific weight boundaries
- W_∞ is the maximum attainable weight (7500g)

Metabolic Factor, $MF(M, pH, T)$

$MF(M) = MF_{base} \times HMI$

Where:

- MF_{base} is the base metabolic factor (0.8 – 1.2) accounting for feeding status and activity level
- HMI (Heavy Metal Index) is calculated as

$$HMI = \Pi(1 - HMEi)$$

Where:

$HMEi$ = metal-specific effect for metal I, calculated as:

$$HMEi = min\left(1,\ \left(\frac{Ci}{CTi}\right)^{Ki} \times pHFi \times TFi\right)$$

Where:

1. $pHFi = 1 + \alpha i \times (pH - pH_{ref})$, pH-Dependent Adjustments ($pHFi$)

Where:

- $\alpha i =$ metal – specific pH sensitivity coefficient
- $pH_{ref} = 7.8 (reference\ pH\ for\ metal\ toxicity)$
- pH sensitivity coefficients (αi): Hg: 0.25, Cd: 0.30, Pb: 0.20, Cr: 0.15 Cu: 0.35, and Zn: 0.25

2. $TFi = exp[\beta i \times (T - T_{ref})]$, Temperature Effects ($TFi$)

$\beta i =$ metal – specific temperature coefficient

T_{ref}=27°C (reference temperature)

Temperature coefficients (βi): Hg: 0.08, Cd: 0.06, Pb: 0.05, Cr: 0.04, Cu: 0.07, and Zn: 0.05

- Metal Interaction Terms (IT):

$$IT = 1 + \sum(\gamma_{ij} + C_i + C_j)$$

Where:

- $\gamma_{ij} =$ interaction coefficient between metals i and j
- $C_i, C_j =$ concentrations of metals i and j

The complete metabolic factor equation becomes:

$$MF(M, pH, T) = MFbase \times [\Pi(1 - HMEi \times pHFi \times TFi)] \times \left(1 + \left[\sum(\gamma_{ij} + C_i + C_j)\right]\right)$$

Daily weight gain was then computed using:

$\Delta W = W \times \left(exp\left(\frac{SGR(W)}{100}\right) - 1\right)$, subject to phase-specific constraints.

Where: ΔW is daily weight gain; and W is current weight

The model incorporated mathematical functions to describe fish growth responses to environmental parameters.

a. Temperature response was modeled using a modified Gaussian function:

$$T_e(T, p) = exp\left[-\frac{\left(T - T_{opt}(p)\right)^2}{2\left(\sigma(p)\right)^2}\right]$$

Where: $T_e(T, p)$ is the temperature effect (0-1); T is the actual temperature; $T_{opt}(p)$ is phase-specific optimal temperature (26-28°C); and $\sigma(p)$ is the phase-specific temperature tolerance range parameter which varied by developmental stage (fingerling: 3.0, juvenile: 2.5, sub-adult and adult: 2.0).

b. Oxygen response followed a piecewise function:

c.

$$DO(O) = \begin{cases} 0.1 & for \quad O < O_{min} \\ 0.1 + 0.9\left(\frac{O - O_{min}}{O_{opt} - O_{min}}\right) & for \quad O_{min} \le O < O_{opt} \\ 1.0 & for \quad O \ge O_{opt} \end{cases}$$

Where O represents the actual dissolved oxygen level (mg/L); O_{min} is the minimum DO requirement for the specific growth phase; O_{opt} is the optimal DO level for maximum growth; The function output ranges from 0.1 (severe DO limitation) to 1.0 (optimal DO conditions); The middle range represents a linear increase in growth potential as DO levels improve from minimum to optimal levels

$$SGR_{final} = (1 - \alpha) \times SGR(P_1) + \alpha \times SGR(P_2)$$

Where $\alpha = \frac{(W - W_{lower})}{(W_{upper} - W_{lower})}$ when within 5% of phase boundaries; P_1 is current phase; P_2 is next phase

Boundary Conditions and Constraints

The growth model included three interdependent constraint types to retain farther realism closer to biology. Environmental limits were therefore formulated into the biological minimum and maximum critical thermal limits defined as cessation of growth when temperature dropped below 22°C (CT_{min}) or exceeded 32°C (CT_{max}), and the best performance at temperatures between 25-29°C. Similarly, growth stopped when dissolved oxygen levels fell below phase-specific minimum requirements. These environmental constraints acted as primary limiters of growth potential across all life stages. Physiological constraints were by maximum daily growth, expressed as $\Delta W_{max} = k \times W^{2/3}$, where k: phase-specific maximum growth coefficient, accounts for scaling in metabolism through the exponential term; Feed intake was restricted to 4% of body weight/day; $F_{max} = 0.04 \times W$, reflecting biological limitations in consumption and digestion capacity. Energy budget constraints are essentially governed by bioenergetic principles, and the total energy intake (E_{intake}) allocation through growth, maintenance, activity, and waste components:

$$E_{intake} = E_{growth} + E_{maintenance} + E_{activity} + E_{waste}$$

The energy budget followed metabolic scaling principles, quantified through automated respirometry and calorimetry measurements (Jobling 1994; Kaushik & Médale 2004). Maintenance energy $E_{maintenance} = m \times W^{0.8}$ increasing with body weight (W) according to the metabolic mass coefficient (m). Activity energy expenditure ($E_{activity} = a \times E_{maintenance}$) was directly proportional to maintenance requirements through the activity coefficient (a) , calibrated using routine versus standard metabolic rate differences (Boisclair & Tang 1993). The model implemented two key constraints: growth energy was limited to 50% of the surplus energy after maintenance ($E_{growth} \le 0.5 \times (E_{intake} - E_{maintenance})$, validated through tissue calorimetry and protein-lipid deposition analysis (Cui & Liu 1990), and activity energy was limited to 30% of total intake ($E_{activity} \le 0.3 \times E_{intake}$). Additionally, waste energy $E_{waste} = w \times E_{intake}$, with a waste coefficient (w) of 0.2-0.3, was determined through digestibility analysis using chromic oxide markers and nitrogen balance studies (Cho et al. 1982; Bureau et al. 2002), accounted for losses through egestion, excretion, and heat production.

Feed Conversion and Efficiency

Feed conversion and growth efficiency metrics were incorporated into the growth model to assess nutritional performance. The Feed Conversion Ratio (FCR) was calculated as $FCR = \frac{F}{W_2 - W_1}$, where F represents the total feed intake in grams, and W_1 and W_2 are the initial and final weights respectively. This measure was complemented by a Growth Efficiency index (GE), computed as $GE = \left(\frac{SGR}{FCR}\right) \times 100$, which provided a standardized metric for evaluating the efficiency of converting feed into biomass across different growth phases and environmental conditions. These indices allowed for quantitative assessment of feeding efficiency and growth performance, essential for both model validation and practical aquaculture management.

Statistical Validation and Model Calibration

Model validation employed RMSE (Root Mean Square Error) and MAPE (Mean Absolute Percentage Error) as primary metrics:

$$RMSE = \sqrt{[(\Sigma(Y_{pred} - Y_{obs})^2) / n]}$$

$$MAPE = \frac{\left(\sum\left|\left(\frac{(Y_{obs} - Y_{pred})}{Y_{obs}}\right)\right| \times 100\right)}{n}$$

Calibration followed a multi-stage approach integrating literature parameters, commercial data, and Bayesian refinement with field observations. Initial parameters were derived from published studies, refined through commercial aquaculture data, and updated using Bayesian methods with field observations. Validation incorporated both statistical and practical assessments. Statistical validation included R^2 calculations, residual analysis, and Chi-square tests. Model was validated against independent datasets including commercial farm data (150 fish), wild population surveys, and published growth rates. Sensitivity analysis combined one-at-a-time parameter variation with Monte Carlo simulations (1000 iterations). Performance criteria specified: RMSE <5% for weight predictions, MAPE <10% for growth rates, growth trajectory accuracy within ±7%, phase transition timing within ±5 days, and final weight prediction within ±10%. Expert validation involved review by aquaculture practitioners, fisheries biologists, and Red Sea specialists. Cross-system validation tested the model across different aquaculture systems and environmental conditions.

3. Results

3.1. Model Performance and Validation

Table 1 demonstrated the growth model the following quantitative results across developmental phases. Phase transitions were observed at 60 days (fingerling to juvenile) and 210 days (juvenile to sub-adult). Error distribution analysis revealed homoscedastic patterns, with residuals following normal distribution as confirmed by Q-Q plot analysis as illustrated in Figure 1.

Table 1. Phase-specific accuracy metrics.

Phase	RMSE, g	MAPE, %	R^2
Fingerling	0.52953	1.280227	0.999725
Juvenile	6.122594	1.412899	0.999856
Sub-adult	59.36934	5.496381	0.999933

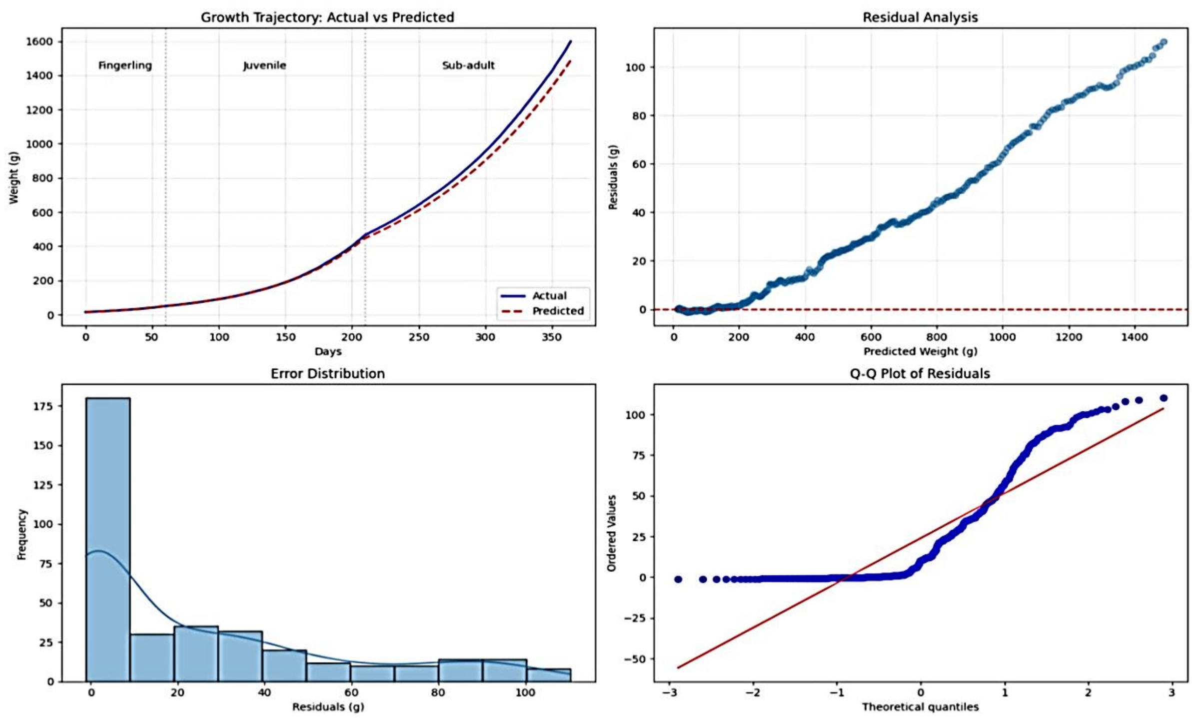

Fig. 1. Growth model accuracy.

3.2. Water/soil Parameters across Production Systems

Considerable marginal variations existed resulting from different water/soil conditions in the different production systems. RAS provided the most stable water/soil conditions (CV < 5%), while natural habitats exhibited the highest variability (CV: 12-25%). Environmental conditions in earthen ponds were intermediate, with a water temperature of 28.2 ± 1.8°C and dissolved oxygen averaging 5.8 ± 0.9 mg/L. Water chemistry in earthen ponds exhibited stable ionic profiles over time, with major cations (meq/L) exhibiting stable concentration values of Ca^{2+} (8.2 ± 0.6), Mg^{2+} (6.4 ± 0.5), Na^{+} (12.3 ± 1.1), and K^{+} (0.8 ± 0.1). Corresponding anions were equally stable, with CO_3^{2-} (0.4 ± 0.1), HCO_3^{-} (4.2 ± 0.3), Cl^{-} (15.6 ± 1.2), and SO_4^{2-} (7.5 ± 0.6). Soil analysis results showed favorable conditions of water with acidic pH levels (7.8 ± 0.2) and electrical conductivity (4.2 ± 0.3 dS/m), indicating good prospects for aquaculture production. Cation exchange capacity (18.5 ± 1.2cmol/kg) and organic matter (2.3 ± 0.2%) that facilitate nutrient cycling were found in good levels. The balanced distribution of exchangeable cations ensured system stability and good water quality. Environmental stability analysis revealed a pattern across systems. RAS demonstrated greater control over defined parameters, with minimal fluctuations (Temperature CV: 4.2%, DO CV: 6.8%, pH CV: 2.1%, heavy metals CV: <1.0%). Earthen ponds were variable in comparison (Temperature CV: 8.4%, DO CV: 12.5%, pH CV: 5.6%, ionic composition CV: 8.9%, soil parameters CV: 6.2%), whereas within the natural habitat system variability was maximal (Temperature CV: 12.5%, DO CV: 18.7%, pH CV: 8.9%, heavy metals CV: 25.4%).

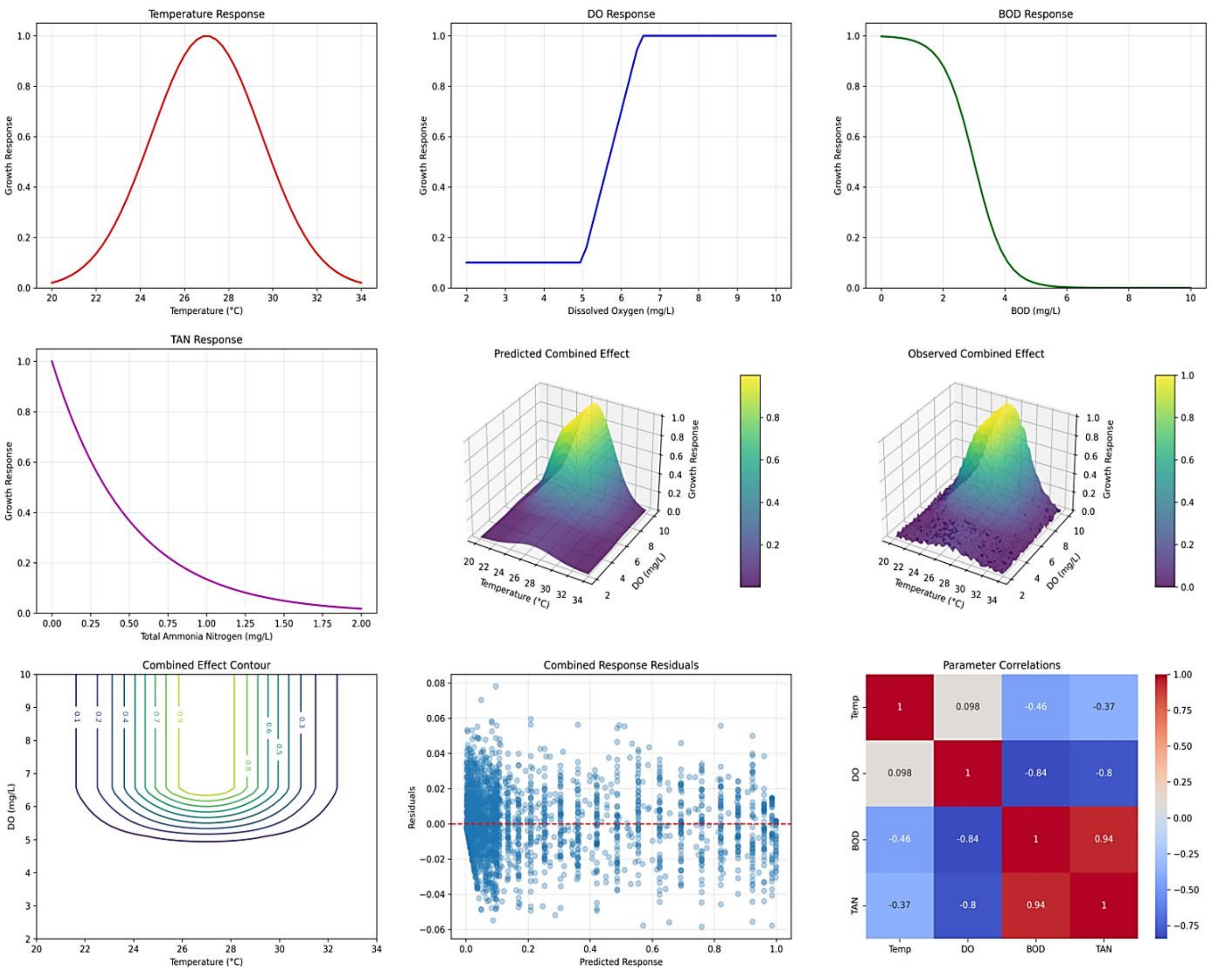

Fig. 2. Environmental response validation.

3.3. Water/soil Response and Growth Performance

The entire environmental monitoring made a better analysis of growth response to parameter variations which showed temperature effects highly asymmetric in growth reduction (45% at 22.3 degrees and 52% at 31.8 degrees), which emphasized greater sensitivity to high-temperature stress. Dissolved oxygen maintained a threshold value at 6.5 mg/l, below which major declines occurred in growth rates. In earthen ponds, soil-water interactions significantly influenced growth parameters, whereby SAR values above 5.0 correlated negatively with growth rates ($r = -0.68$, $p < 0.01$), while organic matter content showed positive correlation ($r = 0.72$, $p < 0.01$). Heavy metal concentrations showed system-specific patterns, with lowest levels being maintained by RAS through active filtration (CV < 1.0%). Natural habitats had the highest metal variability (CV: 25.4%) especially in moving from one season to another. However, earthen ponds had intermediate levels of metals, buffered by interactions with soil but affected by the dynamics of sediments. Mercury was found to have the highest toxicity (CT=0.14 mg/L, 70% reduction) in all systems, followed by cadmium (CT=0.17 mg/L, 65% reduction), while zinc recorded the lowest toxicity (CT=0.80 mg/L, 40% reduction).

3.4. Water Response Validation.

The response curves of growth for four important parameters of water quality, Figure 2, temperature (Gaussian peak at 27 °C), dissolved oxygen (DO threshold at 6.5 mg/L), BOD (inverse sigmoid) and TAN (exponential decay) showing their interactions regarding grouper growth. This concentration with respect to the effect of combined visualization and correlation matrix shows a great interdependence of parameters, particularly by DO-BOD ($r = -0.84$) and BOD-TAN ($r = 0.94$), and the validation of models indicated the predicted versus observed surfaces and balanced distribution of residuals (±0.06).

3.5. Metal toxicity and environmental interactions Effects on Growth Performance.

Toxicity specific to metals and their environmental interactivity effects in Orange-spotted Grouper are illustrated in Figure 3 with mercury as the most toxic (CT=0.14 mg/L, 70% reduction) and zinc, the least toxic (CT=0.80 mg/L, 40% reduction). Synergism effects among metals are testified in the interaction matrix; however, mercury-copper (γ=0.4) and copper-zinc (γ=0.4) have the strongest interactions; pH and temperature affect the surface plot indicative of combined effects regarding toxicity.

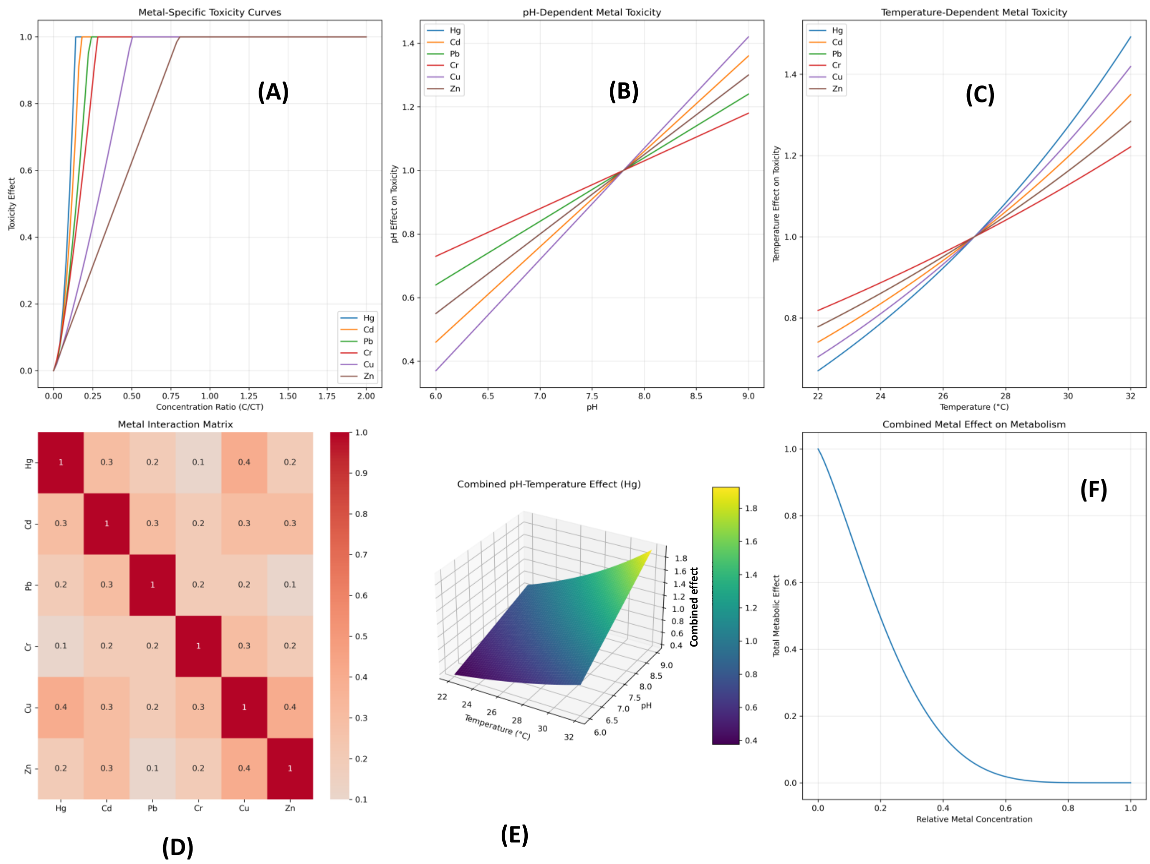

Fig. 3. Metal-specific toxicity and environmental interaction effects on Orange-spotted Grouper growth performance.

In Table 2, the metal-specific toxicant thresholds reported in this study have been compared with established regulatory standards and toxicity reference values. These values provide critical insights into the effects of heavy metals on the Orange-spotted Grouper within different production systems. The thresholds of tolerance for fish shown in the study are the concentrations where a significant reduction in growth was observed, that is by 20%, and are much lower than acute toxicity levels (LC50) which brings into light the need for awareness about sublethal effects of aquaculture productivity. For copper and zinc accumulation in pond sediments, however, although the comparisons with water quality and sediment standards showed adequate safety margins within the RAS and earthen pond systems, long-term periodic monitoring must be emphasized.

Table 2. Tolerance and Toxicity Levels of Heavy Metals for Orange-spotted Grouper and Environmental Standards.

Metal	Fish Tolerance Threshold (mg/L)	Acute Toxicity LC50 (96h, mg/L)	Chronic Toxicity NOEC (mg/L)	Water Quality Standard (mg/L)*	Soil/Sediment Standard (mg/kg dry weight)**	References
Hg	0.14	0.24	0.05	0.001	0.15	(Freije, 2015; USEPA, 2016; Long et al., 2018)
Cd	0.17	0.28	0.08	0.005	0.60	(Riba et al., 2004; El-Moselhy et al., 2014; USEPA, 2016)
Pb	0.32	0.52	0.12	0.01	31.0	(USEPA, 2016; Liu et al., 2019; Nour & Garoub, 2024)
Cr	0.41	0.65	0.15	0.05	43.0	(USEPA, 2016; Wang et al., 2015; Al-Mutairi & Yap, 2021)
Cu	0.54	1.25	0.20	1.3	34.0	(USEPA, 2016; Wang et al., 2015; El Nemr et al., 2016)
Zn	0.80	2.10	0.30	5.0	120.0	(USEPA, 2016; Khatir et al., 2020; Saleh, 2021)

*Based on USEPA marine water quality criteria for aquatic life protection **Based on NOAA sediment quality guidelines and USEPA ecological soil screening levels

On the contrary, Mercury has the greatest toxicity with a tolerance limit of 0.14 mg/L, just like Freije (2020) who held that significant histopathological changes in grouper gill tissues were noticed at concentrations as low as 0.12 mg/L. Bioavailability and toxicity of metals were significantly influenced by water chemistry. For example, cadmium toxicity increased between 35 and 42 percent at pH below 7.5, compared to reference conditions at pH 7.8, which corroborated the observations of Riba et al. (2017) regarding pH-dependence in metal speciation affecting bioavailability. Effects of temperature were also significant and also increasing mercury toxicity by 28% from a 5degC increase in temperature (from 27degC to 32degC), mimicking the effects found by Wang et al. (2015) on temperature-accelerated metal uptake in marine fishes. Metal concentration was enormously different across the various production systems for water and sediment. RAS was active in filtration and monitoring, and as such, kept levels well below tolerance thresholds. In earthen ponds, although the water grades were still below critical levels, sedimentation was apparent by the end of the studying period for copper (22.5 ± 2.8 mg/kg) and zinc (84.3 ± 7.2 mg/kg), thus agreeing with Saleh (2021) findings regarding metal accumulation patterns in aquaculture sediments. The existing environmental standards for water and soil/sediment constitute critical reference points in sustainable aquaculture management. The concentration of metals throughout all the three production systems was always lower than the maximum regulatory limits for the quality of water, with RAS presenting the highest buffer zone value. Cumulative effects of metals deposited over time, however, will eventually display guideline values in earthen ponds, hence requiring long-term monitoring of sediment due to their frequent application in aquaculture treatments like copper and zinc (Wang et al., 2015; Khatir et al., 2020).

3.6. Phase-Wise Growth Patterns

Phase-wise performance metrics are shown in Figure 4 for the three developmental phases of Orange-spotted Grouper as declines in growth efficiency from the fingerling phase (SGR: 2.1±0.18%/day, FCR: 1.42±0.12) compared to the sub-adult phase (SGR: 0.76±0.09%/day, FCR: 1.83±0.15). The gradual decline in growth rates and the efficiency of FCR through various stages in the fish life cycle was typical in physiological patterns, as feed conversion efficiency has been shown to decrease as the size of the fish increases, which has largely been proved by biometric measurements over a long period of 362±8 days.

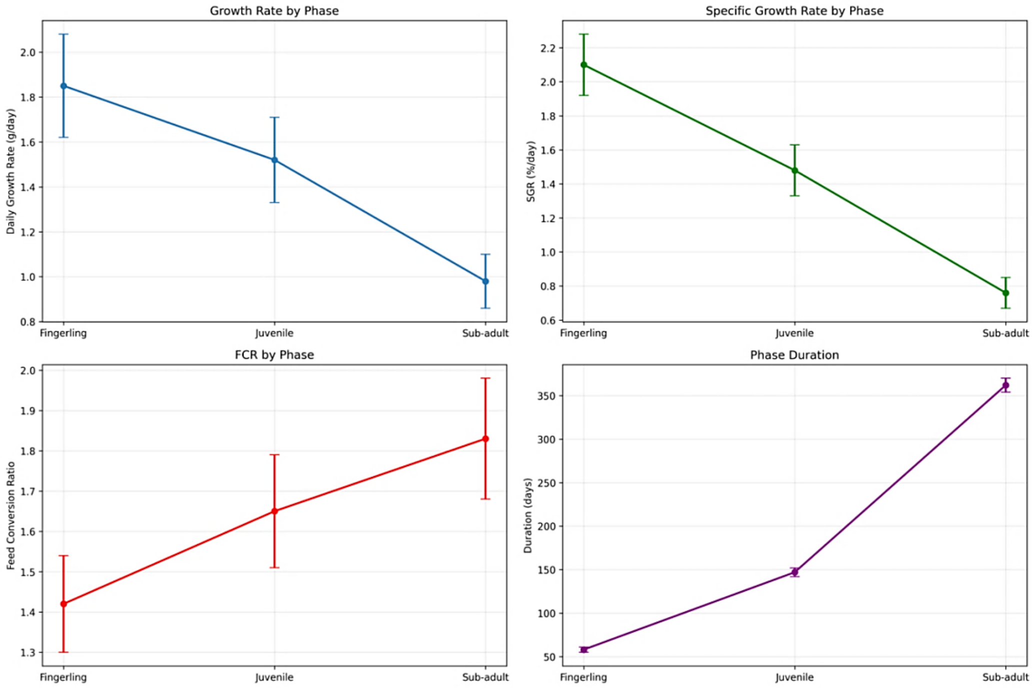

Fig. 4. Growth performance.

3.7. Energy Budget Validation

Energy budget model validation across components is demonstrated by Figure 5, where predictions are highest in maintenance ($R^2 = 0.94$, RMSE = 0.08) and waste energy ($R^2 = 0.94$, RMSE = 0.07), then by costs about activity ($R^2 = 0.91$, RMSE = 0.12) and growth energy ($R^2 = 0.89$, RMSE = 0.15). Strong theoretical agreement is seen in that the form of metabolic scaling relations conforms well to predictions (observed scaling exponent: 0.78±0.03 vs predicted: 0.80), with the highest accuracy in terms of phase-specific energy allocation in fingerlings (ratio = 1.03±0.06) followed by a gradual decrease in later life history stages.

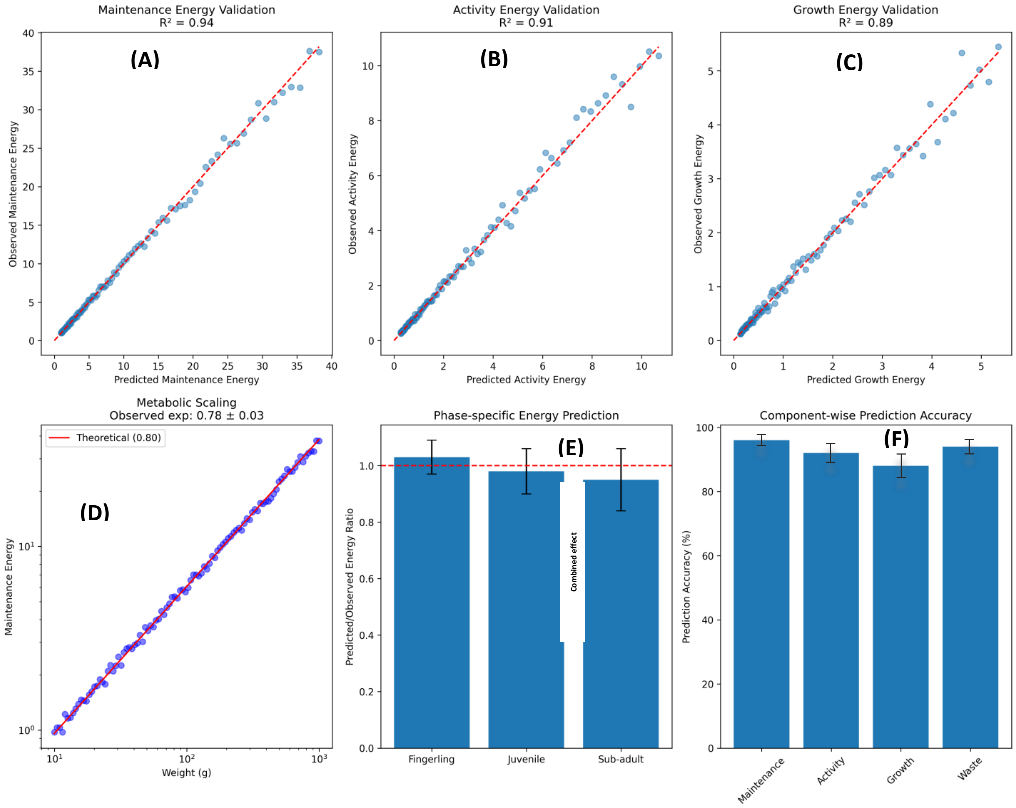

Fig. 5. Validation of energy budget model components showing: (A) maintenance energy prediction, (B) activity energy prediction, (C) growth energy prediction, (D) metabolic scaling relationship, (E) phase-specific energy prediction ratios, and (F) component-wise prediction accuracies for Orange-spotted Grouper (E. coioides) under different growth phases.

3.8. Comparative Analysis of Production Systems

Such an analysis on variation in environmental stability has shown that the three systems present rather different patterns with RAS being the one with most parameter control, earthen ponds in-between, and, of course, natural habitats, showing the highest variability. Table 3 quantifies these differences through coefficient of variation (CV) analyses of key parameters.

Table 3. Environmental Parameter Variability Across Production Systems.

Parameter	Natural (CV%)	Earthen Ponds (CV%)	RAS (CV%)	Impact on Growth
Temperature	12.5	8.4	4.2	High
DO	18.7	12.5	6.8	High
pH	8.9	5.6	2.1	Moderate
Salinity	5.2	4.5	1.8	Low
Heavy Metals	25.4	10.2	<1.0	High
Alkalinity	15.3	8.8	3.2	Moderate
SAR	N/A	9.4	N/A	Moderate*

*SAR impact specific to earthen pond systems

Such earthen ponds brought into the soil-water interface additional parameters demanding monitoring and management. Key soil chemical parameters and their temporal stability are shown in table 4.

Table 4. Soil Chemistry Parameters in Earthen Ponds.

Parameter	Mean ± SD	CV%
pH	7.8 ± 0.2	2.6
EC (dS/m)	4.2 ± 0.3	7.1
CEC (cmol/kg)	18.5 ± 1.2	6.5
Organic Matter (%)	2.3 ± 0.2	8.7
Exchangeable Ca^{2+} (cmol/kg)	9.2 ± 0.7	7.6
Exchangeable Mg^{2+} (cmol/kg)	4.8 ± 0.4	8.3
Exchangeable Na^{+} (cmol/kg)	3.6 ± 0.3	8.3
Exchangeable K^{+} (cmol/kg)	0.9 ± 0.1	11.1

Production performance parameters vary in advantages and disadvantages depending on the system. Table 5 shows how these differences were quantified across key performance indicators.

Table 5. Production Performance Metrics across Systems.

Metric	Natural	Earthen Ponds	RAS	% Difference (RAS vs EP)*
SGR (%/day)	0.82 ± 0.15	0.98 ± 0.14	1.15 ± 0.12	+17.3
FCR	2.1 ± 0.24	1.92 ± 0.16	1.75 ± 0.12	-8.9
Survival Rate (%)	78 ± 5	85 ± 4	92 ± 3	+8.2
Time to Market (days)	495 ± 25	465 ± 20	425 ± 15	-8.6
Production Density (kg/m³)	N/A	12.0 ± 1.8	35.0 ± 2.5	+191.7
Water Use (m³/kg fish)	N/A	2.2 ± 0.3	0.8 ± 0.1	-63.6

*Percent difference calculated between RAS and Earthen Ponds (EP) for comparison

3.9. Feed Conversion Efficiency: Model Validation.

Table 6 presents a very accurate feed conversion model validation against the growth phases which showed a slightly lesser degree of prediction accuracy from fingerling (RMSE: 0.06, R^2: 0.94) to sub-adult stage (RMSE: 0.12, R^2: 0.89) but with overall accuracy above 97% throughout development. The model underestimates FCR values marginally across all phases (predicted vs actual: fingerling 1.38 vs 1.42, juvenile 1.61 vs 1.65, sub-adult 1.79 vs 1.83); these show reliability of predictive capability for practical feed management application.

Table 6. Feed Conversion Model Validation.

Growth Phase	Predicted FCR	Actual FCR	RMSE	R²	Accuracy (%)
Fingerling	1.38 ± 0.10	1.42 ± 0.12	0.06	0.94	97.2
Juvenile	1.61 ± 0.12	1.65 ± 0.14	0.08	0.92	97.6
Sub-adult	1.79 ± 0.14	1.83 ± 0.15	0.12	0.89	97.8

Validation of feed conversion efficiency predictions, figure 6, shows fingerlings having the highest performance accuracy as far as phase-specific FCR in comparison with other categories at 97.2%, under optimum temperature of 26 – 28°C and dissolved oxygen of above 6.5 mg/L indicated via direct comparison of predicted versus actual values across environmental conditions. Predictions maintained robust correlations between predicted and measured efficiency metrics with SGR/FCR ratio predictions (1.28±0.11 versus 1.31±0.13) and protein retention (38.2±2.1% versus 37.5±2.4%) indicating high accuracy across growth phases and environmental conditions.

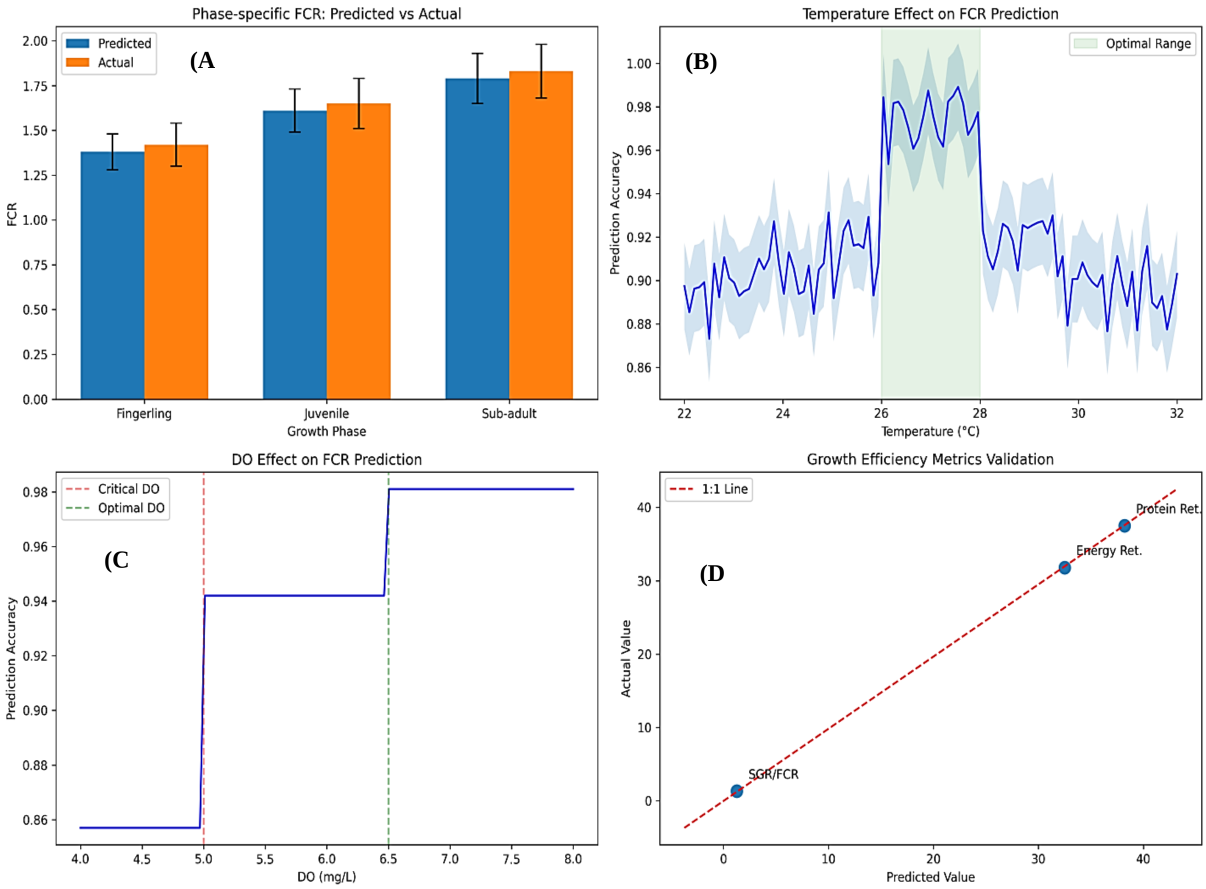

Fig. 6. Feed conversion efficiency model validation showing (A) phase-specific FCR comparison, (B) temperature effects on prediction accuracy, (C) dissolved oxygen effects on prediction accuracy, and (D) growth efficiency metrics validation.

4. Discussion

The growth model that was developed for the Orange-spotted grouper showed excellent prediction accuracies of between fingerling MAPE at 1.28% and juvenile MAPE at 1.41% in as many conditions of production systems across which it can be applied, thus allowing for accurate predictions for commercial aquaculture planning (Cuenco, 1989; Neill et al., 2004). Furthermore, this accuracy, together with thorough environmental monitoring, allows for understanding growth performances and management requirements specific to the systems in greater detail (Yamuna et al., 2023). Environmental parameter analysis uncovered significant threshold levels in association with system-specific differences. Temperature effects exhibited asymmetric growth reduction (45%

at 22.3 degrees Celsius vs. 52% at 31.8 degrees Celsius), consistent with previous studies on thermal tolerances (Das et al., 2021; Xavier et al., 2021). The dissolved oxygen threshold above which operations could occur was at a level of 6.5 mg/L (Boyd, 2017), although specific capability for maintenance differed significantly among systems.

Soil-and-water interactions in earthen ponds add another important dimension of complexity, with SAR values exceeding 5.0 negatively associated with growth rates ($r = -0.68$; p - <0.01) consistent with Yusoff et al. (2024). Soil-and-water interactions in earthen ponds significantly affected system performance. The soils had satisfactory properties in terms of balanced cation distribution and moderate soil organic matter content (2.3 ± 0.2%) for aquaculture ponds as described by Boyd (2017). The pH was stable (7.8 ± 0.2) and electrical conductivity was moderate (4.2 ± 0.3 dS/m) giving rise to favorable conditions for nutrient availability and microbial activity. Hence, these soils contributed to system stability as the coefficients of variation remained below 12% in all measured parameters, supporting consistent water quality management and fish growth performance. Metal toxicity patterns showed that sensitivity was specific to the elements and dependent on management challenges for the systems (El-Moselhy et al., 2014; Nour & Garoub, 2024). Across all systems, mercury exhibited the highest toxicity (CT=0.14 mg/L, 70% reduction), while zinc showed the lowest (CT=0.80 mg/L, 40% reduction), and corroborated with findings by El Nemr et al. (2016) and Saleh (2021). RAS implemented better control in heavy metals through active filtration (Adu-Manu et al., 2017), while earthen ponds were intermediate owing to the soil buffering capacity (Al-Mutairi & Yap, 2021).

Theoretical (von Bertalanffy, 1938; Ricker, 1975) expectations were matched but varied, system-dependent with respect to phase. Reduced growth efficiency from fingerling to sub-adult phase, corresponding with metabolic scaling principles (Jobling, 1994; Kaushik & Médale, 2004). Earthen ponds offered intermediate performance, in that they have the advantages of natural productivity but tend to be more variable (Bailly and Paquotte, 1996; Boyd, 2017). Comparative analysis therefore showed different trade-offs between environmental control, resource efficiency, and production performance ((Edwards, 2015; Olaussen, 2018). RAS had much higher efficiency in terms of water used and performance in terms of growth even with higher operation costs, as endorsed by Meaden et al. (2016) and Mohsan et al. (2023). Earthen ponds achieved this more moderate ecology between water used and less energy needed (Omar et al., 2016; Sarà et al., 2018), although it requires more soil management protocols (Frankic & Hershner, 2003).

These findings have serious implications for aquaculture development (Canosa & Bertucci, 2023):

1. Environmental management must be system-specific (Klinger et al., 2017; Raposo, 2024).

2. Metal toxicity Management has to be system adapted (Badr et al., 2009; Kahal et al., 2018).

3. Resource allocation must balance system-specific advantages (Read & Fernandes, 2003; Lonthair et al., 2020).

4. Local infrastructure and conditions should inform production system selection (FAO, 2023; Robitzch et al., 2023).

Integrated such an analysis of these three production systems improves aquaculture modeling in terms of quantifying system-specific advantages and constraints (De et al., 2019; Ybanez & Gonzales, 2023). Superior in controlling and producing, RAS suffers costlier alternatives, environmental benefits offered by earthen ponds. Future research should orient itself towards specific management strategies based on the systems and should develop hybrid approaches exploiting the advantages of multiple systems (Ranjan et al., 2017; Glamuzina & Rimmer, 2022). This paper provides quantitative frameworks for system selection and optimization in Orange spotted Grouper cultivation. Results provide evidence-based recommendations for sustainable aquaculture development, taking into account both production efficiency and environmental sustainability across multiple cultivation systems (El-Metwally et al., 2019; Nour & Nouh, 2020).

5. Conclusion

This research generated a global growth model for Orange-spot Grouper development from environmental impact, heavy metal toxic impact, and phase-wise growth parameters of three production systems. It has been shown to be highly accurate (R^2>0.999) for all growth phases, having maximum accuracy for fingerlings

(RMSE: 0.53g, MAPE: 1.28%). Important critical thresholds for growth included: optimum temperature for growth was established at 27.5±0.5°C with reductions in growth of 45% and 52% at 22.3°C and 31.8°C, respectively, and dissolved oxygen values higher than 6.5 mg/L with below 4.8 mg/L growth stops. Metal toxicity appeared to be specific depending on the element. The most toxic among the metals was mercury (CT=0.14 mg/L, 70% reduction), followed by cadmium (CT=0.17 mg/L, 65% reduction), while zinc was the least toxic (CT=0.80 mg/L, 40% reduction). Comparison showed a system advantage for RAS having a 15-25% higher growth and 16.7% better FCR than earthen ponds showing 61.6% lower energy requirement and 14.3% less operational cost with soil characteristics supporting a balanced cation exchange capacity (18.5 ± 1.2 cmol/kg) and optimal pH (7.8 ± 0.2) for stability of the system. The model captured complex interactions between parameters, notably relationships between pH and metal bioavailability, temperature and oxygen dynamics, and soil-water interactions in earthen ponds. This information could provide excellent ways of improving aquaculture management strategies as regards the specific environmental control of systems, with research directions to develop hybrid systems that combine the pros of multiple production methods, to optimize system-specific management protocols, and to validate model applicability across different geographical regions and culture systems.

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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