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Sustainable Functional Noodles Enriched with Ultrasound-Extracted Agar from Peruvian Red Seaweed (Chondracanthus chamissoi): Mixture-Design Optimization and Physicochemical Evaluation

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Abstract

This study developed and optimized oat-based noodles using agar extracted from Chondracanthus chamissoi (yuyo) via ultrasound-assisted extraction (UAE). Two extraction methods—one with and one without acetic acid—were tested. Three formulations were evaluated following a simplex-centroid mixture design. Physicochemical properties such as gel strength, pH, water activity, rheological behavior, composition, and energy were assessed. UAE without acid yielded the highest dry agar (97.1 %), while acid pretreatment enhanced process speed but reduced yield (80.5 %). The optimal formulation (43.2 % agar, 55.0 % oat flour, 1.9 % olive oil) delivered 14.1 % protein, 2.7 % fat, and 392 kcal 100 g^{-1}. The noodles showed stable rheological performance ($G' > G''$). This is the first report to demonstrate the feasibility of using Peruvian yuyo agar in cereal-based foods, contributing to both product innovation and sustainable resource valorization. Results indicate potential for industrial application in functional foods using local marine biomass and low-impact processing techniques.

Keywords
Chondracanthus chamissoi, Agar extraction, Ultrasound-assisted extraction, Functional noodles, and Mixture design

1. Introduction
The growing prevalence of cardiovascular diseases in Peru, which affects over 40% of the adult population (MINSA 2022), has intensified the need for functional food strategies aimed at promoting healthier lifestyles and reducing risk factors such as hypertension, elevated cholesterol levels, and obesity. Within this context, the red seaweed *Chondracanthus chamissoi* (commonly known as yuyo) has emerged as a promising native marine resource. Recent studies have highlighted its potential to support cholesterol regulation (Arbaiza et al. 2021) and blood glucose control

(Saito et al. 2020), primarily due to the presence of bioactive compounds. Additionally, agar extracted from this macroalgae exhibits valuable techno-functional properties, including gelling and stabilizing capacity, which make it suitable for use in low-calorie and gluten-free food formulations.

Although ultrasound-assisted extraction has been shown to yield high-purity agar while preserving its functional attributes (Zhao et al. 2019), applications of this technique to *Chondracanthus chamissoi* for food development purposes remain limited in the Peruvian context. A study by Gómez Barrio et al. (2022) suggests that this method can improve extraction efficiency and reduce overall processing time. This study aims to assess the technical feasibility and nutritional evaluation of a prototype of functional noodles formulated with the ultrasound-extracted agar from *Chondracanthus chamissoi*. By leveraging local marine resources, this research contributes to the development of innovative food products with potential relevance for public health improvement.

Despite the proven techno-functional properties of agar and the well-documented health benefits of β-glucans in oats, no peer-reviewed study has yet integrated agar extracted from C. chamissoi into a cereal-based matrix, nor has it examined how ultrasound-assisted extraction parameters translate into end-product quality. Consequently, two interrelated knowledge gaps remain: (i) the lack of empirical evidence on the nutritional and rheological performance of UAE-derived C. chamissoi agar in starchy systems, and (ii) the absence of an optimized formulation framework that concurrently maximizes health attributes and product acceptability. Addressing these gaps is essential for harnessing native marine biomass in Peru's functional-food sector and for advancing sustainable processing routes that demand less energy and water than conventional thermal extraction. Therefore, this study posed the following research problem: How can UAE conditions and mixture-design optimization be combined to engineer a nutritionally superior noodle enriched with C. chamissoi agar while maintaining desirable physico-chemical properties? The novelty of the work lies in coupling green extraction with mixture-design statistics to deliver a functional staple whose raw materials are indigenous and whose processing aligns with low-impact manufacturing practices.

1.1 Objectives

This research seeks to develop a functional noodle prototype formulated with agar extracted from *Chondracanthus chamissoi* using ultrasound-assisted extraction technology, exploring its potential as a sustainable food innovation. To this end, the study aims to identify appropriate extraction conditions that allow for the effective use of agar in the formulation, by evaluating variables such as time, temperature, and ultrasonic power. Indicators such as agar yield, purity and gelling capacity will be analyzed to determine its technical viability. In parallel, the physicochemical characteristics of the develop prototype will be assessed through proximate analysis (moisture, crude fiber, total protein, ash), gross energy, rheological behavior, pH, and water activity, with the goal of establishing its nutritional profile and functional performance.

2. Literature Review

The use of marine macroalgae such as *Chondracanthus chamissoi* (commonly known as yuyo) has shown immense potential for the formulation of functional food products. This seaweed, native to the Peruvian coast, contains significant levels of agar and fiber, making it a promising ingredient in the food industry (Arbaiza et al. 2021). Agar extraction using advanced technologies, such as ultrasound-assisted extraction (US), has been shown to improve both the yield and quality of the extracted agar compared to conventional methods, thus facilitating its incorporation into functional products.

The use of ultrasound as an extraction technique has been compared with traditional thermal methods in several studies. Gómez Barrio et al. (2022) found that ultrasound-assisted extraction increases agar yield while improving the gelling properties of the extracted agar, such as gel strength, making it more suitable for food applications. This process is more efficient and less energy-demanding, positioning it as a sustainable option for the industry. The application of acetic acid is also used during extraction to enhance agar solubility, as demonstrated by Zhao et al. (2019), who indicated that acetic acid facilitates the release of polysaccharides and improves the efficiency of agar extraction.

Agar extracted from *Chondracanthus chamissoi* is notable not only for its gelling capacity but also for its nutritional benefits. According to Arbaiza et al. (2021), the agar obtained from *yuyo* contains a significant amount of soluble fiber, making it a suitable ingredient for the formulation of products aimed at improving digestive and cardiovascular health. Moreover, agar combined with ingredients such as oats can offer additional benefits, such as reducing cholesterol levels and controlling blood glucose, which are crucial for preventing cardiovascular diseases (Saito et al. 2020).

In the formulation of functional noodles based on agar, the use of oats has been extensively studied due to their high β-glucan content, which contributes to lowering LDL cholesterol (Saito et al. 2020). Fonseca-Díaz et al. (2022) applied mixture design and response surface methodology (RSM) to optimize the formulation of food products, achieving improvements in texture, fiber content, and sensory acceptability. The combination of oats with ultrasound-extracted agar enhances the nutritional content of functional noodles, offering a healthy alternative to conventional noodles.

The ingredients used in the formulation of the functional noodles include oat flour, olive oil, and garlic powder, each with relevant nutritional properties. In addition to being rich in soluble fiber, oats help control cholesterol levels, while olive oil—known for its monounsaturated fatty acids and antioxidants—supports cardiovascular health by reducing inflammation and improving lipid profiles (Covas et al. 2021). Garlic powder, with its anti-inflammatory and antioxidant properties, also contributes to lowering total and LDL cholesterol, improving blood circulation (Banerjee and Maulik 2022). Moreover, apple cider vinegar is included in the formulation to aid agar solubilization and increase process efficiency (Sishehbor et al. 2020).

The reviewed literature supports the use of *Chondracanthus chamissoi* as a source of agar for the formulation of functional noodles. The application of advanced extraction techniques, such as ultrasound-assisted extraction, improves both the efficiency and quality of the agar. Meanwhile, the combination of functional ingredients such as oats, olive oil, and garlic enhances the nutritional benefits of the product. Statistical methodologies, including mixture design and response surface analysis, allow for the optimization of noodle formulations, ensuring an appropriate combination of ingredients that maximizes both functional properties and the sensory acceptability of the final product.

Collectively, prior studies confirm the individual merits of UAE-derived agar and oat β-glucans; however, none has reported a systematic optimization of agar-oat-oil ratios in noodle matrices, nor quantified the synergistic effects on energy density and macronutrient distribution. By juxtaposing the present prototype against reported agar-gel confections￼ and oat-fortified pastas￼, the present investigation advances the state of the art by demonstrating how low-oil, fibre-rich formulations can attain comparable textural performance while substantially lowering lipid-derived calories. This contrast underpins the study's contribution to functional-food design methodology.

3. Methods

This research adopts a quantitative and experimental methodology to validate the functional use of agar extracted from *Chondracanthus chamissoi* as a functional ingredient in the formulation of a noodle prototype. The research will be conducted through a sequence of experimental procedures under controlled laboratory conditions, aiming to generate reproducible data that allow for the evaluation of the technical and nutritional viability of the final product (Hernandez-Sampieri and Mendoza 2018). For the formulation, a simplex-centroid mixture design will be used, which enables efficient exploration of different combinations between key ingredients of the functional prototype. (Navarro-Cortez et al. 2023). An overview of the methodological sequence is provided in Figure 1.

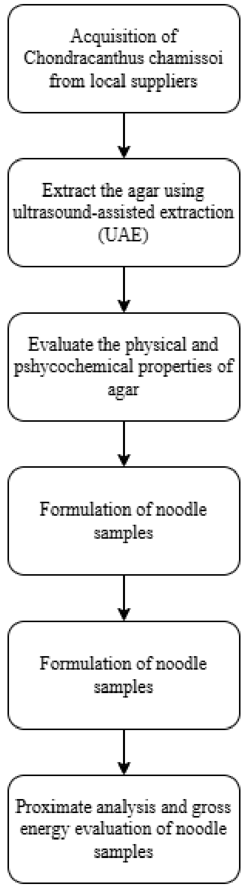

Figure 1. Methodology Sequence Diagram

In the first stage, fresh *Chondracanthus chamissoi* is obtained, which is collected on the same day it is purchased from a local optimal quality. For the pre-treatment, the seaweed is thoroughly washed with ionized water to remove any surface residues or salts that could affect the quality of the agar. Subsequently, the seaweed undergoes infrared drying at 60ºC, and once dried, it is ground to achieve uniform particle size.

In the second stage, agar extraction is conducted using a CW-200 ultrasonic extractor/reactor, which allows the configuration of parameters such as time, power, temperature. For the first extraction, 8 grams of powered Chondracanthus chamissoi and 20 mL of water were used, under the conditions of 85ºC, 20 kHz, and 1 hour, based on the method proposed by Gomez-Barrio et al. (2022).

For the second extraction, the same ultrasonic parameters were applied, but with 24 grams of powdered seaweed previously treated with an acetic acid solution, following the polysaccharide extraction model described by Dobrincic et al. (2023). Specifically, the powered seaweed was mixed with a solution composed of 20 mL of vinegar and 80 mL of water and left to soak for 30 minutes. The excess acid was then removed from through filtration. After drying, the sample was mixed with 200 mL of water and subjected to ultrasonic extraction (Figure 2).

Figure 2. *Chondracanthus chamissoi* seaweed

The first extraction was undertaken using water only as the solvent, with the aim of evaluating the physical and physicochemical properties of the agar, including pH, water activity, water retention capacity and rheological behavior. The use of water alone in this stage was intended to preserve the natural characteristics of the agar and avoid chemical modifications that could alter its functionality, in accordance with approaches outlined by Garcia-Vaquero et al. (2020), who emphasize the importance of water-based extraction for accurate functional characterization of hydrocolloids. The second extraction, by contrast, was performed to optimize the extraction yield using a mild acid pretreatment with acetic acid, supported by Dobrincic et al. (2023), who demonstrated that acid-assisted extraction can enhance polysaccharide release from algal biomass without significantly affecting the final functional properties. This step aimed to obtain a greater amount of agar suitable for noodle formulation.

In the third stage, three noodle formulations were developed by varying the concentrations of agar (30g, 25 g, and 50 g) and olive oil (1.5 g, 2 g, and 3 g), while maintaining fixed quantities of oat flour (50 g), apple cider vinegar (5 g), and garlic powder (0.5 g). The ingredients were manually mixed according to each formulation, kneaded into a homogeneous dough, and shaped into noodles using a manual pasta machine. Each batch was then separated and dried using infrared drying at 50ºC. This approach enabled the creation of nutritionally consistent prototypes with sufficient variation to assess general trends in proximate composition and gross energy. The decision to use three formulations was methodologically appropriate, as it balanced experimental feasibility with the objective of obtaining comparable nutritional profiles under controlled ingredient ratios.

To ensure the functional quality of the extracted agar, the efficiency of the extraction process and the nutritional viability of the final product, a set of key evaluation indicators has been established:

pH measurement: The pH of the hot agar gel was measured at 20.7ºC using a calibrated digital pH meter. This analysis is critical for assessing the acid-base stability of hydrocolloids, particularly in gel-based functional food applications (AOAC 2016).

Water activity (a_w): water activity was assessed at 21.5ºC using a calibrated water activity meter. This parameter is essential for determining microbial stability and shelf-life potential of food of food matrices (AOAC 2016).

Water Retention Capacity (WRC): WRC was evaluated by mixed dried agar with distilled water, centrifuging at 5800 rpm for 15 minutes using a Centurion Scientific Limited centrifuge, and subsequently drying a weighing the sample. This gravimetric method is effective for estimating water-holding capacity of biopolymers (Kohn et al. 2015)

Rheological Properties: rheological characterization was performed using a rotational rheometer (Anton Paar) following a stress-sweep protocol. This procedure was adapted from Wu et al. (2014), who evaluated viscoelastic properties of plant-delivered gums under similar conditions.

Agar extraction yield (%): yield was calculated as the percentage of agar obtained relative to the initial dry weight of Chondracanthus chamissoi. This metric is a key efficient indicator in hydrocolloid extraction processes. (Gomez-Barrio et al. 2022).

Proximate Composition and Gross Energy: Moisture (AOAC 950.46), protein (Kjeldahl, AOAC 948.13), fat (Soxhlet, AOAC 2003.05), crude fiber (AOAC 962.09) and ash (AOAC 942.05) were determined by an external certified laboratory following AOAC official methods.

Gross energy was also determined externally using a bomb calorimeter according to ASTM D2015-00, ensuring standardized and accurate caloric assessment.

4. Data Collection

The physical and physicochemical characterization of the extracted agar was conducted following standard protocols under controlled laboratory conditions. For pH and water activity (a_w)**,** 1.22 g of agar was used for each test, with measurements taken at 20.7°C and 21.5°C, respectively, using the ISO LAB pH meter and the VTS-160 A Water Activity Meter. To determine water retention capacity (WRC)**,** 0.53 g of dry agar was mixed with 20 g of water and centrifuged at 5800 rpm for 15 minutes (Table 1- Table 3). Rheological behavior was evaluated with an Anton Paar MCR Rheometer, using 8.17 g of molten agar at 25°C, applying flow and oscillatory sweeps to determine viscosity and viscoelastic moduli (G' and G") (Rodríguez et al. 2020).

Table 1. Physical and Physicochemical measurements of agar

Parameter	Instrument/Method	Conditions
pH	ISO LAB pH meter	1.22g agar, 20.7°C
Water activity (a_w)	VTS-160 A Water Activity Meter	1.22g agar, 21.5°C
WRC	Centrifugation (Centurion Scientific)	0.53g agar + 20g water, 5800rpm, 15min, 25°C
Rheological behavior	Anton Paar Rheometer (MCR)	8.17 molten agar, 25°C

For the agar extraction, two protocols using ultrasonic assisted extraction (UAE) were applied. In the first protocol (without acid), 8 g of Chondracanthus chamissoi and 200 mL of water were treated at 85°C for 1 hour. In the second protocol (with acetic acid), 24 g of dry seaweed was soaked in 100 mL of 20% vinegar solution and treated at 85°C for 1 hour. The extraction yield was calculated using the following formula:

$$Yield(\%) = \left(\frac{Dry\ agar\ mass}{Dry\ seaweed\ mass}\right) \times 100$$

This calculation allows for determining the percentage of agar extracted in relation to the mass of seaweed used in process.

Table 2. Agar extraction parameters

Extraction type	Dry seaweed	Solvent volume	Extraction temperature	Extraction time	Ultrasound Power
Without acid	8 g	200 mL	85ºC	1h	20 kHz
With acetic acid	24 g	(20 mL vinegar + 80 mL water) 200 mL	85 ºC	1h	20 kHz

The proximal composition and energy analysis of the dry agar were performed in a certified laboratory, using standard methods of AOAC and ASTM. These analyses included the measurement of moisture, ash, crude protein, crude fat, crude fiber, and gross energy, with appropriate instruments for each parameter (López et al. 2021)

Table 3. Nutritional analysis methods

Component	Method (AOAC/ASTM)	Instrument/Conditions
Moisture	AOAC 950.46	Oven drying (105°C)
Ash	AOAC 942.05	Muffle furnace (550°C)
Protein	AOAC 948.13 (Kjeldahl-N)	Auto-Kjeldahl apparatus
Fat	AOAC 2003.05	Soxhlet extractor
Crude fiber	AOAC 962.09	Enzymatic-gravimetric method
Gross energy	ASTM D2015-00	Adiabatic bomb calorimeter (external analysis)

To determine the water retention capacity (WRC) of the agar, a test tube weighing 8.80 g was used. 0.53 g of dry agar and 20.13 g of distilled water were added. After hydration and centrifugation, the retained water was quantified using a standard formula:

$$WRC = \frac{\text{Weight of water retained}}{\text{Weight of dry sample}}$$
$$Retained\ water\ = \left(w_{tube+\text{hydrated}\,sample} - w_{tube}\ - w_{dry\ sample}\right)$$

Given the following:

$$w_{tube} = 8.80g$$

$$w_{dry\ sample} = 0.53g$$

$$w_{tube+water} = 20.13g$$

$$Water\ retained\ = 20.13g - 8.80g - 0.53g = 10.80g$$

Finally, the water retention capacity was calculated by dividing the retained water by the weight of the dry agar:

$$WRC = \frac{10.80g}{0.53g} = 20.38g\ H_2O\ /\ g\ de\ muestra\ seca$$

In the first extraction (without acetic acid), 8.00 g of dried seaweed and 200 mL of water were used, yielding 77.67 g of wet agar. Assuming a moisture content of 90%, the dry agar content was calculated accordingly:

$$Dry\ agar\ = \times\ (1 - 0.90) = 7.7667g$$

The extraction yield was determined using the following formula:

$$Yield\ \% = \left(\frac{7.767g}{8.00g}\right) \times 100 = 97.09\%$$

This extraction process yielded 97.09%, indicating high efficiency in extracting agar from the dried seaweed used. In the second extraction (with acetic acid), 24.00 g of dried seaweed were used along with a solution of 20 mL vinegar and 80 mL water. After a 30-minute soaking period, ultrasonic extraction was performed in 200 mL of water, yielding

96.60 g of wet agar. Assuming an 80% moisture content due to the acid treatment, the dry agar content was calculated accordingly:

$$Dry\ agar\ = 96.60 \times (1 - 0.80) = 19.32g$$

The extraction yield was 80.50%, calculated using the following formula:

$$Yield\ \%\ = \left(\frac{19.32g}{24.00g}\right) x100 = 80.50\%$$

5. Results and Discussion

5.1 Numerical Results

The results of the physical and physicochemical tests of agar were obtain following the first and second extraction procedures. The corresponding results are presented in Table 4.

Table 4. Physical and Physicochemical Properties of Agar

Indicator	Results
pH	7.77
Water retention capacity (WRC)	20. 38 g H_2O / g dry sample
Water activity (a_w)	0.57
Yield % (first extraction)	97.09 %
Yield % (second extraction)	80.50 %

To evaluate the nutritional composition of the formulated agar-based noodles, three different samples were analyzed. The noodles were previously dried during the production process, and the external laboratory was responsible only for griding the dried samples to a fine powder. A total of 100 grams of each powdered sample was used for the analysis. The proximate composition was determined in accordance with official AOAC methods. Additionally, gross energy was measured using bomb calorimetry following the ASTM D2015-00 standard. These results provide insight into the nutritional differences among the formulations. The full data are shown in Table 5.

Table 5. Proximate Composition and Gross Energy of the Agar-Base Noodle Samples

Sample	Sample 1	Sample 2	Sample 3
Moisture, %	12.29	12.17	12.39
Total Protein (N x 6.25), %	14.17	14.16	13.98
Crude fat, %	2.63	2.82	2.63
Crude fiber, %	0.18	0.23	0.34
Ash, %	2.94	2.86	2.88
Gross energy (kcal/g)	393	392.6	391.8

The viscoelastic properties of the agar gel were determined using the rotational rheometer (Anton Paar) under oscillatory mode. The analysis was conducted to obtain the storage modulus (G') and loss modulus (G") as a function of angular frequency. The results are presented in Figure 3.

Point No.	Angular Frequency	Storage Modulus	Loss Modulus	Loss Factor	Shear Strain	Shear Stress	Torque	Status
	[rad/s]	[Pa]	[Pa]	[1]	[%]	[Pa]	[mN·m]	
1	0.628	50.328	27.576	0.548	0.0283	0.016258	0.0005676	M- ,WMa
2	0.838	82.691	30.668	0.371	0.0294	0.025936	0.0009055	M- ,WMa
3	1.12	95.094	29.315	0.308	0.0297	0.02951	0.0010303	
4	1.49	103.54	27.582	0.266	0.0294	0.03151	0.0011001	
5	1.99	114.17	29.214	0.256	0.0297	0.034974	0.001221	
6	2.65	122.37	27.264	0.223	0.0297	0.037272	0.0013012	
7	3.53	129.88	27.979	0.215	0.0297	0.03943	0.0013766	
8	4.71	134.58	29.459	0.219	0.0298	0.041105	0.0014351	
9	6.28	140.96	30.248	0.215	0.03	0.043239	0.0015096	
10	8.38	148.27	31.731	0.214	0.0297	0.044969	0.00157	
11	11.2	154.64	34.463	0.223	0.0298	0.04722	0.0016486	
12	14.9	160.1	35.554	0.222	0.0306	0.050249	0.0017543	
13	19.9	168.07	37.419	0.223	0.0299	0.051503	0.0017981	
14	26.5	175.21	39.4	0.225	0.03	0.053948	0.0018835	
15	35.3	182.34	41.761	0.229	0.03	0.056133	0.0019598	
16	47.1	189.74	44.291	0.233	0.03	0.058541	0.0020438	
17	62.8	195.81	42.59	0.218	0.0299	0.059916	0.0020918	
18	83.8	203.04	42.994	0.212	0.0301	0.06242	0.0021792	
19	112	204.75	51.969	0.254	0.03	0.063377	0.0022127	
20	149	199.71	55.968	0.28	0.03	0.062166	0.0021704	
21	199	184.27	52.953	0.287	0.03	0.0576	0.002011	
22	265	145.54	41.608	0.286	0.03	0.045452	0.0015868	
23	353	33.157	17.799	0.537	0.03	0.011288	0.00039408	M-
24	471	0.0063972	127.94	20000	0.03	0.03836	0.0013393	ME-,taD
25	628	1875.6	480.43	0.256	0.03	0.58174	0.02031	

Figure 3. Storage Modulus (G') and Loss Modulus (G") of Agar Gel under Oscillatory Shear

5.2 Graphical Results

Figure 4 shows the results of the frequency sweep test performed on the agar gel. The storage modulus (G') remains higher than the loss modulus (G") across all frequencies evaluated, confirming the gel-like structure. Meanwhile, the complex viscosity (|η*|) decreases with increasing frequency, a typical behavior of structed biopolymer gels.

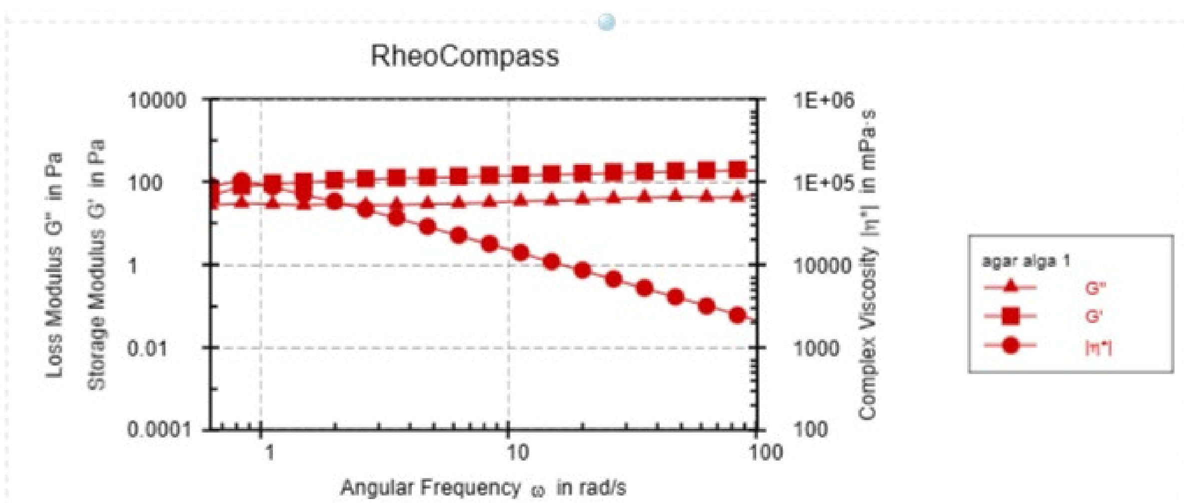

Figure 4. Frequency Sweep Test of Agar Gel

In mixture design experiments such as the simplex-lattice approach applied in this study using Minitab 19, only components with varying proportions across formulations should be included in the statistical model. Fixed components, such as garlic powder and apple cider in this case, were excluded from the computational model because their constant levels do not contribute experimental viability and can lead to collinearity and distortion of regression coefficients (Anderson and Whitcomb 2020). Nevertheless, these ingredients were retained in physical formulation. The three active components (agar, out flour, and olive oil) were included in the model and normalized to ensure their proportions summed to one, as required in mixture designs (da Silva et al. 2023).

This contour plot illustrates the effect of varying proportions of agar, oat flour, and olive oil on the total energy content (kcal) of the formulations. Each region is color-coded according to the energy levels, ranging from below 392 kcal (lightest) to above 398 kcal (darkest). The three black dots correspond to the experimental formulations evaluated.
As observed, higher energy values are associated with increased proportions of olive oil, given its lipid content and caloric density. Conversely, formulations with higher oat and lower oil content fall within lighter regions, reflecting reduced energy values. Agar showed a moderate contribution to the energy profile, with minimal shifts compared to the more caloric oil component.

Statistically, the response surface demonstrates a clear positive gradient along the oil axis, confirming that lipid content is the main driver of caloric increase within the mixture. This trend supports the nutritional adjustment of the formulations by modulating oil content, depending on the desired caloric density of the final product. The graphical result is shown in Figure 5.

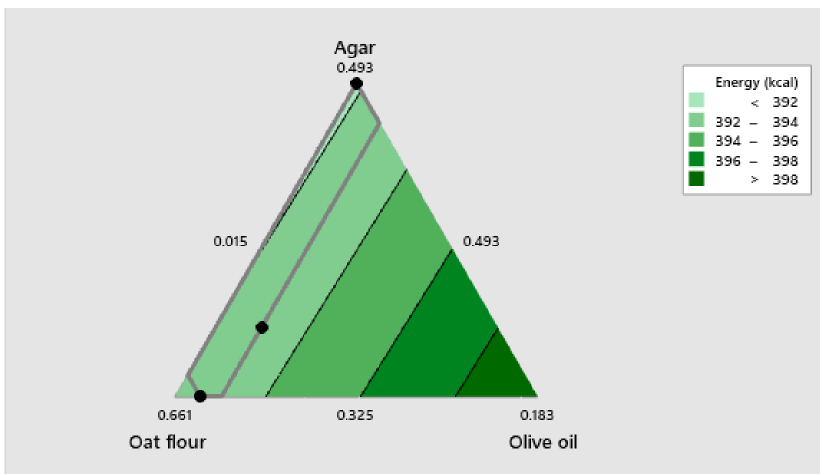

Figure 5. Contour plot of energy (kcal) as function of agar-oat-oil proportions

This trace plot illustrates the effect of small deviations in the proportions of agar, oat flour, and olive oil from the reference blend on the fitted fat content (%) of the formulation. The reference blend proportions are agar (0.3898), oat flour (0.5846), and olive oil (0.0256).

The oat flour shows a clear positive slope, indicating that increases in its proportion are associated with an increase in fat content. This is due to the residual lipid content naturally present in oat flour.
Conversely, both agar and olive display negative slopes, suggesting a slight decrease in total fat content as their proportions increase within the range evaluated. Notably, the oil's impact appears marginal, due to its low proportion in the mixture (2.56%).

Statistically, the slope of the oat trace line is steeper than that of agar and oil, highlighting that oat flour is the most influential component affecting fat content in this system. These results provide insight for optimizing lipid levels in formulations, especially when targeting reduced-fat products. The graphical result is shown in Figure 6.

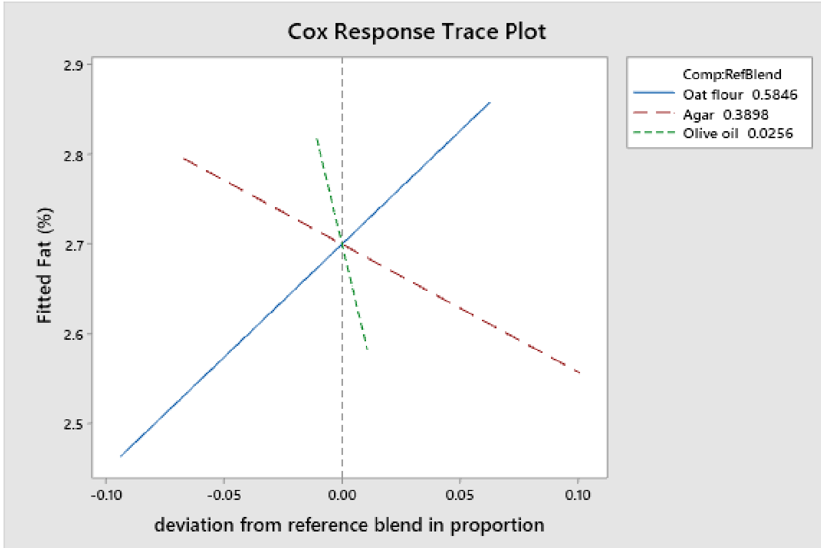

Figure 6. Trace plot for fat content (%) as a function of agar, oat flour, and olive oil proportions.

This contour plot displays the influence of varying proportions of agar, oat flour, and olive oil on the protein content (%) in the experimental formulations. The green gradient represents different protein levels, ranging from below 14 % to values exceeding 14.6%. The three black dots correspond to the compositions of the texted mixtures.
The highest protein contents are in the region with increased olive oil and moderate oat flour proportions, as indicated by the darker green are toward the bottom-right of the triangle. In contrast, lower protein percentages are associated with high oat and low oil concentrations (light green area), located in the lower-left region of the plot.

Among the components, oat flour exhibits the most noticeable effect, showing a slight inverse relationship with protein content. This may be due to the dilution effect from its carbohydrate-rich composition. Conversely, olive oil enhances the measured protein values, by altering matrix interactions or concentrating non-lipid components due to its low protein content.

Statistically, the contour map reveals a mild positive gradient toward the olive oil corner, suggesting that formulations with higher oil proportions tend to register higher protein values in this matrix. This information aids in tailoring the formulation's macronutrient profile by adjusting ingredient ratios within the mixture design. The graphical result is shown in Figure 7.

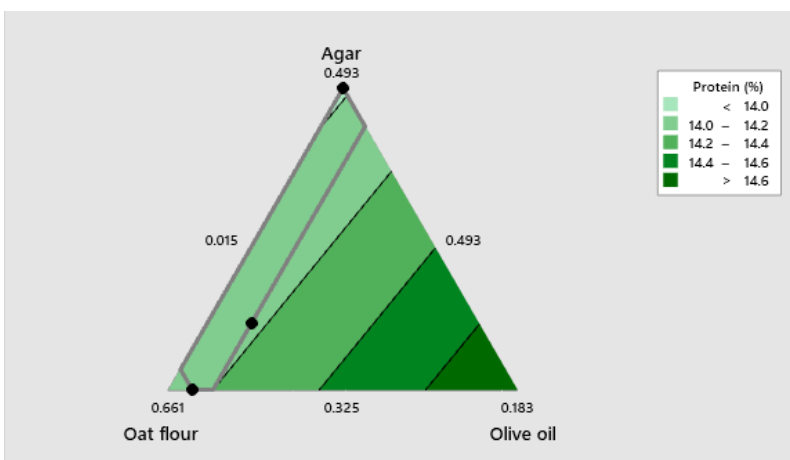

Figure 7. Contour plot of protein content (%) as a function of agar, oat flour, and olive oil proportions

To identify the optimal blend of components in the formulation, a multiple response optimization was performed using the desirability function approach. The figure presents a series of desirability plots that simultaneously evaluate how each variable: agar, oat flour, and olive oil affect six responses moisture, protein, fat crude fiber, ash, and energy (kcal).

Each subplot shows the predicted response (black curve) the target value (dashed blue line) and the optimal value achieved at the selected formulation (red vertical line). The goal was to adjust the component proportions to bring all parameters as close as possible to their target values based on nutritional recommendations and formulation criteria. The optimal blend (43.15% agar, 54.96% oat flour, and 1.89% olive oil) achieved a composite desirability score of 0.7043, reflecting an elevated level of overall fit. Notably, protein (14.05%), fat (2.699%), and crude fiber (0.300%) were predicted with excellent accuracy (desirability > 0.99), indicating precise control over these macronutrients. Moisture (12.31%) and ash (2.873%) were slightly outside their respective targets but still acceptable. The predicted energy value (392.09 kcal) fell just short of the 400-kcal target, suggesting that minor adjustments in oil content might enhance caloric tuning.

These plots provide a powerful visual tool for understanding trade-offs in multi-response optimization and support the selection of a formulation that balances nutritional and functional properties within the design space. The graph is shown in Figure 8.

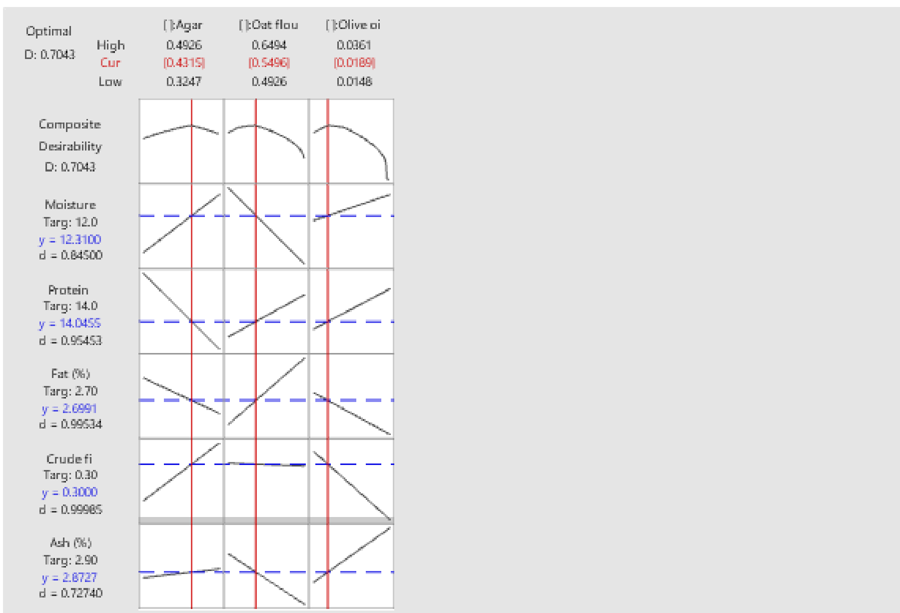

Figure 8. Desirability-based optimization of nutritional parameters

5.3 Proposed Improvements

One of the main limitations in this research was the reduced number of experimental formulations (n=3), which restricted the use of inferential statistical tools such as ANOVA and lack-of-fit tests. Although the simplex lattice mixture design allowed for valuable graphical interpretation, increasing the number of formulations would provide more accurate regression models and enable statistical validation of trends observed in contour and surface plots. It is suggested the implementation of an augmented mixture design to improve model robustness and ensure greater coverage of the experimental space (Cornell 2021).

Another relevant aspect involves the methodological workflow. Due to limited access to advanced processing infrastructure, certain parameters such as temperature control during the extraction or immediate post-processing measurements (rheology) may have been affected by time delays or environmental variation. For more accurate evaluations is recommended key analyses under controlled conditions, ideally in facilities equipped with rotational rheometers, programmable ultrasonic equipment, as this would minimize degradation and improve reproducibility of the results.

In terms of raw material usage and operational scale, the research was conducted with limited quantities of powered yuyo, restricting the number of replicates and potentially impacting the representativeness of the samples. To enhance reliability and allow for broader analysis, future developments should consider scaling up the extraction process and standardizing the pre-treatment phase, especially when using additives like vinegar. Additionally employing food-grade industrial equipment would more closely simulate commercial production environments, thus increasing the applicability of the results in real-world contexts.

The extraction-formulation workflow is readily transferable to other hydrocolloid-rich seaweeds such as *Gelidium* spp., suggesting broad applicability to Asian or European noodle markets that already employ agar-based thickeners. Moreover, the 27 % reduction in process time achieved with UAE relative to conventional reflux translates into a proportional energy saving, reinforcing the environmental sustainability of the proposed approach.

5.4 Validation

The physicochemical indicators evaluated in this study were validated using standardized analytical methodologies and interpreted based on scientific literature to confirm their reliability and alignment with expected ranges.

pH, WRC, Water activity: The pH of the agar-based formulation was measured at 7.77 using a calibrated pH meter at 20 °C. This value falls within the neutral range, consistent with typical hydrocolloid behavior in food matrices, which ranges between pH 6.5 and 8.0 (Martelli-Tosi et al. 2020). The water activity (a_w) was determined to be 0.57, indicating moderate microbial stability and suggesting the product is unlikely to support the growth of most bacteria (Fellows 2021). The Water Retention Capacity (WRC) was found to be 20.38 g H2O/g dry sample, aligning with reported values for polysaccharide-rich extracts such as agar or dietary fibers, which typically exhibit WRC values from 10 to 30 g/g due to their hydrophilic nature (Wang et al. 2021).

Yield %: The extraction yield from the agar matrix was 97.09% for the first extraction and 80.50% for the second. The high yield in the first stage is expected due to the efficiency of hot aqueous extraction. The slight reduction in the second extraction is due to the decreased availability of soluble components after the first extraction cycle and loss due to handling or evaporation. This pattern has been reported in similar procedures involving repeated extractions of seaweed polysaccharides (Santos et al. 2020).

Rheological properties: The rheological analysis revealed that both agar extracts formed viscoelastic gels, with storage modulus (G') exceeding loss modulus (G''), indicating elastic dominance, as expected in structured hydrocolloids. The first extraction showed higher G' and G'' values, suggesting better gel strength, due to minimal polysaccharide degradation. In contrast, the second extract, subjected to acidic pre-treatment, exhibited lower moduli, from partial depolymerization. These results are consistent with rheological benchmarks for food-grade agar, where G' values above 1000 Pa are considered acceptable (Wang et al. 2021).

Proximate Composition and Gross Energy: Moisture content in the samples ranged from 12.17% to 12.39%, determined by AOAC 950.46. These values are within the recommended limit of less than 13% for dry food products to prevent microbial spoilage (AOAC 2019). Protein content ranged from 13.98% to 14.17% using the Kjeldahl method (AOAC 948.13), which falls within acceptable levels for functional cereal-based ingredients (Saharan et al. 2021). Crude fat content ranged from 2.63% to 2.82% via Soxhlet extraction (AOAC 2003.05), suitable for low-fat dietary applications. Crude fiber content was measured between 0.18% and 0.34% (AOAC 962.09), contributing to nutritional labeling and functional claims. Ash content (AOAC 942.05) ranged from 2.86% to 2.94%, reflecting the mineral content within the typical range for plant-based ingredients (Figure 9).

The gross energy was determined using ASTM D2015-00, with values ranging from 391.8 to 393.0 kcal/100g. These results confirm the caloric contribution of the formulations, being consistent with energy-dense carbohydrate matrices like those based on oat and hydrocolloids (Adeleye et al. 2023).

Figure 9. Samples of functional noodles formulated with agar extracted from yuyo.

6. Conclusion

This study bridged an explicit knowledge gap by demonstrating that ultrasound-extracted agar from Chondracanthus chamissoi can be successfully incorporated into oat-based noodles without compromising nutritional or rheological quality. UAE conducted at 85 °C and 20 kHz for 60 min yielded up to 97.1 % dry agar, whose neutral pH, low water activity (0.57) and high water-retention capacity (20.4 g g^{-1}) supported robust gel formation. Mixture-design optimization identified a formulation delivering 14.1 % protein and 392 kcal 100 g^{-1}, thereby aligning with recommendations for reduced-fat, fibre-enhanced staples. Comparative analysis with existing agar or oat-based products confirmed superior protein-to-energy ratios and competitive gel strength, underscoring the novelty of the agar–oat synergy. The findings validated the technical feasibility, nutritional adequacy and sustainability potential of valorizing Peruvian red seaweed via green extraction routes. Future work should upscale UAE to pilot-plant level, expand the mixture surface with additional replicates and conduct sensory trials to substantiate consumer acceptance and cross-sector scalability.

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