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Optimization of Processing Conditions for Sea Grape (*Caulerpa racemosa*) Sauce Using Response Surface Methodology

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Abstract *Caulerpa racemosa,* a green seaweed traditionally consumed fresh in coastal Indonesia, holds untapped potential as a functional food ingredient due to its rich content of bioactive compounds. However, its high moisture content and enzymatic activity limit shelf life, hindering commercialization. This study aimed to develop a functional seaweed-based sauce by optimizing the processing conditions using Response Surface Methodology (RSM). A Box-Behnken design was employed to investigate the impact of cornstarch concentration (2–4%), cooking temperature (70–100 ℃), and cooking time (30–60 minutes) on the sauce's physical properties, specifically pH and Total Dissolved Solids (TDS). Statistical analysis identified a significant quadratic model for TDS ($R^2 = 0.76$, $p < 0.05$) and a linear model for pH ($p < 0.0001$), with starch concentration having the most dominant effect. The optimal formulation, consisting of 2.99% cornstarch, 86.35 ℃, and 44.11 minutes, yielded a sauce with a pH of 3.435 and a TDS of 23.2%, as confirmed through experimental verification with minimal deviation. The acidic pH ensures microbiological safety, while high TDS reflects superior viscosity and nutrient retention. Organoleptic testing also indicated favorable acceptance for appearance, aroma, and taste, especially in formulations near the optimal condition. This approach enables efficient extraction of seaweed bioactives and effective gelatinization of starch, resulting in a stable, shelf-ready product. The study demonstrates a novel application of *C. racemosa* in processed foods, offering a sustainable solution to valorize local marine resources and expand the market for functional foods.

Keywords *Caulerpa racemosa*, Seaweed Sauce, Response Surface Methodology (RSM), Optimization

1. Introduction

Caulerpa racemosa is a green seaweed from the *Caulerpa*ceae family, traditionally used by coastal communities in Indonesia, especially in the Takalar area, South Sulawesi, Indonesia. As a local food source, C. racemosa is commonly consumed in its fresh form as a vegetable. Its use in general is still limited to fresh vegetables on the daily menu. However, this seaweed has a significant limitation: a relatively short shelf life due to its high water content and enzymatic activity, thus posing challenges in distributing and commercializing fresh products. *Caulerpa* seaweed has a diverse nutritional and phytochemical profile, with potential Health benefits [1–3].

Previous research has shown that C. racemosa contains a variety of bioactive compounds [4], including sulfate polysaccharides, flavonoids, alkaloids, and terpenoids, which exhibit pharmacological activities such as antioxidants [5], anti-microbial [6], anti-cancer [7], and anti-inflammatory [8]. Additionally, the high content of dietary fiber and minerals supports its use as a functional food ingredient [9,10]. However, most existing research still focuses on characterizing bioactive components and has not led to the development of ready-to-consume food products with these functional values.

The use of seaweed as an innovative raw material in the food industry has undergone rapid progress. However, most studies focus more on brown seaweed types, such as Sargassum, or red seaweed, such as Eucheuma. At the same time, exploration of C. racemosa is still limited, particularly in the form of sauce products. Previous studies on the processing of C. racemosa primarily centred on the drying aspect [11,12], fermentation [13], and flour making [14,15], and have not specifically developed a sauce formulation with a systematic process parameter optimization approach.

Sauce is a semi-liquid food product that is generally made from basic ingredients such as fruits, vegetables, or other food ingredients that are mashed and mixed with various spices, then processed through cooking [16]. Sauces serve as a food complement that can enhance dishes taste, aroma, and appearance. The composition of the sauce (high in water content, acidifying compounds, and thickening agents) allows for complex interactions between ingredients, which can affect the product's final characteristics. The quality of the sauce is affected by various process parameters, such as the concentration of thickening ingredients [17], cooking temperature [18], and the length of cooking time [19]. The interaction between these three parameters directly affects the sauce’s physical and chemical characteristics, including pH and total dissolved solids, which are important indicators in assessing the product's stability and final quality.

Optimization of processing conditions is a crucial stage to ensure that the resulting products are not only of optimal quality but also economically efficient and reproducible. To achieve this, systematic statistical approaches such as *the Response Surface Methodology* (RSM) are widely used because they can evaluate the simultaneous influence of several independent variables on one or more response variables [20,21]. The RSM method allows the formulation of mathematical models that can quantitatively describe the relationships between variables. This approach enables the determination of the optimal combination of variables to produce the desired response, such as the pH and total dissolved solids of C. racemosa sauce. The advantage of this method lies in the efficiency of the number of experiments required and the accuracy of the optimization results.

Previous studies have used RSM extensively in the optimization of the processing of fishery products, such as the optimization of fish protein hydrolysate [22], Fish Fryer Optimization [23], Optimization of fish skin gelatin extraction [24], Optimization in the processing of fish crackers [25], and Alginate Extraction Optimization [26]. The processing of sauces from seaweed aims to extend the shelf life and maintain the nutritional and functional value of its natural raw materials. Optimally developed seaweed sauce has the potential to be a natural flavor enhancer product. Based on this background, this study aims to optimize the processing conditions of C. racemosa sauce by varying three main parameters, namely the concentration of cornstarch as a thickening agent, cooking temperature, and cooking time. Optimization utilizes the RSM method, based on the Box-Behnken design, to obtain a combination of process conditions that yields the best sauce characteristics in terms of pH and total dissolved solids (TDS). The results of this research are expected to make a scientific and practical contribution to the innovation of seaweed-based products, supporting the sustainable development of the local food industry.

2. Materials and Methods

2.1. Materials and Tools

The main ingredient in this study is fresh *Caulerpa racemosa* seaweed obtained from aquaculture ponds in Takalar Regency, South Sulawesi. This seaweed is used as the basic ingredient for making sauces. Additives used in formulations include cornstarch (as a thickening agent), sugar, salt, and water as a solvent. Additionally, professional analysis chemicals are used for laboratory analysis purposes to determine the physical characteristics of the sauce, including pH and total dissolved solids.

2.2. Experimental Design

The design of this study uses the *Response Surface Methodology* (RSM) approach with *a Box-Behnken Design* (BBD) design consisting of three independent variables, namely: cornstarch concentration (A, 2–4%), cooking temperature (B, 70–100 ℃), and cooking time (C, 30–60 minutes). In total, 17 treatment combinations were randomly generated by the Design Expert® software version 7.0. The observed response variables included pH values and total dissolved solids (% Brix), which reflected the physical quality of the sauce.

2.3. Procedure for Making *Caulerpa* Sauce

The preparation of the seaweed sauce (*Caulerpa racemosa*) began with washing the seaweed using running water to remove dirt, sand, and salt that had stuck to it. After being cleaned, the seaweed was drained for approximately 10 minutes and then weighed to 1 kg. The weighed seaweed was mashed using a blender until a homogeneous, smooth pulp was obtained. Separately, cornstarch was weighed to a predetermined concentration and then dissolved in water until a clump-free solution was formed. The seaweed slurry was mixed with the cornstarch solution in a saucepan and then cooked at a temperature corresponding to the treatment. The mixture was stirred constantly to maintain temperature homogeneity and stability. After the mixture began to thicken, additional ingredients, such as sugar, table salt, citric acid, or food vinegar, were added to enhance the taste and stability of the product. Once the cooking process was complete, the sauce was filtered using sterile gauze or a fine sieve to produce a softer texture. It was then cooled to room temperature (approximately 25–30 ℃) under hygienic conditions. The sauce that had been cooled was packed into glass bottles and filled almost completely to minimize air space.

2.4. Response Analysis

Analysis of pH values was carried out using a digital pH meter [27]. Meanwhile, the measurement of the total dissolved solids (% Brix) was carried out using a digital refractometer, referring to [28]. Each combination of treatments was tested with three replicates, and the measurement results were recorded for further statistical analysis.

2.5. Organoleptic Test

Organoleptic testing of *Caulerpa racemosa* sauce was conducted to evaluate consumer acceptance based on key sensory attributes, including appearance, aroma, and taste. A total of 30 semi-trained panelists participated in this test, comprising lecturers and students with experience in sensory evaluation. Each panelist was given a sample of the sauce that had been randomly coded and served at room temperature in calm environmental conditions, free from aroma disturbances. The assessment was conducted using a nine-point hedonic scale that measures the level of likability for each attribute. The highest score of nine indicates "very like", while the lowest score of one indicates "reject". This hedonic score serves as the basis for evaluating the most preferred sauce formulas. It is used as a consideration in determining the optimal formulation that is not only physically and chemically superior, but also sensory, according to consumer preferences.

2.6. Statistical Analysis and Optimization

The data obtained were analyzed using Design-Expert software version 7.0. The appropriate regression model was selected based on the results of *the Analysis of Variance* (ANOVA), with significance criteria ($p < 0.05$), a high *Adjusted R-squared* value, and an insignificant *Lack of Fit* value ($p > 0.05$). The best models are then used to build a response surface in 2D contour and 3D graphs. Furthermore, process parameters are optimised using the numerical optimization feature to obtain a combination of variables with *the highest desirability* value. Optimization aims to maximise total dissolved solids, keep pH values within the standard range (3–4), and minimise energy and raw material use.

2.7. Verification of Optimum Conditions

After the optimal conditions are obtained, the verification stage is carried out by reapplying the sauce formulation according to the optimization recommendations of the results. The resulting sauce product is then re-analysed to measure the pH and total dissolved solids. The verification results were compared to the model's predictive values using *the 95% Confidence Interval (CI) and the 95% Prediction Interval (PI*) to assess the model's accuracy.

3. Results and Discussion

3.1. Optimization of Processing Conditions for Sauce

Physical characteristics, such as pH and total dissolved solids, are the leading indicators in determining the quality and stability of sauce products, especially those with seaweed-derived base ingredients like *Caulerpa racemosa*. pH plays an important role in maintaining microbiological stability and influencing taste and shelf life. At the same time, total dissolved solids are closely related to the product's viscosity, consistency, and taste perception. Variations in the concentration of thickening agents (such as corn starch), heating temperatures, and processing times can significantly impact these two characteristics. Industry standards for sauce products typically include a pH range of 3.0 to 4.0 to ensure microbiological resistance and a total dissolved solids content of at least 20%, guaranteeing adequate viscosity and texture.

The effect of corn starch concentration is evident from the comparison between formulas with starch content of 2%, 3%, and 4% (Table 1). The higher the concentration of starch, the lower the pH and the higher the TDS value. For example, at a temperature of 85 ℃ and 60 minutes, the pH decreases from 3.8 (2% starch) to 3.6 (4% starch), while the TDS increases from 26% to 29%. The process of gelatinization of starch, in which heating causes the release of amylose and amylopectin compounds into the solution, increases the content of dissolved solids [29]. A drop in pH can be attributed to the possible interaction between starch and acidic compounds from seaweed released during heating, resulting in a product with more potent acidic properties [30].

Table 1. pH and total dissolved solids *Caulerpa* sauce by processing conditions

Formula	Corn starch (%)	Temperature (°C)	Time (min)	pH	Total Dissolved Solids (mg/L)
F1	2	70	45	3.6	24
F2	4	70	45	3.5	25
F3	2	100	45	3.2	25
F4	4	100	45	3.3	28
F5	2	85	30	4.0	22
F6	4	85	30	3.2	25
F7	2	85	60	3.8	26
F8	4	85	60	3.6	29
F9	3	70	30	3.1	22
F10	3	100	30	3.8	23
F11	3	70	60	3.3	21
F12	3	100	60	3.5	26
F13	3	85	45	3.0	23.4
F14	3	85	45	3.3	24
F15	3	85	45	3.2	23
F16	3	85	45	3.6	23.5
F17	3	85	45	3.4	22

Processing temperature is a variable that directly affects the extraction intensity of bioactive compounds from *Caulerpa racemosa*. When the temperature is raised from 70 °C to 100 °C (at a fixed concentration and time), there is a decrease in pH and an increase in TDS. A formula with 2% starch and a time of 45 minutes exhibited a decrease in pH from 3.6 (at 70 °C) to 3.2 (at 100 °C) and an increase in TDS from 24 mg/L to 25 mg/L. Heat treatment increases the solubility of polysaccharides and bioactive compounds in seaweed [31,32]. High temperatures can also accelerate the hydrolysis reaction of complex compounds into simpler, soluble forms, thereby increasing TDS levels.

This study identified that a combination of corn starch concentrations of 3–4%, temperature of 85–100 °C, and heating time of about 45 minutes is the optimal range to produce *Caulerpa racemosa* sauce with a relatively stable pH (3.2–3.6) and high TDS content (23–29 mg/L). Too short a cooking time can cause the gelatinization process of the starch to be incomplete, resulting in a diluted and unstable texture [33], Meanwhile, too long a time causes structural degradation, water loss, and reduced viscosity [34]. The cooking duration needs to be precisely set to balance the formation of the desired viscous structure and prevent damage to the active compounds. The 45-minute treatment seems to be a relatively practical middle point, as it produces a texture and physical stability that meets the quality criteria of the sauce, while maintaining the sensory and chemical characteristics of the seaweed base.

The ANOVA analysis performed for each response showed differences in the form of the corresponding model and its statistical significance. For the pH variables (Table 2), a linear model was used and proved to be very significant ($P < 0.0001$), which indicates that the main variables, namely corn starch concentration (A), temperature (B), and heating time (C), collectively exert a significant influence on the pH value of *Caulerpa racemosa* sauce. However, a *lack of fit* value of 0.3307 indicates a model mismatch with the data, indicating that the linear model may not fully capture the complexity of the relationship between variables and responses. This can be due to interactions or quadratic effects not accommodated in the linear model. Therefore, alternative modeling approaches, such as quadratic models, can be considered for further analysis to enhance suitability.

Meanwhile, the quadratic model showed more representative results for the total dissolved solids variable (Table 2). With a significance value of 0.0143 ($P < 0.05$), this model is considered valid in explaining the influence of variables on response. *A lack of fit* value of 0.1416 (> 0.05) indicates that the model fits well with the experimental data and is reliable for prediction and interpretation. The resulting quadratic model equation was $Y = 23.18 + 1.25A + 1.25B + 1.25C + 0.5AB + 1BC + 2.41A^2 - 0.09B^2 - 0.09C^2$, which explains that the three main variables contribute positively to the increase in total dissolved solids, especially from the quadratic effect of corn starch concentration (A^2) that shows the most significant impact.

Table 2. Model linear of Sea grape sauce (ANOVA)

Response	Model	Equation	Significant (P<0.05)	*Lack of fit* (P>0.05)	R^2
pH	Mean	Y = 3.44	< 0.0001	0.3307	0.00
Total Dissolved Solids (%)	Quadratic	$Y=23.18+1.25A+1.25B+1.25C+0.5AB +1BC+2.41A^2-0.09B^2-0.09C^2$	0.0143	0.1416	0.76

Based on these equations, it can be seen that the increase in the value of dissolved solids is not only influenced by the direct increase of each variable (A, B, and C), but also by the interaction between variables (AB and BC), as well as the quadratic influence. The highest contribution comes from the concentration of starch ($A^2 = 2.41$), indicating that at specific concentrations, the addition of starch has a greater effect on increasing viscosity and solids. In contrast, the relatively small adverse effects of B^2 and C^2 (-0.09) suggest that the temperature and heating time have a saturation point, beyond which further increases will not result in the addition of solids. They may even decrease them due to degradation or evaporation of active compounds. This is in line with the previous discussion that too long a heating time or too high a temperature can cause a decrease in the quality of texture and stability of food products [35,36].

ANOVA results support the empirical findings from previous experimental data. The significance of the model and the magnitude of the coefficient of determination ($R^2 = 0.76$ for the total dissolved solids) suggest that the quadratic model has a sufficiently strong predictive capability to describe the C. *racemosa* sauce formulation system. The dominant influence of starch concentration on this viscosity parameter reinforces the assumption that thickening materials play a central role in shaping the final physical characteristics [37–39]. A non-linear model is needed to describe the pH response, showing that the sauce's acidity changes result from a complex reaction process during heating that is not linear to the treatment.

3.2. Response Analysis pH Value

The pH value is a crucial parameter in the formulation of liquid food products such as sauces, as it affects not only the microbiological safety but also the organoleptic quality of the product. The pH value ranges from 3 to 4, with a predicted average value of 3.43529. This value indicates that *Caulerpa racemosa* sauce is classified as a food product with high acidity, so it is within a safe range from the potential growth of pathogenic microorganisms such as *Clostridium botulinum,* which generally do not grow at pH < 4 [40]. The low pH value of the sauce can maintain the integrity of the pigment and prevent the oxidation of fats in processed products in liquid form [41].

The 3D surface graph (Figure 1) shows that increasing temperature and cooking time simultaneously tends to lower the pH value, especially at high concentrations of corn starch. Possible hydrolysis of organic compounds in *Caulerpa racemosa* when heated, resulting in acidic compounds such as free fatty acids and amino acids [42]. In addition, corn starch added in high concentrations can be a source of partial Maillard reactions, especially at high temperatures, resulting in acidic organic compounds that lower pH [43].

The distribution of residual values to pH values on the standard graph of the plot of residuals shows a distribution that follows the normal distribution. This indicates that the regression model constructed meets the basic assumption of residual normality, which is crucial for the validity of using Response Surface Methodology (RSM). The data points are symmetrically scattered around a straight line, indicating that there are no significant deviations from the standard distribution assumption and supporting the feasibility of this pH prediction model for mathematical process simulation and optimization.

The combination of high temperatures (>80 ℃) with long cooking times (>10 minutes) and starch concentrations >2% resulted in a sharp decrease in pH values. This may be due to the degradation of polymeric components in *Caulerpa racemosa*, such as polysaccharide sulphates, which produce acidic functional groups [44]. On the other hand, treatment with a moderate temperature (70-75 ℃) and a short cooking time (5-7 minutes) at a low concentration of corn starch shows a tendency for the pH value to be close to neutral, which can result from the lack of complex compound breakdown reactions. These results reveal the sensitivity of the active compounds in algae to thermal treatment.

Comparing these results with similar studies on seaweed-based sauces [45,46], *Caulerpa racemosa* produces a lower pH, signalling higher antioxidant potential and fermentative activity. *Caulerpa* contains acidic phenolic compounds and active pigments [47,48]. Therefore, using *Caulerpa racemosa* as the main ingredient and as a natural acidifier is an innovative approach to developing sea-based functional sauces. Process parameters significantly control the pH value, opening up opportunities for more precise flavour engineering and sauce functionality. Adjustments to starch concentration, temperature, and cooking time should be made to produce the desired texture and viscosity, while also controlling the acidity profile to maintain sensory quality and ensure product safety.

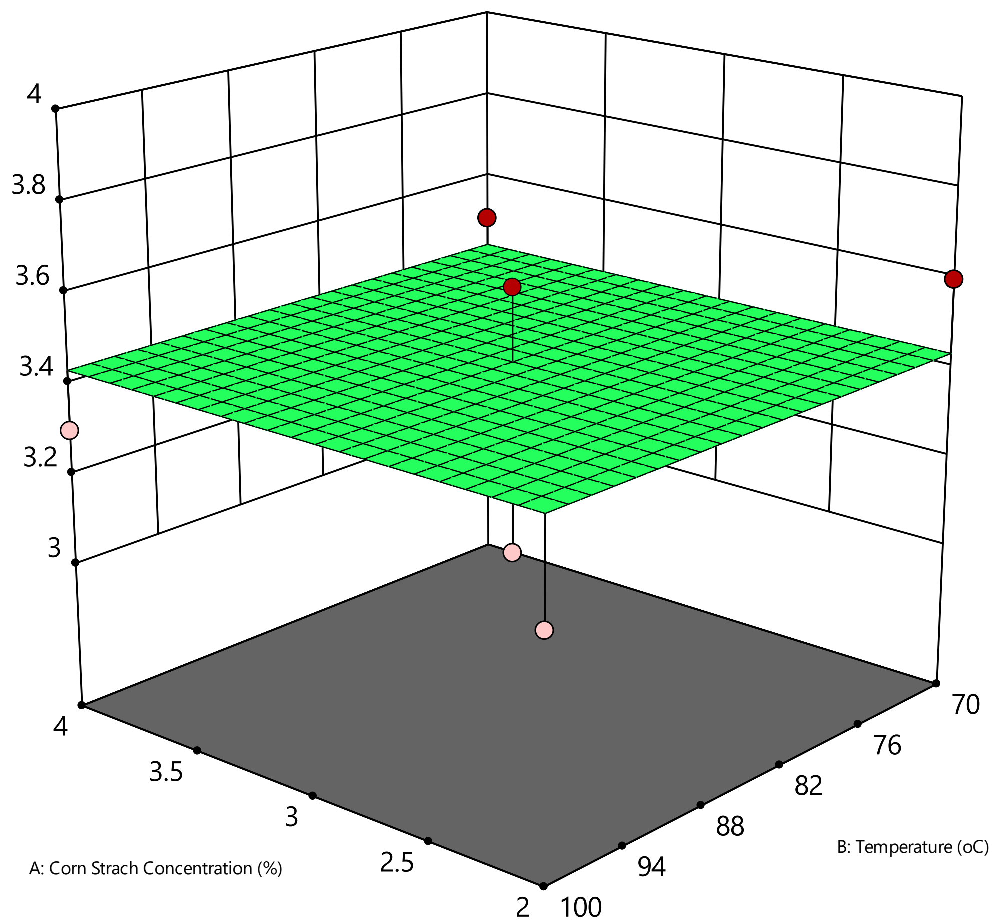

Figure 1. 3D response surfaces of pH response test

3.3. Analysis of TDS Value Response

Total Dissolved Solids (TDS) is an important indicator that reflects the number of dissolved compounds in liquid products, such as sauces, and plays a direct role in determining the taste, viscosity, and shelf life of these products. A high TDS can signify maximum extraction of nutrients and bioactive substances during thermal processing, providing functionally and sensorily added value. Seaweed contains dissolved compounds that are highly responsive to temperature treatment, especially water-soluble polysaccharides such as ulvan and agar [49,50]. Research by Souto-Prieto et al. [51] states that the structural components of the algae cell wall are easily degraded and dissolved when heated, which contributes to the increase in TDS.

Three-dimensional (3D) contour and surface graphs show increasing TDS consistent with rising *Caulerpa racemosa* (CSC) concentrations and heating temperatures (Figure 2). An increase in CSC from 2% to 4% results in a sharp increase in TDS, indicating a direct contribution from dissolved compounds in algae biomass. Marine algae are rich in soluble components such as fucoidan and minerals, which can be efficiently extracted through heating [52]. Higher temperatures (94–100 ℃) also appear to facilitate the dissolution of these compounds, as shown by the results of the study of Trubetskaya et al. [53], who reported that heat treatment can accelerate the release of bioactive components from the seaweed matrix. The combination of increased temperature and material concentration creates a synergistic effect in the extraction of solutes, as evidenced by the peaks on the TDS surface 3D graph.

Mathematical models indicate that all three variables, Caulerpa concentration (A), temperature (B), and time (C), contribute positively to the increase in TDS. Linear regression coefficients (+1.25) and interactive effects such as AB (+0.5) and BC (+1) indicate a synergy between these factors. Research by Rajauria et al. [54] shows that the increase in temperature and the length of cooking time greatly affect the ability to release the active components from the marine algae. However, it should be noted that the quadratic effect on CSC shows a significant positive value (+2.41), indicating that up to a certain point, an increase in algae concentrations will exponentially increase TDS, but could plateau or even decrease in the event of saturation. These findings corroborate the report by Pires et al. [44], which explains that thermal degradation of bioactive compounds can occur at high temperatures or too long processing times, resulting in decreased extraction efficiency.

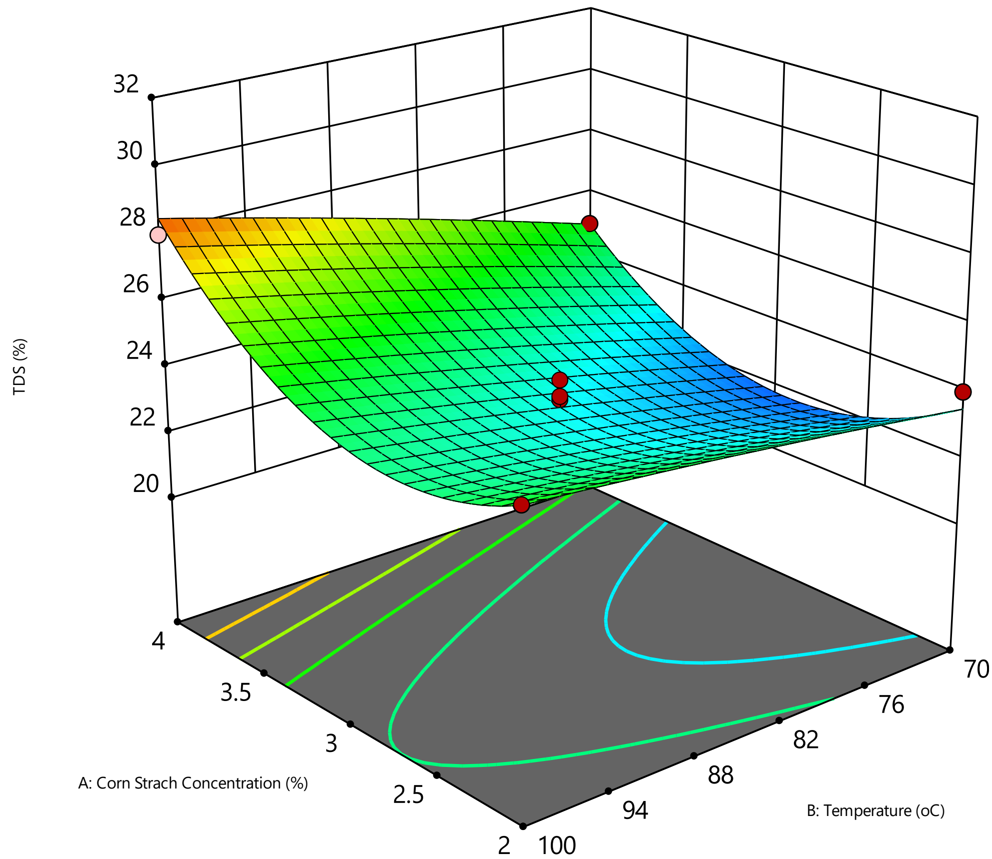

Figure 2. 3D response surfaces of TDS response test

Compared to previous studies, the results of this study support the finding that *Caulerpa racemosa* is a natural source of high TDS and has potential as a functional ingredient in food products. *Caulerpa racemosa* contains high levels of minerals and soluble compounds, including magnesium, potassium, and iodine, which play an important role in increasing TDS values [4,55]. The use of thermal treatment on algae can increase the release of water-soluble carbohydrates, which are a major contributor to TDS in the final product [56]. Based on the data and analysis model, the TDS parameter can serve as an indicator to evaluate the success of *Caulerpa racemosa*-based sauce formulations. Optimal TDS values lead to formulations with the best sensory and nutritional potential. Increased TDS in algae-based products correlated positively with natural umami flavour and emulsion stability in sauces [57].

3.4. Optimization of the Sauce Conditioning Process

Optimizing *Caulerpa racemosa* sauce using the Response Surface Methodology (RSM) approach yielded the optimal combination of process parameters at a corn flour concentration of 2.99%, 86.35 ℃, and a heating time of 44.11 minutes. In this condition, a pH of 3.435 and a TDS of 23.1992 mg/L with a desirability value of 1.000 were obtained (Table 3).

The pH measurement results showed a value of 3.435, within the optimal range for sauce products. Generally, the pH quality standard for sauces is 3.0 to 4.5, depending on the type and formulation of the sauce. These pH values have important implications for the product's microbiological stability, taste, and durability during storage. High temperatures in the fermentation process significantly lower the pH through the mild decomposition of organic acid compounds naturally found in *Caulerpa racemosa*, such as alginic acid and sulfonic acid from fucoidan. The thermal process can accelerate the release of acidic compounds from the structure of the seaweed cell, which contributes to the acidity of the final product [58]. The study supports that pH control in sauces not only acts as a natural preservative, but also as a determinant of the distinctive flavour and sensory profile of fermentative marine products such as *Caulerpa* sauce.

Table 3. The formula resulted from the optimization phase

No	Corn Starch Concentration(%)	Temperature (℃)	Time (minutes)	pH	TDS (mg/L)	Desirability
1	2.99	86.35	44.11	3.4	23.2	1

The Total Dissolved Solids (TDS) level of 23.1992 mg/L indicates a high dissolved solids content, primarily composed of bioactive compounds and nutrients from seaweed and other sauce-forming components. TDS is an important indicator in evaluating the quality of liquid products such as sauces, as it is directly related to the flavour intensity, viscosity, and nutrient content. The standard TDS value of sauce ranges from 20–30 mg/L, depending on the formulation and concentration of solid ingredients. The value in this study is in the ideal range. High-temperature heating in a controlled time can increase the extraction of dissolved components from seaweed, such as water-soluble polysaccharides and marine minerals, thus contributing significantly to the increase in TDS [59]. This suggests that the process of regulation can be directed to retain nutrients while improving the sauce's sensory characteristics.

The optimal processing temperature of 86.35℃ indicates its effectiveness in the gelatinization process of cornstarch, which serves as a thickening agent in sauce formulations. At this temperature, the starch granules disintegrate and form a stable gel matrix, increasing the product's viscosity and homogeneity [60]. It explains that the gelatinization temperature for corn starch ranges from 80–90℃, depending on the moisture content and composition of the starch. High temperatures also play a role in the inactivation of oxidizing enzymes, which may lead to the degradation of seaweed's color and bioactive compounds. Precisely controlled high temperature can improve the color stability and functional components in seaweed sauce [61]. Therefore, the temperature of 86.35℃ in this study is ideal for physical processes and supports the biochemical stability of the final product.

The heating time of 44.11 minutes balances the extraction of active compounds, gelatinization, and water evaporation in the system. This time is in the effective range as research [62], which emphasizes the importance of heating time as a crucial factor in processing foodstuffs rich in functional compounds. This duration is sufficient to denature the structural proteins in *Caulerpa racemosa*, accelerate the dissolution of polysaccharides, and aid in the thickening of corn starch. However, this time is also not too long, so it can prevent thermal damage to vitamin C, phenolic compounds, and natural pigments, such as chlorophyll, which give it its natural green color typical of seaweed. This finding aligns with the *principle of minimum processing*, which aims to optimize product quality while maintaining functional nutritional content.

A desirability value of 1,000 obtained from the optimization process indicates that the tested parameters have produced an optimal point that meets all the defined quality criteria. In the RSM approach, desirability is a statistical measure that indicates how closely the actual parameters align with the ideal target value. A desirability value close to 1 indicates high efficiency in the optimization process, especially in multivariate systems such as food product formulation [20]. The model's success in this study demonstrated that the combination of process inputs (concentration, temperature, and time) yielded a sauce with pH and TDS stability meeting industry standards. This also makes a new contribution to the development of functional products from *Caulerpa racemosa*, which is still relatively new in processed sauce products, and opens up opportunities for diversifying marine products with high economic value.

3.5. Verification of the Optimization Process

The results of verifying the optimization process of *Caulerpa racemosa* sauce showed that the predicted pH value was 3.43529, with a 95% prediction range of 3.07191 to 3.79868 (Table 4). The TDS value was 23.1992 mg/L, with a 95% prediction range of 21.3839 to 25.0146. This data indicates a high level of model confidence, supporting the validity of using the Response Surface Methodology (RSM) in the formulation process of seafood products (Table 4). In the research by Choobkar et al. [63] in the formulation of sauces based on natural ingredients, it is also emphasized that this approach can formulate optimal points with high accuracy to quality parameters, including pH and TDS.

The pH value of 3.43529, resulting from the verification process, indicates that *Caulerpa racemosa sauce* is within safe and stable limits for marine-based products. pH within this range is crucial in suppressing the growth of pathogenic microorganisms and preventing spoilage, thereby maintaining product shelf life. Food products with a pH value below 4.5 are very effective as natural preservatives, especially in products that do not use synthetic chemicals [64]. The pH of seaweed sauce in the range of 3.2–3.5 provides a balance between microbiological stability and sensory suitability. Thus, the pH value verified in this study provides a positive value for the functional quality and acceptability of the product by consumers.

Table 4. Results of linear model verification in the process of making Sea Grape Sauces

Analysis	Predicted Mean	Predicted Median	Std Dev	n	SE Pred	95% PI low	Data Mean	95% PI high
pH	3.43529	3.43529	0.27	3	0.17141	3.07	3.46	3.799
TDS	23.1992	23.1992	1.05	3	0.76771	21.38	24.23	25.01

The verified Total Dissolved Solids (TDS) of 23.1992 mg/L indicate that the formulated sauce contains high amounts of dissolved compounds derived from seaweed, thickeners, and reactions during heating. This TDS value follows the standard sauce product, which ranges from 20–30 mg/L. High TDS is typically attributed to the presence of bioactive compounds, including polysaccharides, marine minerals, and dissolved amino acids. Thermal processes can increase the release of bioactive components and minerals that increase TDS [65]. This study shows that high temperatures in a controlled time can accelerate the dissolution of nutrients from seaweed into liquid media such as sauces.

Verifying pH and TDS values within a narrow prediction range, using actual data, shows consistency between optimization results and laboratory reality. This shows that the built model is robust and reliable in industrial-scale product development. In the study of the formulation process, accurate prediction is an important indicator of the method's validity. Valid predictive values that match actual data strengthen the application of RSM in the development of innovative products [66]. In the context of food products, it shows that the conformity of predictions with actual test results can shorten time and cost in the large-scale production stage. Therefore, these results have significant practical implications in industrial process planning.

The relatively low standard deviation in the verification results (0.27 for pH and 1.05 for TDS) indicates that the formulation process has produced a product that is both physically and chemically consistent. This deviation value indicates the homogeneity of the formulation, which is important in the development of ready-to-eat food products. In processing seaweed sauce, high physical variations will affect the perception of quality and stability during storage. Physical consistency in pH and TDS is crucial for maintaining the product's integrity during distribution and storage. Low deviation values in functional product formulation will improve quality control and consumer satisfaction.

3.6. Organoleptic Value of *Caulerpa* Sauce

The development of seaweed-based food products, such as *Caulerpa*, requires a formulation approach that considers the sensory perception of consumers, as organoleptic characteristics strongly influence product acceptance. The addition of cornstarch as a thickening agent and texture stabilizer to the sauce is crucial in enhancing the product's appearance, aroma, and taste. In this study, organoleptic tests were conducted on *Caulerpa* sauce with various combinations of heating temperature, processing time, and corn starch concentration, each of which was adjusted to produce the most preferred product by the panelists. Hedonic values were analyzed for appearance, aroma, and taste attributes as key indicators of sensory quality.

The results of the evaluation showed that the formula with the addition of 2% starch and a heating temperature of 70 ℃ for 45 minutes (Formula 1) achieved the highest visibility score (7.9), indicating that it was perceived as "quite like" to "like" by the panelists (Figure 3). A decrease in appearance values was observed in formulas with longer heating times or higher temperatures, such as Formula 5 (2% starch, 85 ℃, 30 minutes), which scored only 6.5. This is in line with the theory of starch gelatinization, where excessively high heating temperatures can lead to degradation of the product's color and viscosity [67]. The addition of cornstarch in the right concentration can improve the appearance to a thick and homogeneous one; however, excessive thermal treatment can cause browning or visual damage.

Aroma, as a volatile attribute, is influenced by heating temperature, which affects the volatility of aroma compounds from *Caulerpa* and additives. The data showed that the best aroma (score of 7.2) was obtained in Formula 6 (4% starch, 85 ℃, 30 minutes), while the lowest score was observed in Formula 17 (3% starch, 85 ℃, 45 minutes), with a value of 6.1 (Figure 3). Corn starch is known to be able to absorb aromatic compounds during the heating process, which can maintain its natural aromatic character if the temperature and time are processed optimally [68]. However, excessive heating time can lead to the loss of important volatile compounds that contribute to the distinctive aroma of seaweed.

In terms of taste, the best formula was recorded in Formula 7 (2% starch, 85 ℃, 60 minutes), with a score of 8.1 ("like" category), followed by Formulas 4 and 9, which both recorded a score of 8.0. This suggests that a moderate temperature (85 ℃) with a longer heating time can increase the diffusion of flavors from the base ingredients and starches into the sauce matrix. The appropriate heating process can enhance the Maillard reaction and mild caramelization, resulting in a more complex, savoury-sweet flavor [69].

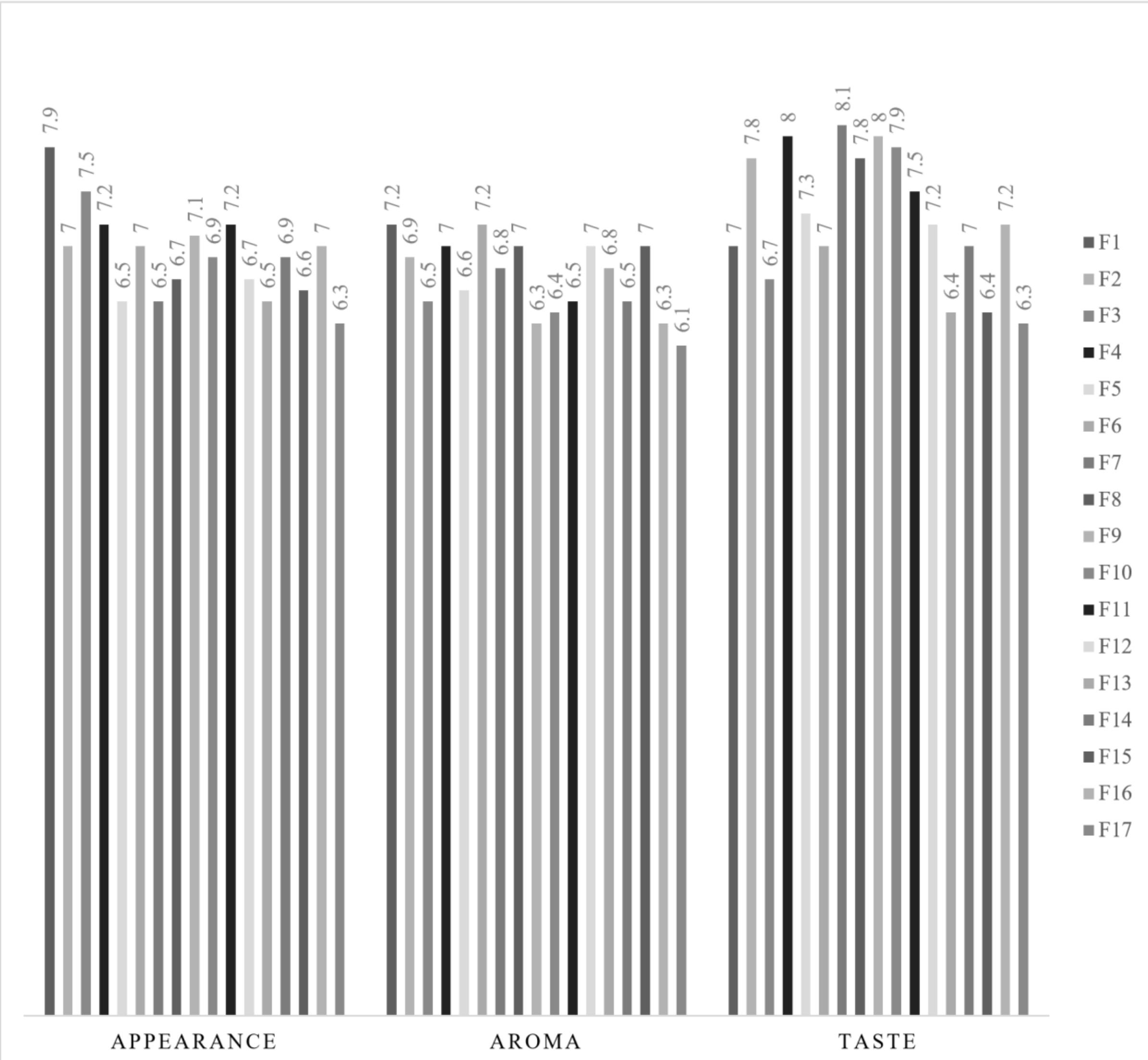

Figure 3. Organoleptic Value of *Caulerpa* Sauce

Findings from organoleptic testing showed that the combination of 85 ℃ temperature, starch concentration of 2–3%, and heating time of 45–60 minutes resulted in the highest score on sensory attributes in general, in line with the results of statistical optimization using the Response Surface Methodology (RSM) approach in the manuscript. The optimal formulation obtained through RSM was 2.99% corn starch, temperature 86.35 ℃, and a time of 44.11 minutes, which resulted in a pH of 3.435 and a total dissolved solid (TDS) of 23.2%. These conditions not only meet industry standards in terms of microbiological stability and product viscosity but also demonstrate consistency, yielding the highest organoleptic scores in hedonic tests. This confirms that an empirical formulation approach based on sensory preferences can be scientifically integrated with RSM-based statistical modelling to produce sensory, physical, and chemically optimal product formulations [70,71]. This convergence between hedonic data and quantitative optimization demonstrates the significant potential of *Caulerpa racemosa* as an innovative base material for functional food products that are stable, consumer-friendly, and ready for commercialization.

4. Conclusions

This research optimized the process of making *Caulerpa racemosa*-based sauce using Response Surface Methodology (RSM) with a Box-Behnken design. The optimal formulation, consisting of 2.99% cornstarch, 86.35 ℃, and 44.11 minutes, produced a sauce with a pH of 3.435 and a TDS of 23.2%, meeting industrial quality standards. Variable interactions significantly influenced product characteristics, with higher temperatures and starch levels increasing TDS, while heating reduced pH due to acid release. A desirability value of 1,000 confirmed optimal outcomes. Organoleptic tests also showed high acceptance, supporting the formulation's potential as a stable, functional, and marketable seaweed-based product.

Conflict of Interest

The authors do not have any conflicts of interest.

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