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Khon Kaen University, Thailand**Comparative Effects of Culture Sites on Agar Yield and Quality Parameters of *Gracilaria edulis* in La Union, Philippines**Andie John D. Tadeo^{1,2*}¹ College of Fisheries, Central Luzon State University, Science City of Muñoz, Nueva Ecija, Philippines² College of Fisheries, Don Mariano Marcos Memorial State University, Sto. Tomas, La Union, Philippines*Corresponding author: ajtadeo@dmmsu.edu.ph

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Abstract

The agar potential of *Gracilaria edulis* cultured at two coastal sites in La Union, Philippines, was evaluated to determine site-dependent differences in yield and quality. Significant variations ($p < 0.05$) were observed between Balaoan and Rosario. While Rosario produced greater biomass, Balaoan yielded significantly higher agar. Proximate composition also differed, with Balaoan exhibiting higher protein and carbohydrate contents. Concentrations of inorganic arsenic (i-As), cadmium (Cd), and lead (Pb) were within the permissible limits set by the Department of Environment and Natural Resources for SB-class waters, indicating environmental safety at both sites. Agar quality parameters showed contrasting trends. Rosario samples demonstrated significantly higher viscosity, gel strength, and 3,6-anhydrogalactose content, suggesting superior gel-forming properties. In contrast, Balaoan agar exhibited higher melting and gelling temperatures, as well as higher sulfate levels. These results confirm that culture site significantly influences agar yield and physicochemical properties of *G. edulis*. The findings provide important insights for optimizing site selection to enhance both productivity and functional quality in commercial agar production.

Keywords: Agar, Chemical analysis, Gel strength, Heavy metal analysis, Proximate analysis, Viscosity**1. Introduction**

Gracilaria edulis is a species collected and cultured in La Union. Traditionally, *G. edulis* in La Union is sold in fresh or dried form for direct human and animal consumption. Due to its abundance and exploitation, *G. edulis* has become an economically important commodity in some areas of La Union. However, the growth of *G. edulis* in the culture system and the monitoring of environmental parameters should be evaluated to attain its sustainability. The development of *Gracilaria* must include both the production and processing technologies to cater to the local and foreign markets. Given this, the purpose of this study is to extract agar from cultured *G. edulis* in order to add value to its traditional use for human and animal consumption.

Agar is a high-value phycocolloid widely used in the food, pharmaceutical, microbiological, and biotechnology industries due to its strong gel-forming ability, thermal stability, and low reactivity. Commercial agar production traditionally relies on red seaweeds such as *Gelidium amansii* and *Gracilaria verrucosa*, which are known for producing agar with high gel strength and low sulfate content. However, overexploitation of wild stocks, seasonal variability, increasing raw material costs, and inconsistent quality have posed challenges to the sustainability of conventional agar sources. These constraints necessitate evaluating alternative agarophytes with stable cultivation potential and acceptable physicochemical properties.

The Philippines is one of the world's major seaweed-producing countries, yet its agar industry remains limited due to inconsistent yield and variable gel quality among locally available species. Among native agarophytes, *Gracilaria edulis* is widely distributed and increasingly cultured in coastal areas of La Union. Unlike other commercially established Philippine agarophytes, *G. edulis* is primarily marketed for fresh or dried consumption rather than industrial agar extraction. Despite its abundance, there is limited site-specific evaluation of its agar yield and functional quality under cultivation conditions. Recent studies [1, 2, 3] have emphasized

that environmental factors such as nutrient availability, salinity, temperature, and water quality significantly influence agar yield, gel strength, viscosity, sulfate content, and 3,6-anhydrogalactose levels in *Gracilaria* species. However, most existing studies focus on species comparisons or laboratory treatments, with limited assessments of site-dependent cultivation effects under actual coastal farming conditions in the Philippines.

Therefore, a clear research gap exists in understanding how different cultural environments influence both biomass productivity and agar quality parameters of *G. edulis*. Evaluating site-specific performance is essential to determine its viability as an alternative agar raw material and to support value-adding strategies for local seaweed farmers. This study aimed to evaluate the influence of the culture site on biomass production and agar quality of *Gracilaria edulis* cultivated in La Union, Philippines.

Specifically, the study sought to:

- Assess and compare biomass yield between culture sites;
- Determine agar extraction yield from cultured *G. edulis*;
- Evaluate physicochemical properties of the extracted agar, including gel strength, viscosity, melting temperature, gelling temperature, sulfate content, and 3,6-anhydrogalactose levels;
- Analyze heavy metal concentrations to ensure environmental safety;
- Examine site-dependent variations in relation to environmental conditions.

2. Materials and methods

2.1 Production site

The culture and harvest of *Gracilaria edulis* were carried out in two coastal municipalities of La Union, Philippines—Rosario and Balaoan, both known as traditional seaweed gathering sites and considered suitable for *G. edulis* cultivation. Rosario, located at approximately 16.2171°N, 120.4173°E, while Balaoan, at around 16.7901°N, 120.3405°E. These coastal areas feature sandy substrates interspersed with rubble rocks and are populated with seagrasses and various seaweeds. Water depth ranges from approximately 1 meter during low tide to about 5 meters at high tide, providing a suitable environment for seaweed cultivation.

2.2 Experimental set-up

Gracilaria edulis was cultured for 45 days using polyethylene ropes (8 mm diameter) inserted into twisted polyethylene netting (28 mm mesh size). The 45-day cultivation period was selected based on previous *Gracilaria* farming practices, indicating that 30–45 days represents an optimal harvest cycle that allows sufficient biomass accumulation while minimizing thallus aging, epiphyte infestation, and decline in agar quality. This duration is commonly adopted in tropical open-water cultivation systems to balance growth performance and biochemical stability.

Each culture module consisted of four 3-m horizontal lines attached to floaters at both ends and secured to steel poles installed in coastal waters at a depth of 0.3–0.8 m during low tide. This rope configuration was adapted from standard fixed off-bottom and monoline systems used in *Gracilaria* farming, which promote adequate water circulation, light penetration, and nutrient exchange while preventing sediment burial. The initial stocking density was standardized at 500 g fresh weight per line (2 kg per module), following recommended density ranges (400–600 g m⁻¹) reported in previous *Gracilaria* cultivation studies to avoid self-shading and intra-specific competition that may reduce growth rate and agar yield. Three replicate modules were established per site to allow statistical comparison.

Environmental parameters were monitored weekly throughout the culture period. Water temperature (°C), salinity (ppt), and pH were measured in situ using a multi-parameter water quality meter (Hanna HI98194, Hanna Instruments, Romania). Light intensity (lux) was measured using a digital lux meter (Extech LT300, Extech Instruments, USA). Water depth (m) was determined using a graduated meter stick at each sampling point. Substrate type was visually assessed and classified as sandy, muddy, or sandy–muddy based on sediment texture.

Water samples for nutrient analysis (nitrate, phosphate, and sulfate) were collected in acid-washed polyethylene bottles and analyzed following standard methods [4]. Heavy metal concentrations (Pb, Hg, Cd, and As) in water, sediment, and seaweed samples were determined using atomic absorption spectrophotometry (AAS) (Shimadzu AA-7000, Shimadzu Corporation, Japan) after appropriate acid digestion procedures. These measurements were conducted to evaluate environmental factors influencing biomass production and to ensure compliance with food safety standards.

2.3 Proximate composition analysis of *G. edulis*

After 45 days of cultivation, *Gracilaria edulis* samples were harvested, thoroughly rinsed with tap water to remove salts, epiphytes, and other extraneous materials, and oven-dried at 105 °C for 5 hours. One hundred grams (100 g) of dried seaweed from each treatment (in triplicate) were submitted to the Department of Science and Technology Laboratory for proximate/biochemical analysis. The analyses included moisture, ash, protein, fat, fiber, and carbohydrate content, which were determined using standard methods by Association of Official Analytical Collaboration (AOAC). All analyses were conducted in triplicate, following protocols adapted from previous studies on *Gracilaria* species [5, 6], to ensure reproducibility and comparability of the results.

2.4 Test Samples for agar production and characterization

Gracilaria edulis cultured from two sites in La Union (Rosario and Balaoan) was used for agar production and property characterization, with commercial food-grade agar (Now Real Food) serving as the control. The study involved three treatments: commercial agar (treatment 1), and agar from Rosario and Balaoan (treatments 2 and 3). Harvested *G. edulis* (3 kg per site) was oven-dried at 60 °C for 48 hours, and 30 g per treatment was alkali-treated in 5% NaOH at 90 °C for 1 hour, washed, neutralized with 3% glacial acetic acid, and rinsed overnight. Agar was extracted by boiling in water at 99–100 °C for 1 hour, filtered hot, solidified at room temperature, frozen at –20 °C for 24 hours, thawed, dried at 60 °C for 48 hours, and ground into powder for analysis.

2.5 Determination of Agar Yield and Gel Physical Analysis

Agar yield was determined by comparing the initial dry weight of the seaweed with the final dry weight of the extracted agar. A 1.5% agar solution (15 g of agar in 1 L of cold distilled water) was prepared to evaluate its physical properties, including viscosity, gel strength, gelling temperature, and melting temperature. The solution was stirred, boiled, and used for testing. Viscosity was measured at 75 °C using a Brookfield Viscometer DV-II Pro (Brookfield Engineering Laboratories, USA), and gel strength was determined using a Brookfield Texture Analyzer CT3 Series (Brookfield Engineering Laboratories, USA). For the gelling temperature, 20 mL of the solution was poured into test tubes with thermometers, and lead shots were added until one remained on the gel, indicating the gelling point. The same gel was left overnight, and the melting temperature was recorded by heating the sample until the lead shot sank. All measurements were conducted in triplicate to ensure accuracy and reproducibility.

2.6 Statistical Analysis

All measured parameters, including biomass yield, environmental variables, nutrient concentrations, heavy metals, and proximate composition, were first tested for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test) to meet the assumptions of parametric analyses. Comparisons between two culture sites were analyzed using an independent t-test, which is appropriate for evaluating differences between independent groups when the assumptions of normality and equal variance are met. For agar yield and physicochemical properties with multiple measurements per site, one-way analysis of variance (ANOVA) was used, followed by the Least Significant Difference (LSD) post hoc test to compare group means. The LSD test was chosen to provide pairwise comparisons while controlling type I error for a limited number of groups, as recommended in similar aquaculture and phycocolloid studies. All statistical analyses were performed using SPSS version 20, and differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

3.1 Yield of *G. edulis* and environmental parameters

Harvest yields and the physicochemical characteristics of water and sediments from two *G. edulis* culture areas in La Union (Rosario and Balaoan) were measured over 45 days (Table 2). *G. edulis* cultured in Balaoan (455 g) yielded significantly more than in Rosario (338 g), suggesting that local environmental conditions favor biomass accumulation. Water salinity, temperature, pH, and depth were similar across sites, except for a slightly higher pH in Balaoan. Both sites experienced epiphyte infestation, consistent with typical marine habitat interactions where microalgae, other seaweeds, and small invertebrates colonize seaweed thalli [7].

3.2 Nutrient analysis

The nutrient analyses of water, sediments, and thalli of *G. edulis* collected from two culture sites in La Union are presented in Table 1. Nitrogen in water and sediments was measured as nitrate (NO_3^-), expressed in $\text{mg}^{-\text{L}}$, while nitrogen in the thalli of *G. edulis* represents total nitrogen content. The nutrient composition of water, sediments, and *Gracilaria edulis* thalli indicates clear spatial differences between the two culture sites. Balaoan consistently showed higher levels of nitrate, phosphate, and sulfate in both sediments and thalli than Rosario, suggesting greater nutrient availability at this site. These differences likely reflect local anthropogenic influences rather than natural variability.

A cement factory located near the Balaoan coast is a probable contributor to elevated sulfate and associated nutrient levels, as cement manufacturing can release sulfate-rich effluents into nearby waters [8, 9]. Additionally, runoff from nearby residential areas and beach resorts may contribute nitrogen and phosphate to the coastal environment, consistent with studies linking coastal eutrophication to domestic wastewater and surface runoff [10, 11]. In Rosario, nutrient inputs are likely dominated by smaller-scale residential and agricultural sources, resulting in comparatively lower nutrient levels.

The higher nutrient content in *G. edulis* thalli in Balaoan reflects the ambient enrichment of the surrounding water and sediments. This pattern supports the well-established relationship between local nutrient availability and seaweed tissue composition, particularly for nitrogen and sulfur compounds [12, 13]. Overall, the findings indicate that local anthropogenic activities, especially industrial and residential discharges, directly influence nutrient dynamics in coastal waters and are mirrored in the biochemical composition of cultured seaweed.

Table 1 Nutrient analysis of water, sediments, and *G. edulis* at two culture areas

Parameter	Nitrogen		Phosphate		Sulfate	
	Rosario	Balaoan	Rosario	Balaoan	Rosario	Balaoan
Water, $\text{mg}^{-\text{L}}$ (Nitrate)	<0.02	<0.02	0.01	0.01	1490±1.15 ^b	1540±3.46 ^a
Sediment, $\text{mg}^{-\text{kg}}$ (Nitrate)	79 ±2.1 ^b	134±2.8 ^a	209±2.9 ^b	320±2.1 ^a	482±2.1 ^b	951±1.8 ^a
<i>G. edulis</i> , $\text{mg}^{-\text{kg}}$ (Total)	1.6±0.1 ^a	2.1±0.2 ^a	2.41±0.8 ^a	1.62±0.6 ^a	7270±1.7 ^b	10100±1.1 ^a

Means in a row superscripted by different letters are significantly different at the 5% level of significance.

3.3 Heavy metal analysis in water, sediments, and *G. edulis*

The heavy metal concentrations of sediments and water at the two seaweed culture sites in La Union are presented in Table 2. Analysis of sediments from the two seaweed culture sites revealed higher concentrations of heavy metals, particularly Pb, Cd, and i-As, in Balaoan compared to Rosario. These levels exceeded the Department of Environment and Natural Resources (DENR) sediment quality guidelines for SB-class waters, indicating a potential ecological concern. Elevated sediment metal concentrations in Balaoan are likely associated with nearby industrial activities, notably the cement plant, as well as boat traffic from fishing and recreational activities. Heavy metals such as arsenic, cadmium, lead, mercury, and zinc are persistent, non-biodegradable, and prone to accumulation in marine sediments, posing long-term environmental risks to benthic organisms and overall coastal ecosystem health [14].

In contrast, heavy metals in water at both sites were below DENR limits and detection thresholds, suggesting that dissolved metal concentrations currently pose minimal direct risk to the broader water column. Nonetheless, sediment contamination represents a long-term reservoir of metals that could potentially remobilize under changing environmental conditions, such as sediment disturbance or changes in pH and redox potential [15].

Table 2 Heavy metals measured in water and sediments at two seaweed culture areas.

Culture Area	Water samples ($\text{mg}^{-\text{L}}$)				Sediment samples ($\text{mg}^{-\text{kg}}$)			
	i-As	Cd	Pb	Hg	i-As	Cd	Pb	Hg
Rosario	<0.008	<0.001	<0.005	<0.002	1.65±1.9 ^a	ND	8.5±1.1 ^b	ND
Balaoan	<0.008	<0.001	<0.005	<0.002	5.20±2.3 ^a	3.15±2.4	27.5±1.7 ^a	ND
DENR Standard	0.020	0.005	0.010	0.005	0.02	0.005	0.01	0.005

Means in a column superscripted by different letters are significantly different at 5% level of significance

Table 3 Heavy metals measured in *G. edulis* cultured at two coastal areas in La Union.

Culture Area	Initial Sampling (DAY 0)				Final Sampling (DAY 45)			
	i-As, mg ^{-kg}	Cd, mg ^{-kg}	Pb, mg ^{-kg}	Hg, mg ^{-kg}	i-As, mg ^{-kg}	Cd, mg ^{-kg}	Pb, mg ^{-kg}	Hg, mg ^{-kg}
Rosario	ND	1.9	14	ND	6.8±0.1 ^b	ND	ND	ND
Balaoan	ND	1.9	14	ND	8.7±0.1 ^a	ND	ND	ND
*Threshold levels for heavy metals	<3.0 (France & USA) NR (EU)	<0.5 (France) <3.0 (EU) NR (USA)	<5.0 (France) <10 (USA) <3.0 (EU)	<0.1 (France, USA, EU)	<3.0 (France & USA) NR (EU)	<0.5 (France) <3.0 (EU) NR (USA)	<5.0 (France) <10 (USA) <3.0 (EU)	<0.1 (France, USA, EU)

Means in a column superscripted by different letters are significantly different at 5% significance level.

ND = Not Detected

*Threshold levels for heavy metals in edible seaweeds sold in France, USA and European Union Regulation [16]

NR = No Regulation

The heavy metal content of *G. edulis* thalli was analyzed after 45 days of hanging culture, revealing that only inorganic arsenic (i-As) was consistently detected, while cadmium (Cd) and lead (Pb) were below detection limits. This reduction compared to the seedstock likely reflects the shift from sediment-attached wild material to hanging culture modules, which minimizes direct contact with contaminated sediments and limits bioaccumulation of certain metals. Comparison with international food safety standards highlights important distinctions: i-As concentrations at both sites were below thresholds set by France and the USA, indicating compliance and minimal consumer risk; Cd levels were below French limits but exceeded EU limits, suggesting a potential compliance issue for markets governed by EU regulations; and Pb concentrations exceeded limits set by France, the USA, and the EU, underscoring the need for careful monitoring and mitigation prior to commercial distribution. These results demonstrate that sediment contamination does not necessarily translate into unsafe seaweed for consumption, particularly when hanging culture methods are employed to reduce metal uptake. Nonetheless, the elevated Pb and Cd relative to certain regulatory standards indicate that ongoing monitoring and quality control are essential to ensure that agar products remain safe and compliant with international markets [17].

3.4 Proximate Composition of *G. edulis*

The results on the proximate composition of *G. edulis* cultured at two coastal areas in La Union are shown in Table 4. Moisture content of *G. edulis* cultured in Rosario (3.7 %) was significantly higher than in Balaoan (2.7 %). Ash content was significantly higher in *G. edulis* cultured in Balaoan (58.73 %) than in Rosario (47.46 %). Protein content was significantly higher in *G. edulis* cultured in Balaoan (7.60 %) than in Rosario (6.47 %). Carbohydrate was significantly higher in *G. edulis* cultured in Balaoan (41.33 %) than in Rosario (32.07 %). There were no significant differences in the fat and fiber contents of *G. edulis* cultured in Rosario (0.006 % and 4.8 %) and Balaoan (0.003 % and 4.97 %).

Table 4 Proximate composition of cultured *G. edulis* at two coastal areas in La Union.

Parameter (%)	Rosario	Balaoan
Moisture	3.60 ± 0.010 ^a	2.70 ± 0.010 ^b
Ash	47.46 ± 0.013 ^b	58.73 ± 0.023 ^a
Protein	6.47 ± 0.003 ^b	7.60 ± 0.000 ^a
Fat	0.006 ± 0.000 ^a	0.003 ± 0.000 ^a
Fiber	4.80 ± 0.160 ^a	4.97 ± 0.063 ^a
Carbohydrates	32.07 ± 0.023 ^b	41.33 ± 0.023 ^a

Means in a row supercripted with different letters are significantly different at 5% level (P<0.05) level of significance

The findings of this study are in agreement with recent research showing variability in proximate components among *Gracilaria* species. For example, studies on the proximate composition of *Gracilaria edulis* and related species have reported moisture contents and ash values that differ markedly depending on species and locality, with some seaweeds exhibiting lower moisture yet higher ash levels than others in comparative analyses [18]. Ash content in *Gracilaria* has been found to vary widely among species and geographic sites, reflecting environmental and mineral availability influences [19]. The higher protein and carbohydrate contents observed in *G. edulis* from Balaoan may similarly be influenced by local nutrient conditions such as nitrogen and sulfate availability. While protein levels in *Gracilaria* often remain modest relative to many terrestrial plant sources, recent compositional surveys have documented crude protein values in red macroalgae generally within a range that overlaps with the results of this study [20].

3.5 Agar Yield

The agar yield extracted from *G. edulis* cultured at two different areas in La Union is presented in Table 5. The proximate composition of *G. edulis* cultured at the two coastal areas in La Union reflects both environmental nutrient conditions and the biochemical processes underlying agar biosynthesis. Moisture content was significantly higher in Rosario (3.7%) than in Balaoan (2.7%), consistent with lower mineral (ash) and carbohydrate accumulation, as water content in seaweed often inversely correlates with polysaccharide deposition [21]. Ash content, representing the total mineral content, was significantly higher in Balaoan (58.73%) than in Rosario (47.46%), reflecting the elevated sulfate and other mineral concentrations in the surrounding water and sediments. These minerals are essential cofactors in agar biosynthesis, particularly for the sulfation of agar polysaccharides, which directly influences gel strength and quality [22].

Protein content was higher in Balaoan (7.60%) than in Rosario (6.47%), likely due to increased nitrogen availability in the water and sediments. Nitrogen is a critical component of amino acids and enzymes involved in agar precursor synthesis, and higher protein levels may enhance enzymatic activity for galactan polymerization and sulfation during agar formation [23]. Carbohydrate content was also elevated in Balaoan (41.33%) compared to Rosario (32.07%), reflecting the biosynthesis of agar polysaccharides, which constitute the major carbohydrate fraction in *G. edulis*. Adequate levels of sulfate and nitrogen facilitate the formation of sulfated galactans, the key structural units of agar [24]. Fat and fiber contents were low and not significantly different between sites, consistent with the general biochemical profile of *Gracilaria* spp. and indicating that polysaccharides rather than lipids dominate metabolic investment in agar production.

Overall, the higher ash, protein, and carbohydrate contents in *G. edulis* cultured in Balaoan suggest that nutrient-rich environmental conditions not only support general growth but also enhance metabolic pathways critical for agar biosynthesis. These findings align with previous studies reporting proximate composition ranges for *Gracilaria* spp., including ash (22.7–53.4%), protein (7–13%), and carbohydrate (25–45%) [25], while providing a mechanistic link between environmental nutrient availability and biochemical processes that determine agar yield and quality.

Table 5 Agar yield extracted from cultured *G. edulis*.

Treatment	Dried Sample (g)	Extracted Agar (g)	Agar Yield (%)
Rosario Agar	25.0	3.89 ± 0.355 ^b	15.5 ± 0.014 ^b
Balaoan Agar	25.0	5.74 ± 0.364 ^a	23.0 ± 0.014 ^a

Means in a column superscripted with different letters are significantly different at 5% ($P < 0.05$) level of significance

3.6 Physical Characterization of Agar

Physical characterization of commercial and extracted agar from cultured *G. edulis* in La Union is presented in Table 6. Results of the viscosity test showed that agar extracted from *G. edulis* cultured in Rosario significantly obtained the highest mean value of 37.26 cP, followed by agar extracted from *G. edulis* cultured in Balaoan with 31.83 cP, and commercial agar with the lowest at 21.20 cP. Previous study found that agar yield was significantly higher in *Gracilaria edulis* ($67.52 \pm 1.43\%$) compared to *G. corticata* ($39.91 \pm 0.17\%$), and *G. edulis* also produced gels with higher viscosity at 70 °C (2.76 ± 0.39 cP) and 80 °C (1.96 ± 0.06 cP). Conversely, *G. corticata* exhibited greater gel hardness (316.7 ± 20.8 g) than *G. edulis* (113.33 ± 12.58 g), indicating species-specific differences in textural properties suitable for food jelly applications [26]. The high-viscosity hydrocolloids are in higher demand in the food industry, and low-viscosity hydrocolloids are in demand in the cosmetics and textile industry [27]. Commercial agar used in this study is a food-grade agar. Therefore, the viscosity of agar extracted from *G. edulis* cultured in Rosario and Balaoan is suitable for the food industry as a thickener and emulsion stabilizer. Comparing the viscosity of agar extracted from cultured *G. edulis* in two culture sites, agar in Rosario was more viscous than in Balaoan. Agar with higher viscosity can be used as a stabilizer and gelling agent in bakery products, water gels, confectionery, dairy products, canned meat and fish products, soups and sauces, and beverages [28].

Table 6 Physical characterization of extracted agar and commercial agar.

Treatment	Viscosity (cP)(@75 °C)	Gel Strength (g/cm ²)	Melting Temperature (°C)	Gelling Temperature (°C)
Commercial Agar	21.20±0.43 ^c	1291.00±2.64 ^a	89.33±0.33 ^a	37.66±0.33 ^c
Rosario Agar	37.26±0.27 ^a	306.33±4.41 ^b	83.66±0.33 ^b	42.00±0.57 ^b
Balaoan Agar	31.83±0.55 ^b	285.67±2.60 ^c	86.66±0.66 ^b	44.66±0.33 ^a

Means in a column superscripted with different letters are significantly different at 5% level ($P < 0.05$) level of significance

Gel strength is a key quality indicator of agar. In this study, commercial agar showed the highest gel strength ($1,291 \text{ g-cm}^2$), followed by agar from *G. edulis* cultured in Rosario (306.33 g-cm^2) and Balaoan (285.67 g-cm^2). The superior strength of commercial agar may be due to its source from different red seaweed species with naturally

higher gel strength. Previous studies have also reported gel strength in agar from unconventional sources, such as wild-collected *Gracilaria* spp. (250–400 g^{cm²}) and alkali-treated *Gelidium* spp. (500–700 g^{cm²}), highlighting the potential of non-commercial agar for specialized applications [29]. Among the cultured samples, Rosario agar had significantly higher gel strength than Balaoan, making it more suitable for food applications like stabilizing ice cream, pie fillings, and meringue. Higher alkali concentrations are known to enhance gel strength by improving the conversion of L-galactose-6-sulfate to 3,6-anhydro-L-galactose.

Gelling temperatures of 37.66 °C, 42.00 °C, and 44.66 °C and melting temperatures of 89.33 °C, 83.66 °C, and 86.66 °C were recorded for commercial agar and agars extracted from *G. edulis* cultured in Rosario and Balaoan, respectively. The gelling temperature was significantly higher in Balaoan agar, while commercial agar had the highest melting temperature. Rosario and Balaoan agars had comparable melting points. These values align with industry standards for food and pharmaceutical applications. However, the higher gelling temperatures in *G. edulis* agars attributed to high methyl ether substitution, a trait typical of *Gracilaria* make them unsuitable for microbiological media, which require gelling below 40 °C. Commercial agar showed a lower gelling point (33.2 °C) and higher melting point (108 °C), further highlighting the distinct properties of *Gracilaria*-derived agar [30]. Overall, the gelling and melting properties observed confirm the potential of Rosario and Balaoan agars for specific industrial applications.

4. Conclusion

Balaoan, La Union shows strong potential for *Gracilaria edulis* cultivation and quality agar production, supported by favorable environmental conditions and nutrient levels, particularly nitrogen and sulfate, which correlated with higher protein and carbohydrate content. Despite slightly elevated heavy metal traces, agar yield and quality were not negatively affected. Agar from Rosario showed higher viscosity and gel strength, ideal for food applications, while Balaoan agar's higher gelling and melting temperatures suit food and pharmaceutical use. Lower yields in Rosario may be due to environmental stress and epiphytes. Future research should explore safer, eco-friendly alternatives to alkali treatment for agar extraction.

5. Ethics Statement

The author confirms that this research article is original work and has not been previously published elsewhere, nor is it currently under consideration, partly or wholly, by any other journal. All data in the manuscript are accurate and authentic, and no part of the study has been fabricated or falsified. Proper citations have been provided for all sources and references used to prepare this manuscript. The authors ensure the work adheres to academic integrity and ethical research practices. All necessary approvals and consents were obtained under institutional and legal guidelines.

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7. Conflicts of Interest

The author declares that they have no conflict of interest.

8. Author Contributions

Andie John D. Tadeo: Conceptualization, Methodology, Supervision, Investigation, Data curation, Formal analysis, Writing –original draft, Writing –review & editing; Investigation, Validation, Resources.

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