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Numerical and Experimental Investigation of Environmental Factors for Abalone Growth Enhancement

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ABSTRACT

Abalone aquaculture is a critical component of the global seafood industry, with growing demand driving the need for optimized breeding techniques. However, challenges such as inconsistent growth rates and prolonged production periods have hindered profitability and operational efficiency within the industry. This study was conducted to address these challenges, specifically focusing on enhancing abalone growth rates. Three months quantitative data were collected from the Abalone farming company on Abalone in response to different environmental factors to study the effects of these factors on the Abalone growth. Each experimental tank was installed with an Automatic Aquatic System integrated with PH, salinity, and temperature sensors for maintaining, monitoring, and controlling the three experimental factors within the set limits. The growth metrics were assessed using the absolute and specific growth rate for a comprehensive comparison across different environmental settings. The study also employed a combination of quantitative methods, like regression analysis and ANOVA, to analyze the impact of these factors. The model results were validated with confirmatory experiments. The results from the study showed that PH and salinity have the highest and lowest influence, respectively, on the Abalone growth with SGR at 2.20%/day (8.5PH, 40ppt salinity, 20℃) and 0.72%/day (8.84PH, 35 ppt salinity, 15℃). Ditto AGR with the highest and lowest value at 4.42g/day and 1.87g/day, respectively, under the same experimental settings. The optimal values of the factors were obtained at PH, salinity, and temperature of 8.18, 31.29 ppt, and 13.62℃, respectively, which yielded 0.88%/day SGR and 2.16g/day AGR. The developed models can therefore be used for an accurate forecast of the AGR and SGR of Abalone under different environmental settings.

1. INTRODUCTION

An essential part of the world's food production is aquaculture, which is the breeding, raising, and harvesting of fish, shellfish, and other aquatic animals in a variety of water conditions [1]. This industry can be divided into several categories, of which algae and shellfish aquaculture are the most common types. This process is known as algae aquaculture. Abalones are the main product of shellfish aquaculture [2]. After being bred and harvested, they are processed and sold all over the world in three different forms: dried, canned, or live [2]. Kelp and Ulva are grown as a natural source of Abalone feed [3].

Within the vast class of gastropoda, the species of sea snail referred to as abalone is an affiliate of the Rhipidoglossan suborder [4]. It is a marine mollusc found in the genus Halitosis and family Halictidae. The shell of an abalone is round, oval in structure, and it can be flattened. Sizes range from 2 to 20 cm, and in particular circumstances, fully grown specimens can reach up to 30 cm [4]. Since its inception in the 1960s in China and Japan, abalone aquaculture has spread throughout the world, mainly serving markets in Asia and some regions of Latin America [5]. Because of its sluggish development rate and need for years of cultivation before it can be processed into a final product, abalone has a high market value [5].

Successful abalone farming requires meticulous control of environmental conditions to simulate the species' natural oceanic habitat. The water temperature must consistently range between 16℃ and 18℃, and the water flow rate should be high to replicate the dynamic ocean environment [6]. The PH level must be maintained within a neutral range of 7.5 to 8.5, and the salinity should be kept between 30 ppt and 40 ppt to ensure optimal growth conditions [6]. These parameters are essential for creating the ideal environment that promotes rapid growth and development of abalones, enabling the company to meet the growing demand efficiently.

To sustain and enhance the supply of both processed and live abalone, optimizing the growth conditions is essential for accelerating their development. Creating an environment that closely replicates the natural habitat of abalones, combined with a diet rich in nutrients that specifically promote rapid growth, can significantly enhance their growth rates. This approach not only reduces the time required for abalones to reach market size but also lowers production costs by improving feed efficiency and overall farm productivity [7]. Additionally, implementing advanced aquaculture technologies, such as automated feeding systems and real-time water quality monitoring, can further fine-tune the growing conditions, ensuring that abalones are consistently raised in the most favourable environment [8]. By adopting these strategies, companies can maintain a reliable and high-quality supply of abalone to meet global demand, ultimately strengthening their competitive position in the increasingly important aquaculture industry [8]. Moreover, such innovations in farming practices can lead to more sustainable operations, as they allow for better resource management and potentially reduce the environmental impact of abalone farming.

The protracted and inconsistent growth rates of abalone within aquaculture operations present a significant challenge to the commercial viability and economic sustainability of enterprises. Despite efforts to optimize environmental conditions and husbandry practices, the time required for abalones to reach marketable size often exceeds projections, leading to inefficiencies and increased operational costs [9]. This unpredictability in growth not only impedes the ability to meet global demand but also undermines the profitability of abalone farming. This can be seen by the decrease in growth in June 2024 from 40 tons to 31 tons [9].

A critical yet underexplored aspect of this issue lies in the type of feed provided to abalones and their interaction with the specific environmental conditions under which they are cultivated [10]. The precise relationship between dietary composition, feeding practices, and abiotic factors such as water quality, temperature, and salinity remains inadequately understood. This gap in knowledge hampers the development of targeted interventions to optimize growth rates.

This study investigates the synergistic effects of optimized environmental conditions on abalone growth rates. It was hypothesized that a specific combination of these factors would significantly enhance abalone growth rates and consistency. By examining the precise relationship between environmental conditions, this research seeks to develop refined management strategies that enhance growth consistency, reduce breeding time, and improve overall production efficiency in abalone farming. Utilizing advanced aquaculture technologies, including real-time water quality monitoring and automated feeding systems, this study will provide novel insights into the interactions between abiotic factors influencing abalone growth, filling a critical knowledge gap in the field. The findings of this study will contribute to the broader understanding of sustainable and profitable abalone farming practices, ultimately strengthening the industry's position in the competitive aquaculture market.

2. EXPERIMENTAL PROCEDURE

Samples of Abalone (Figure 1) of the same sizes were obtained from the Abagold company in South Africa. The initial weight of these samples was taken using a beam balance before subjecting them to different environmental factors inside different tanks. Their weights were also taken daily for three months to assess their growth rates in response to different environmental factors (PH, temperature, and salinity). 20 tanks were used in breeding experiments, and each tank was used to breed 10 samples simultaneously under the same environmental factors. The rest samples were used for the control experiment. The temperature considered in each tank ranges from 10-20°C. The PH and the salinity considered are 7.5-8.5 and 30-40 ppt, respectively. The ranges of environmental factors' values selected in breeding these Abalones are based on literature reviewed and the data obtained from the Abagold farm.

Figure 1. Abalone samples

Table 1. Breeding environmental factors and levels

Factors	Level					
	Code	-1	0	+1	-α	+α
PH	P	7.5	8	8.5	7.16	8.84
Salinity (ppt)	S	30	35	40	26.59	43.40
Temp (°C)	T	10	15	20	6.59	23.40

Table 2. Coded and original values in experimental details

S/N	Coded Value			Original Value		
	PH	Salinity (ppt)	Temp (°C)	PH	Salinity (ppt)	Temp (°C)
1	-1	-1	-1	7.5	30	10
2	+1	-1	-1	8.5	30	10
3	-1	+1	-1	7.5	40	10
4	+1	+1	-1	8.5	40	10
5	-1	-1	+1	7.5	30	20
6	+1	-1	+1	8.5	30	20
7	-1	+1	+1	7.5	40	20
8	+1	+1	+1	8.5	40	20
9	-α	0	0	7.16	35	15
10	+ α	0	0	8.84	35	15
11	0	- α	0	8	26.59	15
12	0	+ α	0	8	43.40	15
13	0	0	- α	8	35	6.59
14	0	0	+ α	8	35	23.40
15	0	0	0	8	35	15
16	0	0	0	8	35	15
17	0	0	0	8	35	15
18	0	0	0	8	35	15
19	0	0	0	8	35	15
20	0	0	0	8	35	15

The operationalization of variables such as PH, salinity, and temperature was achieved through the Automated Aquatic System (AAS), a monitoring and control system integrated with sensors for precise measurement and control. The AAS controller allowed for setting desired levels of PH, temperature, and salinity, which were adjusted through activation of the CO_2 injector, heater, and reverse osmosis system, respectively. The system frequently monitored these parameters to maintain set data points, ensuring precise control. Measurement precision and accuracy were ensured by using ten Abalone samples per tank and computing average values for further evaluation. Potential sources of error were minimized through the use of a reliable monitoring system and precise measurement tools. In the context of the experimental design, Response Surface Methodology (RSM) was employed to determine the optimal combinations of environmental factors, with variables operationalized at three levels (-1, 0, +1) corresponding to low, mid, and high values, respectively, as presented in Tables 1 and 2. For example, the temperature considered ranges from 16-18℃. This implies that the low point of temperature is 10℃, the midpoint is 15℃, and the high point is 20℃. Ditto the PH and salinity values considered. The experimental value located outside the design space, as recommended by the RSM, is represented by -α and +α. After the experiments have been conducted based on the 20 experimental mix recommendations by the RSM, the absolute growth rate (AGR) and specific growth rate (SGR) of Abalone from each tank are evaluated by measuring the mass and percentage increase daily. The average values of ten Abalones from each tank were computed for further evaluation to ensure precision and accuracy.

2.1 Abalone breeding modelling input-output parameters in RSM

The three environmental factors, otherwise known as input parameters (independent variables), used in Abalone breeding are water PH, Salinity, and Temperature. These independent variables relate to the output variables (AGR and SGR) by a quadratic response surface model. This model comprises linear and square terms. It also entails linear interactions as presented in Eq. (1) [11].

$$Y = \beta_o + \varepsilon \sum_{i=1}^{k} \beta_i x_i + \sum_{i-1}^{k} \beta_{ij}\, x_i x_j + \sum_{i=1}^{k} \beta_{ii}\, x_i^2 + \varepsilon \qquad (1)$$

Y,$\beta_o, \beta_i, \beta_{ij}, \beta_{ii}, X_i$ predicted response, mean, input factor, linear interactions, input factor quadratic effect, and random term, respectively.

A multiple regression mathematical model of second-order type was developed to forecast the responses (SGR and AVR). Also, Analysis of Variance (ANOVA) was used to determine the developed model's significance level. The fit analysis of the model was carried out using regression analysis, where the square of the correlation coefficient (R^2), adjusted R^2, predicted $R^{2,}$ and predicted error sum of square (PRESS) are evaluated to determine its adequacy.

2.2 Specific and absolute growth rate measurement

Before the experimental commencement, the Abalone was acclimatized for 14days under the influence of PH, salinity, and temperature in different tanks. Automatic Aquatic System (AAS) was installed in each tank to set and control the environmental factors (PH, salinity, temperature). The environmental factor value set in each tank was based on the RSM recommendation presented in Table 2. The initial weight of the Abalone was measured and recorded. Equal weight sizes were put in each tank. The specific growth rate (SGR) and absolute growth rate (AGR) of Abalone were monitored and evaluated daily by measuring the final weight and comparing it with the initial value by the relation presented in Eqs. (2) and (3) respectively [12].

$$SGR(\%/day) = \frac{l_{nW_2} - l_{nW_1}}{t} \times 100 \qquad (2)$$

$$AGR(g/day) = \frac{W_2 - W_1}{t} \qquad (3)$$

L_n = Natural Logarithm
W_2 = Final Abalone Weight
W_1 = Initial Abalone Weight
t = Time (days)

3. RESULTS AND DISCUSSIONS

3.1 Specific and absolute growth rate results

Table 3 presents the initial value of the environmental factors of the Abalone control sample breed in the facility of the Abagold company, where about 90% of the research was carried out. These values are within the range of standard factors presented in various research papers. It can be seen from the table that temperature, PH, and Salinity play a crucial role in the growth of Abalone.

Table 3. Control samples abalone growth environmental factors values

Environmental Factor	Value
Water Temperature(℃)	15
Salinity (ppt)	36
Nitrate (mg/L)	10
Water Flow(L/min)	14
PH	8.2
Ammonia (mg/L)	0.1
Nitrite	0.1

Table 4. SGR and AGR response to PH, salinity, and temperature

S/N	Original Value			Responses	
Exp. Runs	PH	Salinity	Temp	SGR (%/day)	AGR (g/day)
1	7.5	30	10	0.77	2.16
2	8.5	30	10	0.96	3.02
3	7.5	40	10	0.78	2.30
4	8.5	40	10	1.02	3.17
5	7.5	30	20	0.85	2.66
6	8.5	30	20	1.9	4.32
7	7.5	40	20	0.92	2.88
8	8.5	40	20	2.2	4.46
9	7.16	35	15	0.74	2.02
10	8.84	35	15	0.72	1.87
11	8	26.59	15	1.25	3.46
12	8	43.40	15	1.3	3.74
13	8	35	6.59	1.15	3.31
14	8	35	23.40	1.6	4.18
15	8	35	15	0.83	2.52
16	8	35	15	0.83	2.49
17	8	35	15	0.82	2.49
18	8	35	15	0.83	2.52
19	8	35	15	0.82	2.52
20	8	35	15	0.82	2.49

Table 4 displays the values of specific and absolute growth rates of the Abalone breed under different environmental factors. The specific growth falls between 0.72 to 2.2 %. In experiments order 1 and 2, it was noticed that salinity and temperature were held at 30ppt and 10°C, respectively, while the PH was varied from 7.5 to 8.5. At these values, the SGR rises from 0.77%/day to 0.96 %/day. This gives the significant difference of 0.19%/day and ditto for other PH variations. Also, in experiments order 1 and 3, the PH and temperature were held at constant values of 7.5 and 10°C, respectively, while the salinity was varied from 30-40ppt. In this case, the SGR rose from 0.77%/day to 0.78%/day, given an insignificant difference of 0.01%/day. In experimental orders 1 and 5, the PH and salinity were held constant at 7.5 and 30ppt, respectively, while the temperature was varied between 10°C - 20°C, the SGR rose from 0.77%/day to 0.85 %/day, given an average significance difference of 0.08%/day. All these imply that PH among the three environmental factors considered majorly influenced the Abalone growth more than the other two factors. The least significant factor is the temperature. In all these, the PH significance over temperature on the SGR of Abalone is obvious.

Similarly, the AGR values range from 1.87-4.46 g/day. The AGR follows a similar pattern to SGR. The AGR values at a constant salinity and temperature of 30ppt and 10°C, respectively, at a varied PH (7.5-8.5) in experimental orders 1 and 2 presented in Table 4 rose from 2.16 g/day to 3.02 g/day. This gave a significant difference of 0.86 g/day. Considering experimental orders 1 and 3 (constant PH and temperature of 6.5 and 60°C, respectively), salinity was varied between 30ppt to 40ppt; the increase in AGR was noticed from 2.16 g/day to 2.30g/day with a less significant difference of 0.14 g/day. In experimental orders 1 and 5 at a constant PH and salinity of 7.5 and 30ppt, respectively, but with different temperatures of 10°C and 20°C, the AGR also rose from 2.16 to 2.66 with semi semi-significant difference of 0.50 g/day. All these confirm the PH as the highest significance factor on both AGR and SGR of Abalone compared to the other two factors. It is also confirming the salinity as the least significant factor of significance. PH having a huge impact on the Abalone growth may be attributed to high PH that tends to increase the water oxygen level and thereby boost the Abalone respiration and its energy [13].

3.2 Empirical model

The coded factors were used in the development of the empirical model as presented in Eq. (4) and Eq. (5) for SGR and AGR, respectively.

$$Y_1\,(\%/day) = \{0.8240 + 0.1996A + 0.0384B + 0.2268C + 0.0350AB + 0.2375AC + 0.0375BC - 0.0272A^2 + 0.1654B^2 + 0.2008C^2\} \quad (4)$$

$$Y_2\,(g/day) = \{2.51 + 0.3454A + 0.0821B + 0.3759C - 0.0088AB + 0.1887AC + 0.0087BC - 0.2004A^2 + 0.3848B^2 + 0.4360C^2\} \quad (5)$$

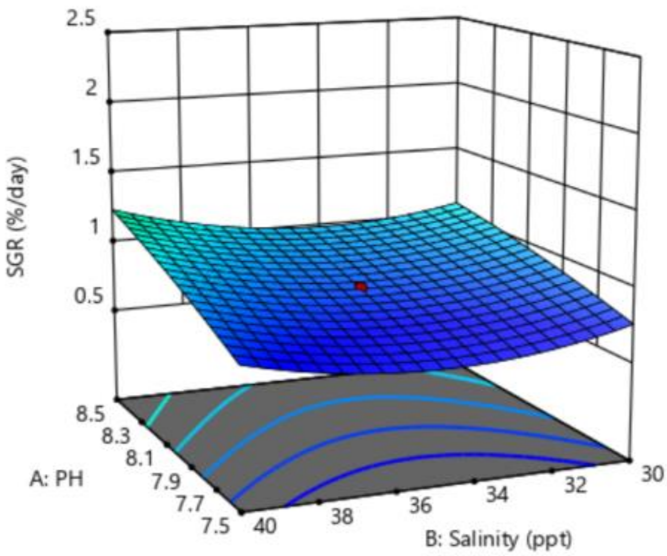
Y_1 = SGR response, Y_2 =AGR response, A= PH, B=Salinity, and C=Temperature.

3.3 Model significance

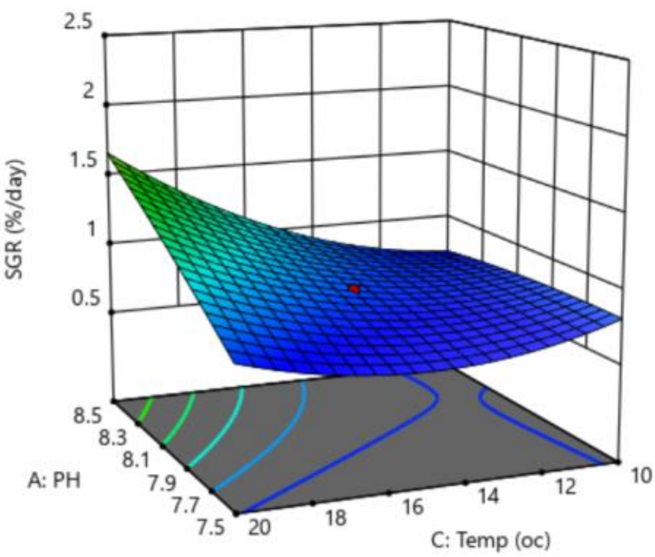
In the reliability Table 5, the factors are considered significant when the adequacy of this model was analysed using ANOVA data of p-value ≤ 0.05 and insignificant if otherwise [14]. Accordingly, the developed models are significant. Considering p-value for PH, salinity, and temperature. PH (A) and temperature (C) have better significance than salinity (B). The PH possesses the greatest impact on the responses. The model significance level of all the environmental factors considered for SGR and AGR is presented in Figures 2 and 3.

Table 5. Model ANOVA significance results

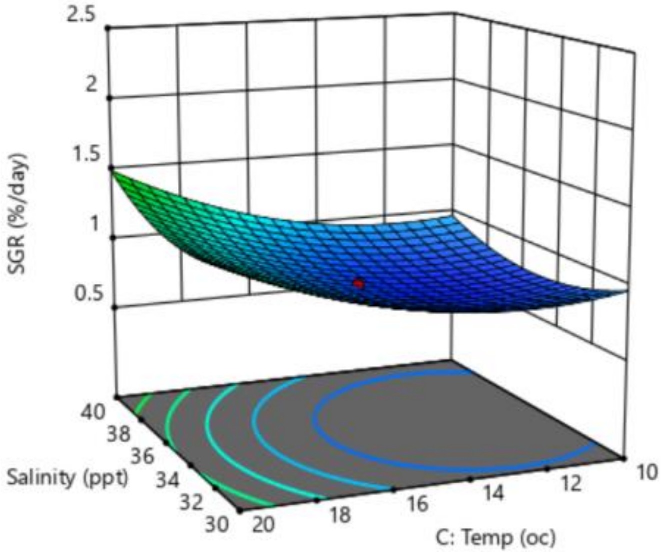
Source	SGR		AGR	
	F-Value	p- value	F Value	p-value
Model	5.91	0.0052	6.56	0.0035
A-PH	10.80	0.0082	10.16	0.0097
B-Salinity	0.3990	0.5418	0.5733	0.4664
C-Temp.	13.93	0.0039	12.02	0.0060
AB	0.1944	0.6686	0.0038	0.9520
AC	8.95	0.0135	1.78	0.2122
BC	0.2235	0.6467	0.0038	0.9520
A^2	0.2123	0.6548	3.61	0.0868
B^2	7.83	0.0189	13.30	0.0045
C^2	11.53	0.0068	17.07	0.0020



(a)

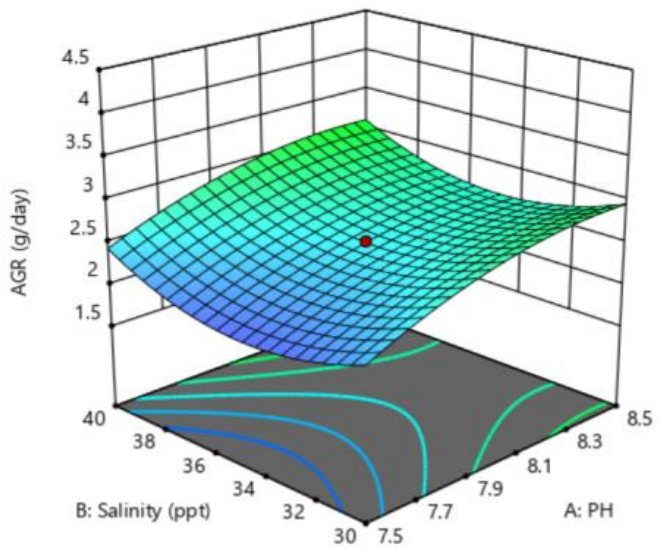


(b)

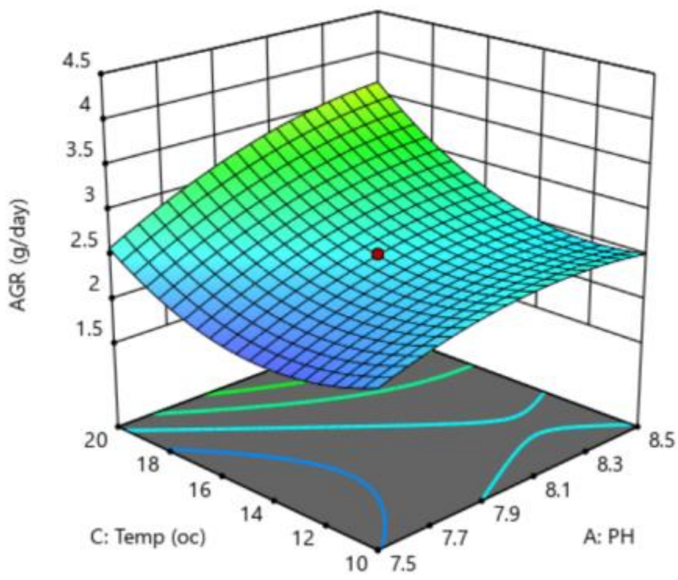


(c)

Figure 2. Responses to specific growth rate (a) PH and salinity (b) PH and temperature (c) salinity and temperature



(a)



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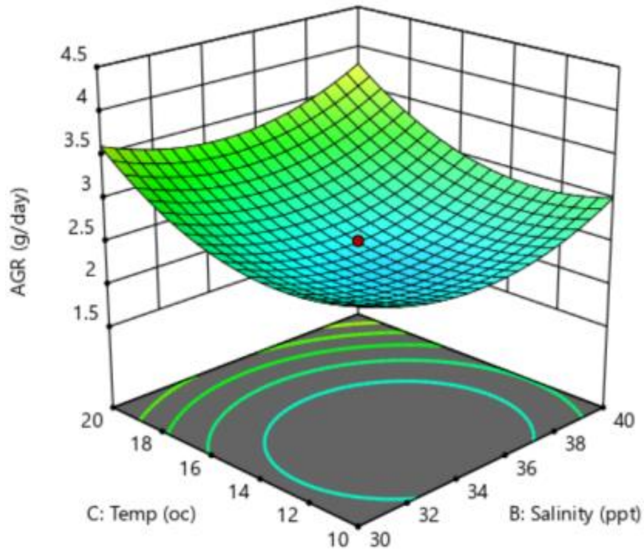


(c)

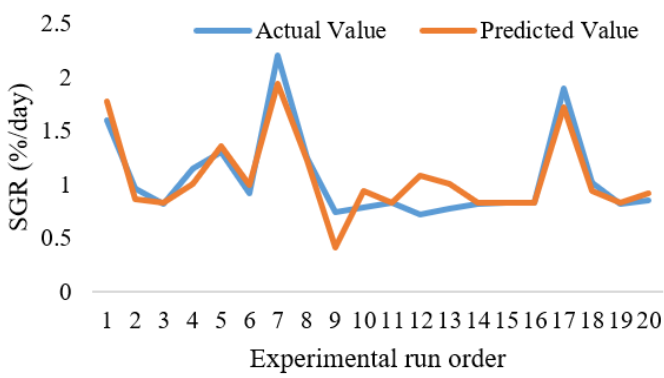
Figure 3. Responses to absolute growth rate (a) PH and salinity (b) PH and temperature (c) salinity and temperature

3.4 Model fitting analysis

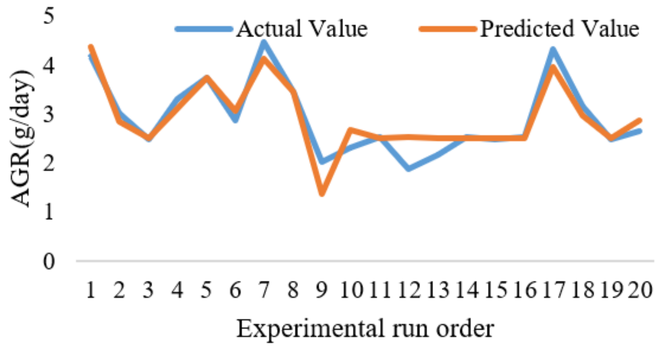
The first condition for an excellent fitting model is when the square of the correlation coefficient (R^2) is greater than or equal to 95% [15, 16]. The second condition is that the difference between predicted R^2 and adjusted R^2 obtained from the model should be less than 10% [15, 16]. Thirdly, the adequate precision, which is the measure of signal-to-noise ratio, should be greater than 4. In Table 6, R^2 for SGR and AGR are 95.50% and 97.63% respectively, which is an indication of a good fit model. Also, the difference between predicted R^2 and adjusted R^2 in SGR and AGR is less than 1%. They are both less than 10% and therefore imply a good fitting model. Adequate precision in both cases is less than 4% which affirms the existing indications of a good fit model, making it statistically stable and therefore can be employed in the navigation of the design space.

Table 6. ANOVA second-order model fitting result

Summary	SGR	AGR
Standard Deviation	3.155	3.116
R^2	0.9550	0.9763
Adjusted R^2	0.9737	0.9671
Predicted R^2	0.9752	0.9197
PRESS	564.61	548.55
Adeq Precision	32.27	32.28



(a)



(b)

Figure 4. Actual vs predicted value of environmental variables to (a) SGR, (b) AGR

Figure 4 presents the comparative plot to show the extent of the experimented value (actual value) and predicted values of all the experimental orders to the SGR and AGR, respectively. It can be deduced from the plots that the Actual value and predicted value exhibit similar behaviour with little deviation. This is an indication that the model is very precise. However, there is a noticeable deviation between the actual from predicted values in experiments 10 to 14 in both cases. These deviations may be due to some experiments conducted outside the design space indicated as -α and + α in Table 1, which are under experiments 10 to 14 in Table 2 as recommended by RSM [17].

3.5 Optimization and confirmation experiments

Through the Design Expert software, the desirability function/approach of the RSM was employed for environmental factors optimization in determining the best combinations of these factors that will yield the best output. The coded value was used. The prediction of the optimum values of the process variables was based on the developed empirical mathematical models presented in Eqs. (2) and (3) for SGR and AGR, respectively. The optimum environmental result obtained at a desirability of 1 based on RSM prediction is 8.18PH, 31.29 salinity, and 13.62 temperature. This will lead to AGR and SGR of 2.67g/day and 0.88%/day, respectively. These are presented in the optimization ramp presented in Figure 5. Confirmation tests were conducted for model result validation. Three confirmation experiments were conducted using the predicted optimum process parameters. The results of these confirmatory experiments to obtain SGR and AGR are presented in Table 7.

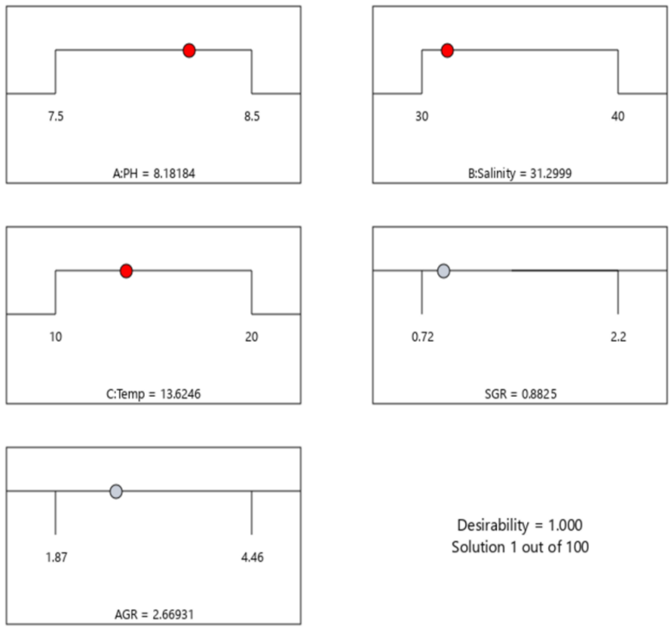


Figure 5. Process optimization ramp

Table 7. Confirmation experiment result for input factor influence SGR and AGR

Trials	SGR		AGR		%Variation	
	Experimented value	Predicted value	Experimented value	Predicted Value	SGR	AGR
1st	0.86	0.88	2.62	2.67	0.02	0.02
2nd	0.86	0.88	2.64	2.67	0.02	0.01
3rd	0.87	0.88	2.60	2.67	0.01	0.03

SGR percentage variation between the experimental values and predicted values for the first, second, and third trials is 0.02, 0.02, and 0.01%, respectively, while AGR percentage variations between experimental and predicted values are 0.01, 0.01, and 0.03. These are very low percentage variations, and the obtained results are an indication of model accuracy [18].

The study's findings on the significant impact of PH on abalone growth, with optimal conditions determined to be around 8.18 PH, 31.29 salinity, and 13.62 temperature, have broader implications for sustainable aquaculture practices and resource management. By optimizing environmental conditions, abalone farmers can potentially improve growth rates, reduce production costs, and promote more efficient use of resources. Furthermore, the study's results can inform strategies for mitigating the environmental impacts of aquaculture, such as water pollution and habitat degradation. The development of empirical models that accurately predict abalone growth rates can also facilitate the development of more sustainable and efficient aquaculture practices, contributing to the long-term viability of the industry. Overall, the study's findings have significant implications for environmental science and industrial engineering and can inform policies and practices that promote sustainable aquaculture and resource management.

4. FINDINGS ALIGNMENT AND DEVIATION FROM THEORETICAL EXPECTATION

The findings of this study largely aligned with theoretical expectations, showing that PH has a significant impact on abalone growth, likely due to its influence on water oxygen levels and later effects on respiration and energy allocation [7]. The results show that PH is the most significant factor affecting both specific growth rate (SGR) and absolute growth rate (AGR) of abalone, with optimal growth occurring at a PH of around 8.18. This is consistent with existing ecological theories and previous research on abalone growth [4].

However, the study's finding that salinity has a relatively minor impact on abalone growth is unexpected, given the importance of salinity in aquatic ecosystems. The study's results have practical implications for the abalone industry, highlighting the importance of optimizing environmental conditions, particularly PH, to promote rapid and consistent growth of abalone. Overall, the study's findings contribute to our understanding of the complex interactions between environmental factors and abalone growth and provide valuable insights for refining management strategies in abalone farming.

5. CONCLUSIONS

This work researched the degree of influence of three environmental factors (PH, salinity, temperature) on the specific growth rate (SGR) and absolute growth rate (AGR) of Abalone, specifically using a modelling and experimental approach. Mathematical models of quadratic form were developed for the prediction of the SGR and AGR. It was discovered that all three environmental factors considered in this research influenced the growth of Abalone, but at different rates. PH has the greatest influence, and the salinity with the least. The predicted optimum factors are 8.18 PH, 31.29 salinity, and 13.62 temperature. The deviations between the experimental results and the models are very small. There is also an agreement between all the correlation coefficients of the models. The developed model can predict the AGR and SGR accurately. Therefore, employing this model by Abalone breeding companies will enable them to predict the growth of abalone and be able to adjust those factors within the safe and profitable limits.

6. RECOMMENDATIONS

Future research directions should focus on validating the study's findings across diverse abalone farming environments, considering factors like varying water temperatures, salinity levels, and PH ranges. Exploring other influencing factors such as water flow rates, dissolved oxygen levels, nutrient availability, and genetic variation could provide a more comprehensive understanding of abalone growth. Additionally, investigating the impact of different species, stocking densities, and feed types on growth rates would be beneficial. Long-term studies and comparative analyses of various abalone species or strains under different environmental conditions would further enhance our knowledge, ultimately informing optimized farming practices. By addressing these limitations and exploring new avenues, researchers can develop more effective strategies for promoting healthy growth and sustainability in abalone farming.

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