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Optimal Feed Formulation for Abalone Growth: Kelp-Ulva-Spirulina Synergy via RSM

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ABSTRACT

This study investigates the natural feed supplements (kelp, ulva, and spirulina) on abalone growth, offering a nutritional solution to problems faced in abalone farming, like insufficient nutrient availability and reliance on expensive commercial feeds. It is a 3-month experiment with a sample size of 50 abalones per treatment group. Using Response Surface Methodology, quadratic models predicting abalone growth based on supplement percentages were developed. The study found that kelp and spirulina feed supplements had the most significant and least significant impact on abalone growth, respectively. The optimal feed composition was discovered at 8.63557% kelp, 8.83486% ulva, 6.06173% spirulina, yielding a 25.17% increase in weight and a 17.42% increase in shell width compared to the control group. This has yielded 3.34857 g/month and 1.07576 mm/month as the predicted responses for abalone weight gain and shell width. The high model's determination coefficient (R^2 = 0.965) and statistically significant regression coefficients (p = 0.0190) established its reliability and accuracy. The research's outcomes integrate numerical applications to make them practical for Abalone breeders, leading to precise predictions and adjustments of feed composition at the optimal level to enhance abalone growth and help in refining abalone farming management techniques to achieve optimized farming practices.

1. INTRODUCTION

The rate at which Abalone farming has evolved over the years cannot be overemphasized, with many feed compositions being used to feed them to enhance their health, growth, and make their breeding business sustainable. One of the major shellfish aquaculture products is Abalone, and it undergoes a series of processes before it can be sold globally in dried and canned form. It can also be sold fresh once after its harvest [1]. Abalones are grouped under marine snail mollusca that survive and breed well in shallow water, especially in rocky areas, temperate and subtropical zones. They can be categorized as herbivores because they feed on seaweeds and algae. At maturity, abalones can be harvested for meat, which is a special delicacy in South Africa due to their aroma and tender nature. As a result of its prolonged growth rate and longer years required to reach the edible stage, its market value keeps increasing every year [1].

Efforts to enhance and make the supply of both fresh and processed abalone sustainable require adequate growth condition optimization to achieve speedy development. It also involves the development of an enabling environment that is equivalent to abalone's natural habitat, in addition to feeding with a diet that is rich in essential nutrients, which can promote accelerated growth and substantially enhance their growth rate. This method not only lowers the time needed for abalones to attain market and edible size but also reduces the cost of production by improving feed efficiency and farm productivity in general [2].

The prolonged and irregular abalone growth rate with aquaculture poses a substantial problem not only to the commercial viability but also to the economic sustainability of the business [2]. Several efforts have been made by many global researchers to optimize feeding practice and environmental factors, but have been unsuccessful because abalone farming often faces challenges in meeting production schedules, as the growth period to reach a marketable size tends to be longer than anticipated. This discrepancy can lead to operational inefficiencies and higher costs.

These growth irregularities retard the capacity to meet global demand for abalone and consequently reduce the profit margin in abalone farming [3].

Abalone feed can either be formulated or supplemented. Its feeds are formulated to meet some specific requirements of nutrients for growth enhancement. Its feeds are formulated for an inclusion of lipids, mineral oil, vitamins, protein, carbohydrates, and other nutrients. Abalones' feed formulation can be achieved by grinding soybeans, fishmeal, and wheat flour and extruding them into pellets. The formulated feed is too expensive and can affect the profit margin of any farm breeding Abalone [4]. Supplementary feeds are derived by enhancing the formulated feed with some natural supplements that can be found in microalgae like kelp, ulva, and spirulina. These micro-algae supplements are rich in essential nutrients needed for Abalone growth if applied in adequate proportion. For example, Kelp has high mineral, vitamin, and antioxidant content, especially fucoidan, a sulfated polysaccharide that promotes absorption of nutrients and enhances gut health, responsible for its advantage over ulva and spirulina, while ulva and spirulina also have high protein, vitamins, and mineral content. Supplementary feeds are more effective and cost less because the micro algae supplements are from natural sources and readily available. Before the adoption of kelp and ulva, abalone farmers relied on other feed supplements. Some of these existing supplements include Fishmeal-based feeds, soybean meal, poultry byproduct, terrestrial-based plants such as corn, millet, etc. Kelp and ulva have become more preferable over these traditional supplements because it match the natural dietary requirements of abalone, it can be cultivated with minimal water and no fertilizers or pesticides, making them more environmentally friendly compared to terrestrial crops or fishmeal, and lastly, it is cost-effective because kelp and ulva farms are cheaper than purchasing or producing traditional feed supplements [4].

Specialized (supplementary) aquatic feeds compounded for abalones need to be meticulously formulated to replicate the natural diet of marine molluscs, which predominantly consists of seaweed, algae, and other marine vegetation [5-9]. These feeds are formulated to provide a balanced blend of essential nutrients (proteins, carbohydrates, vitamins, minerals) and natural supplements (kelp, ulva, spirulina) vital for the optimal growth, health, and development of abalones in aquaculture settings [10]. The introduction of feed supplements like kelp, ulva, and spirulina, which are very popular due to their nutritive contents and palatability, has enabled the abalone to receive adequate nutrients needed for enhanced growth. The application of such specially formulated food helps aquaculture farmers in enhancing the productivity and profitability of their business, because abalones are supplied with a diet that is nutritionally rich, specifically customized to support their physiological requirements and growth rate.

There is a need for extensive research and a refining process in formulating this unique feed that will focus on the optimization of its nutritional quality and effectiveness. In ensuring that abalone gets a diet that can be approximated to its natural food source, the feed manufacturers and scientists formulate the feed composition based on several factors such as abalone species, environmental factor, life stages, and their feeding ways [11]. For example, the nutritional requirements of younger abalones may be different from the bigger ones because the younger abalones need a richer diet to promote their growth and enable shell development, while the bigger ones need feed to ensure good health and boost their reproductive ability [12]. With the controlled production processes, these feeds will ensure adequate integrity and consistency and also enable the abalones to be nutritionally balanced at every feeding session. This consistency is very important in aquaculture, where different feed formulations with different quality can substantially affect the growth rate and health responses of the abalones [13].

There are so many technological advancements that promote the developmental innovations of aquatic feeds. Researchers are frequently exploring modern methods to promote nutrient absorption, digestibility, and palatability, enabling abalones to effectively utilize the nutrients supplied through their diet. For instance, recent research is based on promoting the bioavailability of important nutrients, which enables abalones to absorb and utilize these nutrients more efficiently, leading to improved health and growth rate results. Furthermore, these feeds are usually formulated to reduce waste and the environmental impact on abalone farming. It also promotes more sustainable aquaculture procedures. This is very crucial in the modern aquaculture system, where sustainability is the major factor, and the tendency to enhance abalone growth with a very high quality at reduced environmental influence is a key advantage.

Due to all the highlighted reviews and challenges, this research will focus on formulating a feed with different compositions and investigating the optimal type that gives abalone rapid growth. In contrast to past findings on the Response Surface Methodology (RSM) application in abalone feed composition, this research will enable a comparative analysis of the kelp, ulva, and spirulina effects on abalone growth, optimizing feed composition for enhanced growth rates. This will accelerate abalone growth, enabling them to reach marketable size more quickly and improve the overall efficiency and profitability of abalone farming. This research has contributed to the advancement of sustainable and economically viable practices in the aquaculture industry.

2. MATERIALS AND METHODS

2.1 Sample preparation

Kelp, ulva, and spirulina samples, which are respectively presented in Figures 1(a), (b), and (c), were thoroughly washed and rinsed to prevent them from contamination. These samples were dried and later ground into powder (Figures 1(e)-(f)). The nutritional properties of kelp, ulva, and spirulina powdered samples were characterized before being integrated at various percentages (10-25%) into the existing Abalone feed formulation that comprises soybeans 35-40%, fishmeal 20-35%, wheat flour 15-20% and others like vitamins, protein binders, and supplements, 30. These mixed samples were extruded into a pellet (Figure 1(g)) before subjecting the Abalone to feeding experiments.

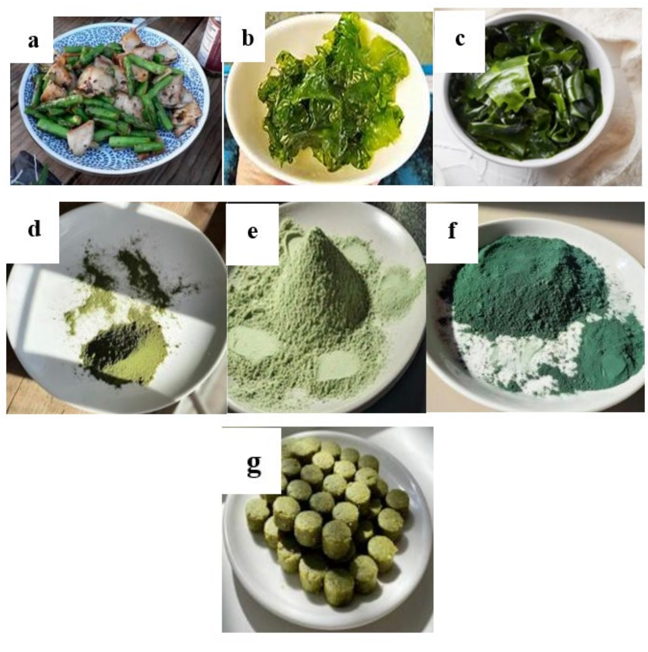


Figure 1. Sample of (a) kelp, (b) ulva, (c) spirulina, (d) powdered kelp, (e) powdered ulva, (f) powdered spirulina, (g) extruded and supplemented abalone feed

2.2 Experimental procedure

This study employed the Response Surface Methodology (RSM) approach of Design Expert software to investigate the effects of varying percentages of kelp, ulva, and spirulina on the weight and shell width of abalone. The experiment involved formulating 20 different feed samples with varying percentages of the three supplements (kelp, ulva, and spirulina), ranging from 25-30%. There was also an establishment of a control group by obtaining the basal feed with zero additives (0% kelp, ulva, and spirulina), to be a baseline for comparing the supplemented feeds. These percentages were selected based on standard practices and recommendations from literature on natural supplement inclusion rates in feed formulation [14, 15]. The experimental design matrix and factor levels are presented in Tables 1 and 2, respectively. which included three levels for each feed formulation: -1, 0, and +1, corresponding to low, mid, and high values, respectively. For instance, kelp percentages ranged from 5-10%, with 5% as the low point, 7.5% as the midpoint, and 10% as the high point. Similarly, ulva and spirulina composition percentages were varied within the same range. Values outside the design space are represented by -α and +α, as per RSM guidelines. Other feed components were maintained constant (35-40%, fishmeal 20-35%, wheat flour 15-20%) in all 20 feed samples that were compounded. This is to meet the nutritional requirements of abalone. The feed samples were then fed to abalone in 20 separate tanks, each containing 50 abalone having an average weight and width of 25.5g and 35.2 mm. The abalone was acclimated in a tank (Figure 2) to the experimental conditions for 2 weeks before the start of the experiment, with water temperature and salinity levels maintained at 18.2 ± 0.5°C and 35.1 ± 1.2 ppt. Abalone weight and its shell width were evaluated every month. In determining the weight of the abalone was measured using a digital top pan balance scale, and the shell was measured with a digital calliper.

Table 1. Breeding feed composition factors and levels

Factors	Level					
	Code	-1	0	+1	-α	+α
Kelp (%)	K	5	7.5	10	3.30	11.70
Ulva (%)	U	5	7.5	10	3.30	11.70
Spirulina (%)	S	5	7.5	10	3.30	11.70

A total of 10 abalones from each tank were sampled, and their measurements were averaged over a 3-month observation period to obtain reliable data for assessment.

Figure 2. Abalone acclimation tank

Table 2. Coded and original values in experimental details

S/N	Coded Value			Original Value		
	Kelp	Ulva	Spirulina	Kelp (%)	Ulva (%)	Spirulina (%)
1	-1	-1	-1	5.00	5.00	5.00
2	+1	-1	-1	10.00	5.00	5.00
3	-1	+1	-1	5.00	10.00	5.00
4	+1	+1	-1	10.00	10.00	5.00
5	-1	-1	+1	5.00	5.00	10.00
6	+1	-1	+1	10.00	5.00	10.00
7	-1	+1	+1	5.00	10.00	10.00
8	+1	+1	+1	10.00	10.00	10.00
9	-α	0	0	3.30	7.50	7.50
10	+α	0	0	11.70	7.50	7.50
11	0	-α	0	7.50	7.50	7.50
12	0	+α	0	7.50	7.50	7.50
13	0	0	- α	7.50	3.30	3.30
14	0	0	+ α	7.50	11.70	11.70
15	0	0	0	7.50	7.50	7.50
16	0	0	0	7.50	7.50	7.50
17	0	0	0	7.50	7.50	7.50
18	0	0	0	7.50	7.50	7.50
19	0	0	0	7.50	7.50	7.50
20	0	0	0	7.50	7.50	7.50

2.3 Feed composition modelling input-output parameters using the Response Surface Methodology approach

The abalone feed formulation consisted of three key supplements: kelp, ulva, and spirulina, whose proportions were treated as independent variables. A quadratic model was employed to describe the relationships between these variables and the response variables (weight and shell width), incorporating both linear and quadratic effects as well as interaction terms, as shown in Eq. (1) [16].

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

In the model, Y represents the predicted response, while β_o, β_i, β_{ij}, β_{ii}, and X_i denote the mean, main effects, interaction terms, quadratic effects, and random error, respectively. A second-order regression model was constructed to predict growth rate and shell width. Model significance was assessed using Analysis of Variance (ANOVA). Model fit was evaluated through regression analysis, focusing on coefficients like R^2, adjusted R^2, predicted R^2, and PRESS to determine model adequacy. Model diagnostics, such as predicted versus residual plot, were employed in evaluating normality and ensuring the response surface model validity.

2.4 Change in weight and width measurements

To measure abalone weight in grams per month and shell width in mm per month in response to various feed compositions with different supplements (kelp, ulva, and spirulina), a standardized procedure aligned with SDG Goal 14 (Life Below Water) was followed. The process involves, preparing experimental feeds with varying supplement percentages, randomly assigning abalone to feeding groups (20) receiving different feeds, monitoring and recording feeding regimes, regularly sampling abalone every month and measuring weight using a digital top pan balance scale and shell width using digital callipers, calculating weight gain/reduction as the change in weight (g/month) or shell width (mm/month) over time using Eqs. (2) and (3), respectively [16]. The last procedure is comparing growth performance among treatment groups to evaluate the effects of different feed compositions. This procedure enables to identification of optimal feed formulations for enhanced abalone growth and informs sustainable aquaculture practices.

$$\text{Change in weight } (g/month) = \frac{W_2 - W_1}{t} \quad (2)$$

$$\text{Change in width } (mm/mouth) = \frac{b_2 - b_1}{t} \quad (3)$$

where,
W_2=Final Abalone Weight (g)
W_1=Initial Abalone Weight (g)
b_2=Final Abalone Width (mm)
b_1=Initial Abalone Width (mm)
t=Time (month)

3. RESULTS AND DISCUSSIONS

3.1 Change in weight and width measurement results

The composition of the standard Abalone feed used in the control group is detailed in Table 3. This feed formulation, which includes significant proportions of soybean and fishmeal as primary protein sources, aligns with the ranges suggested in existing literature [17-19]. Notably, the majority of the study was conducted at the Abagold company, where this feed composition was utilized.

Table 3. Percentage composition of conventional and unsupplemented abalone feed

Feed Constituents	Value (%)
Soybean	40
Fishmeal	35
Wheat flour	20
Mineral oil	14

Table 4 displays the values of Abalone weight and width gain under different feed formulations. The weight and shell width gains fall between 2.2 to 5 g/month, 0.71 and 1.61 mm/month, respectively. The noticed growth response can be connected to the different levels of bioactive compounds and essential nutrients in the supplements. The highest weight gain and shell width of 5 g/month and 1.61 mm/month were observed in experimental order 8, where an equal percentage (10%) of all abalone feed supplements (Kelp, ulva, and spirulina) were used in abalone feed formulation, implying a potential synergistic response to the supplements at the highest levels. The lowest weight gain and shell width of 2.2 g/month and 0.71 mm/month were observed at experimental order 1, where an equal percentage (5%) of all abalone feed supplements were used in feed formulation. These results are because these seaweeds offer a natural, nutrient-rich food source that can enhance abalone growth rates, improve feed efficiency, and promote overall health. However, to ascertain the degree of influence of each natural feed supplement on abalone weight and shell width, there is a need to compare some of the results presented in Table 4. From a critical comparison of experiment orders 1 and 2 in Table 4, it was discovered that the percentage of ulva and spirulina had equal percentages of 5% and the kelp percentage varied from 5% in experiment order 1 to 10% in experiment order 2. This has yielded a weight gain of 1.3 g/month (3.5 g/month in experiment 2, 2.2 g/month in experiment 1) and a shell width increase of 0.42 mm/month (1.13 mm/month in experiment 2, 0.71 mm/month in experiment 1). Also, relating experimental orders 1 and 3 from the same table, where kelp and spirulina have equal percentage of 5% and the ulva percentage was varied from 5% in experimental order 1 to 10 percent in experimental order 3. This has led to an Abalone weight and shell width increase of 1 g/month (3.2 g/month in experiment 3, 2.2 g/month in experiment 1) and 0.32 mm/month (1.03 mm/month in experiment 3, 0.71 mm/month in experiment 1), respectively. Similarly, in relating experimental order 1 with 5, where kelp and ulva have equal percentages of 5% and the spirulina percentage was varied from 5% in experiment 1 to 10% in experiment 5. It was discovered that there is a weight and shell width gain of 0.7 g/month (2.9 g/month in experiment 5, 2.2 g/month in experiment 1) and 0.22 mm/month (0.93 mm/month in experiment 5, 0.71 mm/month in experiment 1).

These results have revealed kelp as the Abalone feed supplement with the most impact on the weight and shell width gain of the Abalone, while spirulina has the least impact on the Abalone growth. This is because the percentage weight and shell width gain when kelp was varied upward was larger compared to when the other two supplements and it is lower compared to the other two when spirulina was varied. The high significance impact of kelp over ulva and spirulina may be attributed to its optimal nutrient profile, palatability, and digestibility. Kelp's nutrient-rich composition, including essential amino acids, vitamins, and minerals, closely matches abalone's dietary requirements, supporting healthy growth and development [5]. Additionally, kelp's natural, marine-based origin might make it more appealing and easily digestible for abalone, leading to improved feed intake and utilization, and ultimately, enhanced growth rates compared to ulva and spirulina. These findings align with past outcomes on the seaweed-based feed supplements application in aquaculture [17-19], suggesting that kelp can be effective in enhancing abalone growth rates and feed efficiency compared to ulva and spirulina. The kelp contains bioreactive compounds such as fucoxanthin, a carotenoid with antioxidant and anti-inflammatory properties, which may be responsible for the noticed growth-enhancing response in abalone, highlighting the potential advantage of adding kelp to aquaculture feed formulations [17].

3.2 Model equations

The developed quadratic equations that can be used to forecast the Abalone weight and its shell width are presented in Eq. (4) and Eq. (5), respectively.

$$Y_1\,(g/month) = \{2.95 + 0.4347A + 0.2317B + 0.1268C + 0.0625AB + 0.125AC - 0.0625BC + 0.1251A^2 + 0.2135B^2 + 0.0544C^2\} \quad (4)$$

$$Y_2\,(mm/month) = \{0.9452 + 0.1530A + 0.0746B + 0.0402C + 0.0200AB + 0.0050AC - 0.0200BC - 0.0416A^2 + 0.0699B^2 + 0.0186C^2\} \quad (5)$$

where, Y_1 = Weight response, Y_2 = Shell width response, A= %kelp, B= % ulva, and C=% spirulina.

Table 4. Weight and width gain response to kelp, ulva, and spirulina percentage feed supplements

Exp. Order	Original Value			Responses	
	Kelp (%)	Ulva (%)	Spirulina (%)	Weight Gain (g/month)	Width Gain (mm/month)
1	5.00	5.00	5.00	2.20	0.71
2	10.00	5.00	5.00	3.50	1.13
3	5.00	10.00	5.00	3.20	1.03
4	10.00	10.00	5.00	4.50	1.45
5	5.00	5.00	10.00	2.90	0.93
6	10.00	5.00	10.00	4.00	1.29
7	5.00	10.00	10.00	3.40	1.09
8	10.00	10.00	10.00	5.00	1.61
9	3.30	7.50	7.50	2.60	0.84
10	11.70	7.50	7.50	3.30	1.06
11	7.50	3.30	7.50	3.30	1.06
12	7.50	11.70	7.50	3.10	1.00
13	7.50	7.50	3.30	2.80	0.90
14	7.50	7.50	11.70	2.70	0.87
15	7.50	7.50	7.50	2.70	0.87
16	7.50	7.50	7.50	3.00	0.96
17	7.50	7.50	7.50	3.00	0.96
18	7.50	7.50	7.50	3.00	0.96
19	7.50	7.50	7.50	3.00	0.96
20	7.50	7.50	7.50	3.00	0.96

3.3 Model significance

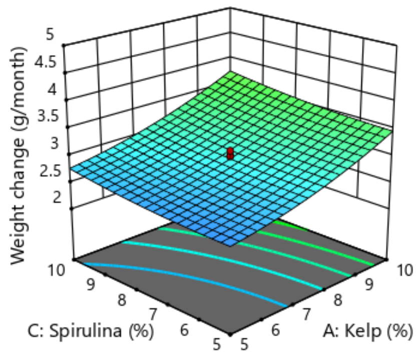
Table 5 presents the significance of the Abalone feed supplement (kelp, ulva, and spirulina) considered in this research for the enhancement of its weight and shell width. Model adequacy was assessed using ANOVA, with a significance threshold of $p \leq 0.05$ [20-22]. The results indicate that the models are statistically significant. Examination of the p-values reveals that kelp (A) and spirulina (C) exhibit stronger significance compared to ulva (B), with kelp having the most pronounced effect on the response variables. The significance levels for weight and shell width are visualized in Figures 3 and 4, respectively.

Table 5. Model ANOVA feed formulation significance results

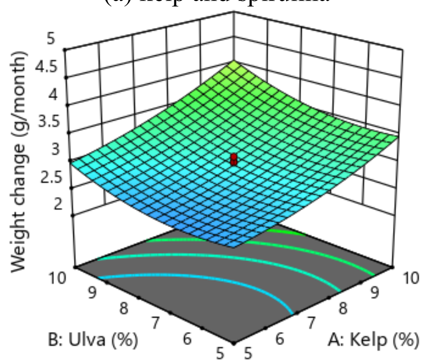
Source	Weight		Shell Width	
	F Value	P Value	F Value	P Value
Model	7.6800	0.0194	7.7800	0.0190
A-kelp	9.7900	0.0103	9.9900	0.0101
B-ulva	6.1800	0.0255	6.3800	0.0254
C-spirulina	6.7910	0.0420	6.6910	0.0425
AB	7.9000	0.0457	8.1000	0.0458
AC	6.1062	0.0551	6.0062	0.0534
BC	6.1100	0.0757	6.1000	0.0758
A^2	9.7883	0.0113	9.7783	0.0198
B^2	8.2100	0.0476	8.2000	0.0369
C^2	5.1657	0.0718	5.1557	0.0702

3.4 Model fitting analysis

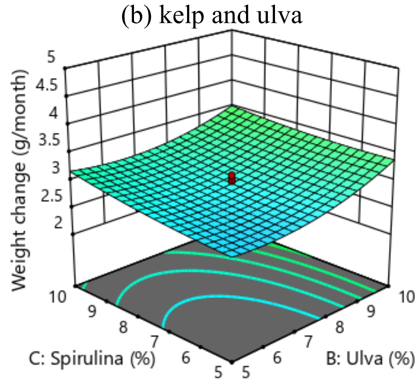
For a model to be considered fit, it must satisfy certain conditions. Firstly, the coefficient of determination (R^2) should be ≥ 0.95, indicating a strong correlation between predicted and actual values [16, 17]. Secondly, the difference between predicted R^2 and adjusted R^2 should be < 0.10, ensuring model stability [16, 17]. Lastly, the adequate precision, a measure of signal-to-noise ratio, should exceed 4.



(a) kelp and spirulina

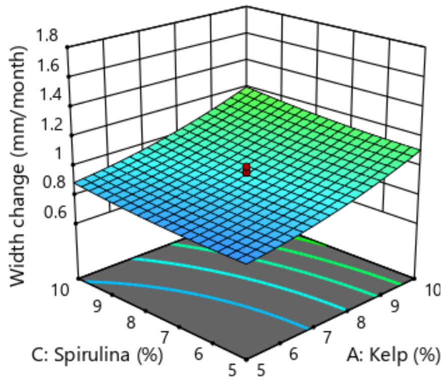


(b) kelp and ulva

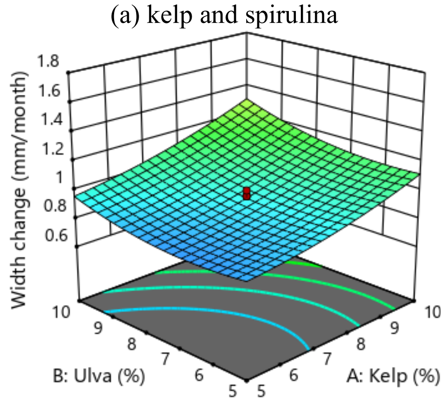


(c) spirulina

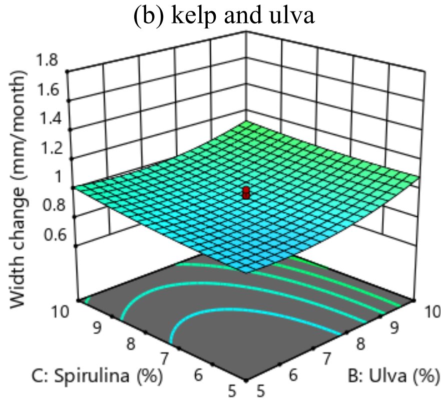
Figure 3. Feed supplement responses to weight



(a) kelp and spirulina



(b) kelp and ulva



(c) spirulina

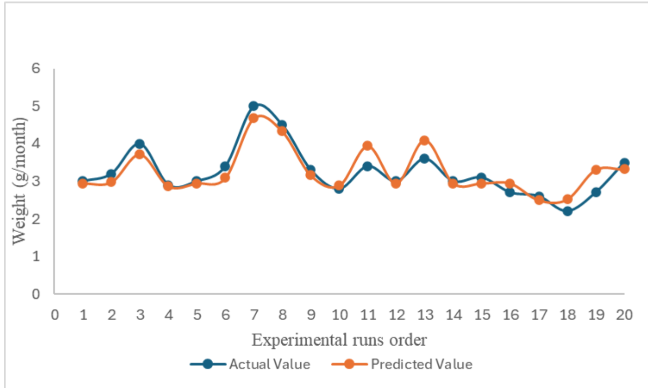
Figure 4. Feed supplement responses to shell width

The results in Table 6 show R^2 values of 96.50% and 97.36% for weight and shell width, respectively, indicating a good fit. The differences between predicted and adjusted R^2 are < 1%, satisfying the condition for model stability. However, the adequate precision values for both cases should be reevaluated, as the statement "less than 4%" seems inconsistent with the requirement for adequate precision to be greater than 4 for a good fit model.

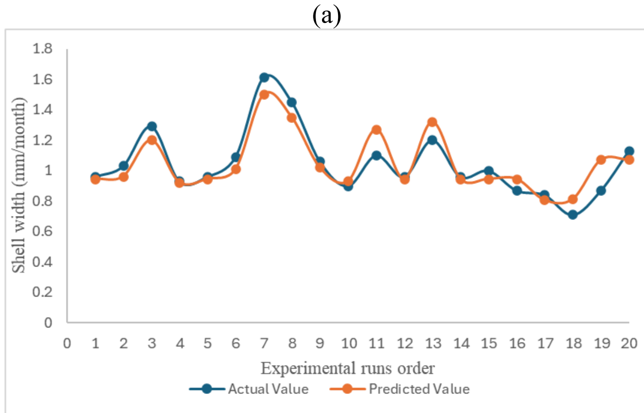
Table 6. ANOVA second-order model fitting result

Summary	SGR	AGR
Standard Deviation	3.851	3.661
R^2	0.9650	0.9736
Adjusted R^2	0.9773	0.9761
Predicted R^2	0.9527	0.9179
PRESS	545.16	545.55
Adeq Precision	32.73	32.81

The comparative plots (Figure 5(a) and (b)) show similar trends between actual and predicted values for weight and shell width, with minor deviations, confirming the model's precision. Notable deviations occur between experiment orders 10-14, likely due to experiments at axial points (-α and +α) expanded the design space (Table 1), as recommended by RSM [18].



(a)



(b)

Figure 5. Predicted vs actual value of kelp, ulva, and spirulina as a supplement to (a) abalone weight, (b) abalone shell width

3.5 Optimization and confirmation experiments

This study employed the desirability function approach of Response Surface Methodology (RSM) through Design Expert software to optimize abalone feed supplements, aiming to determine the optimal combinations that yield the best output in terms of weight and shell width. Empirical models (Eqs. (2) and (3)) were developed using coded values to forecast optimal process conditions for maximizing weight and shell width. The optimization process yielded an optimal feed composition at a desirability of 1, including 8.63557% kelp, 8.83486% ulva, and 6.06173% spirulina. This composition is predicted to result in a weight gain of 3.348357 g/month and a shell width increase of 1.07576 mm/month, as presented in the optimization ramp (Figure 6). To validate the model's accuracy, confirmation tests were conducted using the predicted optimum process parameters. Three confirmation experiments were performed, and the results are presented in Table 7. The percentage variations between experimental and predicted values for weight (1.82%, 2.72%, and 4.44%) and shell width (3.40%, 3.15%, and 3.33%) were low, implying model accuracy [18].

The research outcomes significantly impact sustainable aquaculture practices and resource management. The optimal percentage feed composition derived from this study is: 8.63557% kelp, 8.83486% ulva, and 6.06173% spirulina. This can enable feed formulation methods that enhance efficient resource use, rapid growth rates, and lower cost of production. The empirical model formulation that precisely forecasts abalone growth rate and shell development can contribute to more resilient and efficient aquaculture practices, ultimately supporting the sector's enduring success.

Also, the research outcomes have revealed the degree of kelp importance as a feed supplement in abalone nutrition, and its ability to promote growth rates and sustainable aquaculture practices. The outcomes of this research can inform decision-making and strategies that promote eco-friendly aquaculture and responsible resource stewardship, with potential applications in industrial engineering and aquaculture management.

Figure 6. Process optimization ramp

Table 7. Confirmation experiment results and their percentage variation for weight and shell width

Trials	Weight Gain (g/month)		Shell Width (mm/month)		%Variation	
	Exp.	Pred.	Exp.	Pred.	Weight	Shell Width
1st	3.28754	3.34857	1.03919	1.07576	1.82	3.40
2nd	3.25758	3.34857	1.04191	1.07576	2.72	3.15
3rd	3.19999	3.34857	1.03997	1.07576	4.44	3.33

4. CONCLUSIONS

In conclusion, this study provides valuable insights into the impact of three natural abalone feed supplements (kelp, ulva, and spirulina) on the growth of abalone, specifically weight and shell width. By creating predictive models for abalone growth, we've shown that tailored feed compositions can significantly enhance growth rates and consistency. Notably, our results emphasize the importance of kelp as a crucial supplement, with optimal growth achieved at specific inclusion rates: approximately 8.64% kelp, 8.83% ulva, and 6.06% spirulina. The study's results have practical implications for the abalone industry, enabling breeders to predict and adjust feed within safe and profitable limits.

This study enhances knowledge of the intricate relationships between abalone feed and growth, laying the groundwork for optimized farm management. Future investigations could build upon these findings by verifying their applicability in varied settings, examining other contributing factors, and assessing the effects of species, density, and feed variations on abalone growth performance. It should also ensure the long-term effects (≥6 months) of research on these feed supplements to evaluate their sustained efficacy and potential influences on abalone health and sustainability. Biochemical and metabolomics analysis are also recommended in the future to study the abalone nutrients utilization and absorption verification. Addressing these knowledge gaps, researchers can develop more effective strategies for promoting healthy growth and sustainability in abalone farming, ultimately informing optimized farming practices.

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