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RESEARCH

Evaluation of cultivation potential and carrageenan properties of *Hypnea* sp. from Panay Island, Philippines

Ryuya Matsuda[1] · Joseph P. Faisan Jr.[2] · Hananiah Sollesta-Pitogo[2] · Leobert D. de la Peña[2]

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Abstract

Hypnea is a cosmopolitan genus of red seaweeds and an important source of carrageenan worldwide. However, *Hypnea* species remain largely unutilized in seaweed aquaculture in the Philippines. This study aimed to evaluate the growth performance and carrageenan properties of an indigenous, unexploited *Hypnea* sp. collected from Panay Island and to compare them with those of the commercially cultivated *Kappaphycus striatus*. In a field cultivation experiment, *Hypnea* sp. showed significantly higher biomass (145.1 ± 53.7 g) than *K. striatus* (92.9 ± 10.3 g) up to day 28 ($p < 0.001$), while no significant difference was observed at days 36 and 43. The final yields were 181.0 ± 68.4 g for *Hypnea* sp. and 191.1 ± 33.0 g for *K. striatus* ($p > 0.05$). Semi-refined carrageenan extracted from the cultured *Hypnea* sp. exhibited gel-forming capacity, suggesting the presence of κ-carrageenan. However, both the viscosity and gel strength of *Hypnea* sp. (9.52 ± 3.53 cP; 148 ± 41.6 g cm^{-2}) were significantly lower in *K. striatus* (70.9 ± 49.4 cP; 456 ± 201 g cm^{-2}) ($p < 0.001$), indicating that *Hypnea* sp. possesses distinct carrageenan properties from conventional commercial seaweed. Although further development of carrageenan-based products tailored to its unique properties will be required for commercial utilization, these findings highlight the potential of *Hypnea* sp. as a candidate seaweed for aquaculture in the Philippines.

Keywords Seaweed aquaculture · Carrageenan · *Hypnea* · Philippines

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✉ Ryuya Matsuda
matsudar0337@jircas.go.jp

[1] Japan International Research Center for Agricultural Science (JIRCAS), Owashi 1-1, Tsukuba, Ibaraki, Japan

[2] Southeast Asian Fisheries Development Center, Aquaculture Department (SEAFDEC/AQD), 5021 Tigbauan, Iloilo, Philippines

Introduction

Global seaweed aquaculture production increased nearly threefold from 2000 to 2020 (Fig. S1a). Farmed seaweed production reached a total biomass of 37.6 million tons, accounting for 27.6% of global marine aquaculture production (136 million tons) in 2023 (FAO 2025). This increase over the past two decades has been driven by the expansion of carrageenophyte cultivation in tropical developing countries (Fig. 1Sb). Carrageenophytes are red seaweeds that contain sulfated galactans called carrageenan in their extracellular matrix (Chevenier et al. 2023). Among these, eucheumatoids are a seaweed group comprising the genera *Kappaphycus* and *Eucheuma*, which are the most widely cultivated in tropical countries, particularly the Philippines, Indonesia, and Malaysia (Cai et al. 2021). Their desirable traits such as high growth rate, clonal propagation, and rich carrageenan content make them suitable aquaculture species for low-cost aquaculture, thereby supporting rural coastal livelihoods and artisanal fisheries (FAO 2025).

Carrageenan is a hydrocolloid used in food, pharmaceutical, and cosmetic industries as thickeners, stabilizers, and gelling agents (Necas and Bartosikova 2013). Based on their physical properties, carrageenan is classified into three main types; kappa (κ), iota (ι), and lambda (λ) (Necas and Bartosikova 2013; Bixler and Porse 2011). κ-carrageenan forms firm gels, iota-carrageenan produces soft gels, and lambda-carrageenan is not solidified. The diverse applications of carrageenan have sustained its global demand, positioning it among the major hydrocolloids alongside guar gum, gelatin, xanthan gum, and others. The carrageenan market accounts for approximately 8% of the major hydrocolloids market (cf. 3% for the agar market) and is currently valued at approximately USD 872 million, with an estimated annual growth rate of 5.4% from 2023 to 2030 (Zhang et al. 2023).

Despite its success, global production of eucheumatoids has declined slightly since peaking in 2015 (FAO 2025). This trend is attributed to multiple factors, including disease outbreaks such as "ice-ice disease" and epiphytic filamentous algae, declining seedling quality, abiotic stress linked to climate change, herbivory, and natural disasters such as typhoons (Trono and Largo 2019; Ward et al. 2020; 2022; Faisan et al. 2021). As eucheumatoids account for a large portion of tropical seaweed aquaculture, this trend has significant implications for both the global carrageenan industry and local coastal economies.

In agriculture, relying on a single species or crop increases vulnerability to environmental changes and undermines production stability (Smith et al. 2015). In many tropical countries, seaweed aquaculture depends heavily on *Kappaphycus* and *Eucheuma*, making them susceptible to supply chain disruption. One of the potential solutions is to diversify cultivated seaweed species to reduce disease risk and stabilize production (Hufnagel et al. 2020; Sugumaran et al. 2022). This approach requires exploration and characterization of alternative carrageenophyte species suitable for cultivation in tropical marine environments.

The red seaweed *Hypnea* J.V. Lamouroux (Family Cystocloniaceae) is another carrageenophyte with a broad distribution across intertidal zones in tropical and temperate regions, including Bangladesh, Brazil, India, Indonesia, Japan, Myanmar, and the Philippines, that has been harvested as a source of κ-carrageenan and as traditional food (Zemke-White and Ohno 1999; Tanaka et al. 2011; Yokoya et al. 2020). More recently, *Hypnea* species have attracted attention for their potential in health-promoting applications (Saber et al. 2024). While *H. musciformis* and *H. pseudomusciformis* have been investigated for aquaculture in countries like Bangladesh, Brazil, and India, little is known about their cultivation potential in Southeast Asia, where eucheumatoids remain dominant (Guist et al. 1982; Ganesan et al. 2006; Reis et al. 2008; Castelar et al. 2016; Pereira et al. 2020).

Given this context, research on native *Hypnea* species in Southeast Asia, including the Philippines, is critical to expanding the pool of candidate species for tropical seaweed aquaculture.

Although several studies have succeeded in the experimental cultivation of *Hypnea* spp., these studies focused only on the growth rates, but no analysis was conducted for carrageenan properties (Guist et al. 1982; Berchez et al. 1993; Ganesan et al. 2006; Pereira 2020, 2021; Mohiuddin et al. 2023). According to the study by Castelar et al. (2016), who compared the growth rate and carrageenan yield of *H. pseudomusciformis* (as *H. musciformis*) and *K. alvarezii* under laboratory conditions, *H. pseudomusciformis* exhibited comparable carrageenan content with *K. alvarezii* in laboratory conditions. Subsequent field cultivation experiments of *H. pseudomusciformis* together with *K. alvarezii* were not successful because the seedlings of *H. pseudomusciformis* could not be securely fixed to the tubular nets and likely detached during cultivation (Castelar et al. 2016). The aim of this study is to assess the cultivation potential of *Hypnea* sp. by comparing its growth performance and carrageenan characteristics with those of the commercially cultivated eucheumatoid seaweed *Kappaphycus striatus*. This is the first report to present experimental evidence supporting the feasibility of *Hypnea* species in the Philippines for aquaculture.

Materials and methods

Algal material

Thalli of a red alga resembling members of the genus *Hypnea* were collected from the swash zone along the beachfront of the Southeast Asian Fisheries Development Center, Aquaculture Department (SEAFDEC/AQD) in Brgy. Buyuan, Tigbauan, Iloilo, Philippines (10° 40′ 11″ N, 122° 21′ 14″ E) during low tide in February 2024 (Fig. 1a). The collected material comprised at least two distinct morphotypes (morphotype a and b; Fig. S2). Sequences of the chloroplast *rbcL* and mitochondrial COI regions were obtained (see DNA barcoding analysis section). Molecular analyses based on *rbcL* and COI sequences indicated the presence of two genetically distinct lineages within *Hypnea* species. Because the biomass of morphotype b was limited, morphotype a, hereafter referred to as *Hypnea* sp., was used for the cultivation experiment and carrageenan analyses described in this study. Most thalli of *Hypnea* sp. were washed ashore without holdfasts and tangled together, although some remained attached to small stones (Fig. S3). Seaweed of approximately 200–300 g was placed in 10 L carboys filled with seawater and transported to the hatchery tank facility at the Tigbauan Main Station (TMS) several times. The seaweed mass contained visible debris and other seaweed species, including *Ulva* sp., *Gracilaria* sp., and other *Hypnea* spp., which were removed manually. The thalli of *Hypnea* sp. were washed with UV-treated seawater, then disinfected in 100 ppm iodine for 30 min and rinsed thoroughly. *Kappaphycus striatus* (sacol variety; green morphotype) was originally obtained from a seaweed farm in San Dionisio, Iloilo, Philippines, in June 2023 (11° 17′ 20″ N, 123° 05′ 35″ E; Faisan et al. 2024a). Both *Hypnea* sp. and *K. striatus* were maintained in 300 L fiberglass tanks at TMS supplied with flow-through seawater (salinity 32–35‰) filtered through a 1-µm filter bag, with a 100% daily water exchange rate. Moderate aeration was provided at ambient temperature (daily mean 26.0–28.1 °C). Tanks and thalli were cleaned weekly by shaking the seaweeds to remove debris or epiphytes.

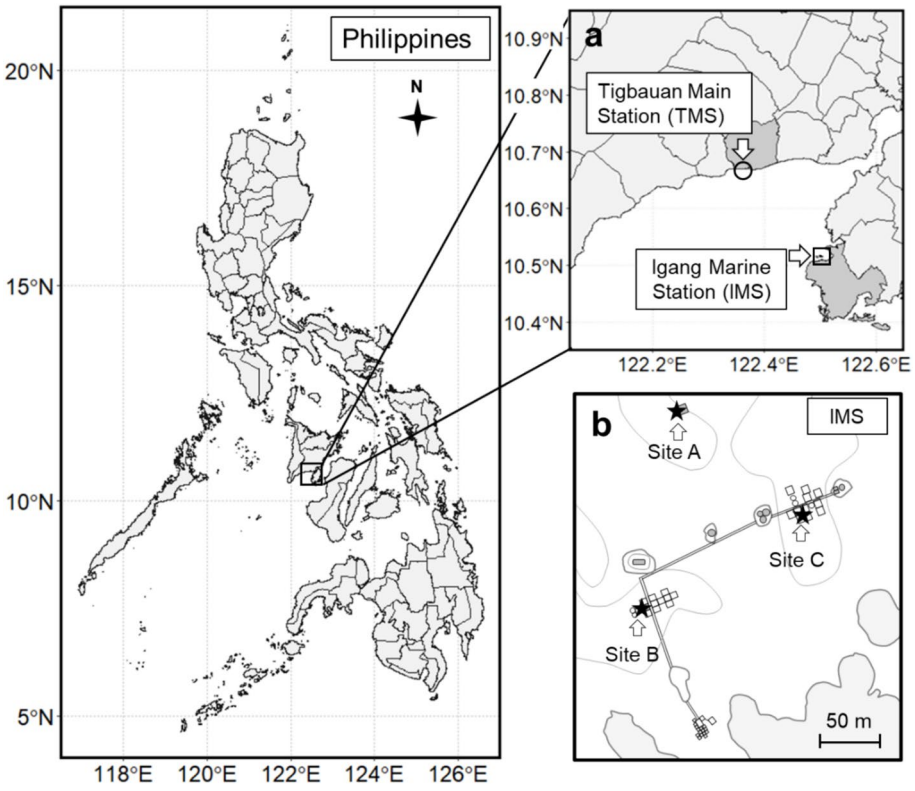


Fig. 1 Map of the collection site and the sea-based culture experiment site. **a** Samples of *Hypnea* spp. were collected at the SEAFDEC/AQD Tigbauan Main Station (TMS), Tigbauan, Iloilo. **b** The sea-based experiment was conducted at the Igang Marine Station (IMS), Nueva Valencia, Guimaras. The positional relationship among the three cage locations (Site A, B, and C) is shown in the lower right panel. The depths at each site were 10–12 m, 5–7 m, and 10–12 m, respectively

DNA barcoding analysis

To identify the species of collected thalli, three thalli each were randomly selected from the brown and green morphotypes for DNA extraction. Total genomic DNA was extracted using a DNeasy Plant Mini Kit (Qiagen, Germany) following the manufacturer's protocol. The chloroplast-encoded *ribulose-1,5-bisphosphate carboxylase/oxygenase* large subunit gene (*rbcL*) and the mitochondrial *cytochrome c oxidase* region, including the intergenic spacers between *cox1* and *cox3* (*cox1–3*), were amplified (Fig. S4). Primers for *rbcL* were manually designed based on alignments of full-length sequences reported by de Jesus et al. (2023). The primer sequences for *rbcL* were 5′-CTGTAGAAGAACGGACAA-3′ and 5′-TCAGCTGTATCTGTAGAAGTATA-3′. The primers for the *cox1–3* region were 5′-TCAACAAATCATAAAGATATTGG-3′ (GazF1; Saunders 2005) and 5′-GGATCTACWAGATGRAAWGGATGTC-3′ (Cox3_rev; Zuccarello et al. 1999). PCR was performed with KOD FX Neo polymerase (Toyobo, Japan) under the following conditions: initial denaturation at 94 °C for 2 min; 35 cycles of 98 °C for 10 s, 60 °C for 30 s, and 72 °C for 2 min; and a final extension at 72 °C for

5 min. PCR products were submitted to the Philippine Genome Center (PGC) Visayas for sequencing.

The *rbcL* (1385 bp) and COI (675 bp; GazF1–GazR1 region) sequences, the latter obtained from within the *cox1–3* amplicons, were compared with reference sequences available in GenBank using BLASTn provided by the National Center for Biotechnology Information (NCBI), and the top 10 matches were examined to assess sequence similarity. In addition, phylogenetic analysis was performed using MEGA version 12.1 (Kumar et al. 2024; https://www.megasoftware.net/). Sequences were aligned with related *rbcL* and COI sequences obtained from GenBank using ClustalW with default settings. Accession details are listed in Tables S1 and S2. Maximum likelihood trees for *rbcL* and COI were constructed using the GTR + I + G model with 500 bootstrap replicates. The most similar sequences against morphotype a were *Hypnea filiformis* (*rbcL* region) and *Hypnea boergesenii* (COI region). On the other hand, morphotype b showed the highest sequence similarity to *Hypnea stellulifera* (Tables S3 and S4) and clustered within the same clade in the phylogenetic tree (Fig. S5). Thus, morphotype a and b are hereafter referred to as *Hypnea* sp. and *Hypnea cf. stellulifera*, respectively, in this study. This information was used solely as a reference to confirm that the cultivated material (*Hypnea* sp.) was distinct from the clade of *H. stellulifera*.

Sea-based culture experiment

The sea-based experiment was employed following the method by Faisan et al. (2024b). Seaweed seedlings maintained in fiberglass tanks were transferred in 10 L carboys filled with UV-sterilized seawater and transported to the sea-based nursery facility at SEAFDEC/AQD Igang Marine Station (IMS), Nueva Valencia, Guimaras, Philippines (Fig. 1b; 10° 30′ 40″ N, 122° 30′ 00″ E). Prior to deployment, seedlings were divided into 10–15 g fresh weight (FW) portions and drained using a salad spinner prior to weighing. The portions were disinfected in 150 ppm povidone iodine solution for 30 min and rinsed with ambient seawater. To prevent physical disturbance (e.g., wave breaks, herbivorous fish) from loss of seaweed biomass, seaweed portions were randomly enclosed in floating plastic trays (41 × 25 × 15 cm) covered with black mesh netting (0.5 cm mesh) and stocked in a 5 × 5 m cage at three experimental sites within IMS (Fig. 1b). To prevent fouling, trays were lifted and shaken daily, and replaced weekly with clean trays. Five replicate trays per species were deployed at each site (2 species × 3 sites × 5 replicates). Specific growth rate (SGR) was calculated according to Luhan and Sollesta (2010):

$$\mathrm{SGR}\,(\%) = \frac{\ln\left(W_t\right) - \ln(W_i)}{T} \times 100$$

where W_t is the fresh weight at day T and W_i is the initial fresh weight. The experiment was conducted from March 6 to April 18 (43 days). Weights were recorded on a weekly basis (days 7, 14, 21, 28, 36, and 43, 6 weeks). This period corresponds to the dry season in Type I regions of the Philippines (November to April; PAGASA definition).

Environmental parameters

Sea surface temperature (SST) was recorded by HOBO UA-002–64 loggers (Onset, USA) attached to cage nets at sea surface level, logging every 5 min. Hourly and daily

means were calculated. For comparison with nutrient sampling, SST was further aggregated as the mean over the interval between two consecutive sampling days ($t-1$ to t), with the day 28–36 interval covering 8 days. Although light intensity was also logged using the same devices, wave action intermittently changed the logger orientation, and the cage net produced intermittent shading, such that the illuminance time series did not reliably reflect incident sunlight at the sites. Accordingly, photosynthetic photon flux density (PPFD) data were treated as indicative only and were not used for analyses in the main text.

Surface seawater of 100 mL was collected weekly from each site and stored at − 20 °C until analysis of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). DIN was calculated as the sum of ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) concentrations ($DIN = NH_4^+ + NO_2^- + NO_3^-$), and DIP was taken as the phosphate (PO_4^{3-}) concentration. Measurements of filtered seawater (Whatman GF/F, GE HealthCare, US) were performed using a Hach DR3900 spectrophotometer (Hach, Germany) with the manufacturer's protocols: NH_4^+ (Method 10,023), NO_2^- (Method 8507), NO_3^- (Method 8192), and PO_4^{3-} (Method 8048). For each sampling event, two separate water samples were collected on the same day and analyzed independently; the reported values represent the mean of these duplicate measurements.

In this study, dissolved oxygen (DO) and pH levels were not measured. According to the previous reports that surveyed these parameters in the field, the reported ranges of DO and pH levels were 4.2–6.3 ppm and 7.8–9.2, respectively (Faisan et al. 2024b; Lames et al. 2025; Lebata-Ramos and Solis 2025).

Carrageenan extraction and quality analysis

Semi-refined carrageenan (SRC) was extracted following Faisan et al. (2024b) with slight modifications. Fresh seaweed samples were air-dried for two weeks at room temperature, then oven-dried at 60 °C for 3 days to determine dry weight (DW). Samples were soaked in 3% KOH for 2 h at 25–28 °C, then boiled in 12% KOH for 1 h in a water bath (80–90 °C). After overnight rinsing in running tap water, samples were minced, air-dried for 3–5 days, and oven-dried at 60 °C for 1 day. The remaining material was weighed as SRC. Moisture content (MC) and carrageenan yield (CY) were calculated as:

$$MC\,(\%) = (1 - \frac{DW}{FW}) \times 100$$

$$CY\,(\%) = \frac{CW}{DW} \times 100$$

where DW is the dry weight, FW is the fresh weight, and CW is the weight of SRC.

SRC samples were ground in an analytical mill (IKA A 10 basic, Germany), sieved (#80 mesh), and stored in sealed containers. A 1.5% (w/v) SRC solution in 0.2% KCl was heated to 70–80 °C for viscosity measurements using a Brookfield LV rotary viscometer (USA) with spindle No. 1 at 30 or 60 rpm. Values were expressed in centipoise (cP). For gel strength, 1.5% SRC solution was poured into 70-mL glass cylinders, cooled overnight at 4 °C, demolded, and tested using an EZ Texture Analyzer (Shimadzu, Japan) with a 50 N load cell and 10 mm compression probe. The load speed was 50 mm/min and the compression depth was 20 mm.

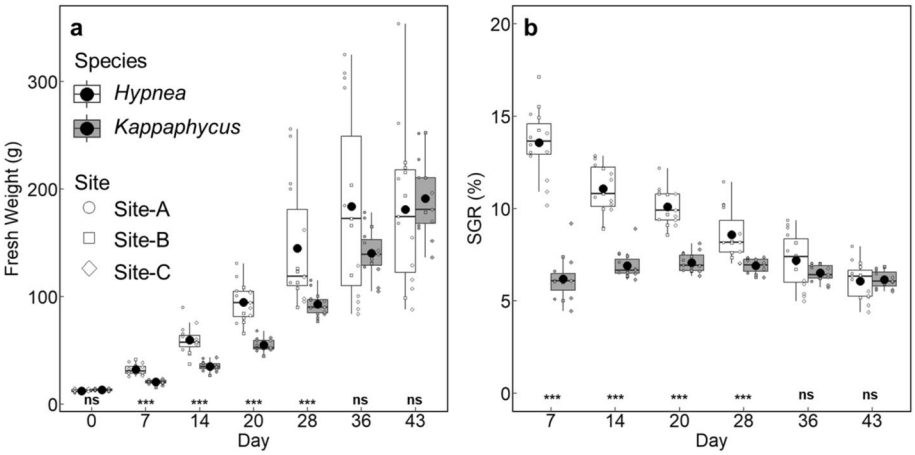


Fig. 2 Growth performance of *Hypnea* sp. and *Kappaphycus striatus* in the sea-based culture experiment. Boxplots show **a** fresh weight at each sampling day and **b** specific growth rate (SGR) based on fresh weight. Symbols represent site values, and filled circles indicate means (per species per site, $n = 15$). Fresh weight and SGR were analyzed using a generalized linear mixed model (GLMM) with a gamma distribution and the Mann–Whitney *U* test, respectively. Significant differences are indicated by asterisks (***, $p < 0.001$; ns, not significant)

Data analysis

Seaweed weight was analyzed separately for each sampling time using generalized linear mixed-effects models (GLMMs; Bolker et al. 2009) with the "lme4" package (Bates et al. 2015) in R 4.4.1 (R Core Team 2024). To account for the positive and potentially skewed nature of the weight data, a gamma distribution with a log link function was assumed (Pinheiro and Bates 2000; Saito et al. 2023). In GLMMs, species was set as a fixed effect, while site was modeled as a random intercept. Except weight at day 0, log-formed initial weight was incorporated as an offset to account for potential dependencies on starting biomass. Similarly, viscosity and gel strength were analyzed with gamma distributions whereas MC and CY were analyzed with binomial distributions with a random effect from sites. SGR was calculated from log-transformed fresh weights, which themselves were analyzed in the GLMM framework described above. Because SGR was treated as a supplementary metric and not the primary response variable, we compared it between species using a nonparametric Mann–Whitney *U* test from "coin" package (Hothorn et al. 2008), disregarding site-specific effects. Statistical significance was set at $p \leq 0.05$.

Results

Sea-based culture experiment

The fresh weight of *Hypnea* sp. was significantly higher than that of *Kappaphycus striatus* at days 7, 14, 20, and 28 ($p < 0.001$ for all comparisons), whereas no significant differences were observed at days 36 and 43 ($p > 0.05$) (Fig. 2a; Tables S5 and S6). Finally, we obtained 181.0 ± 68.4 g FW of *Hypnea* sp. and 191.1 ± 33.0 g FW of *K. striatus*. The

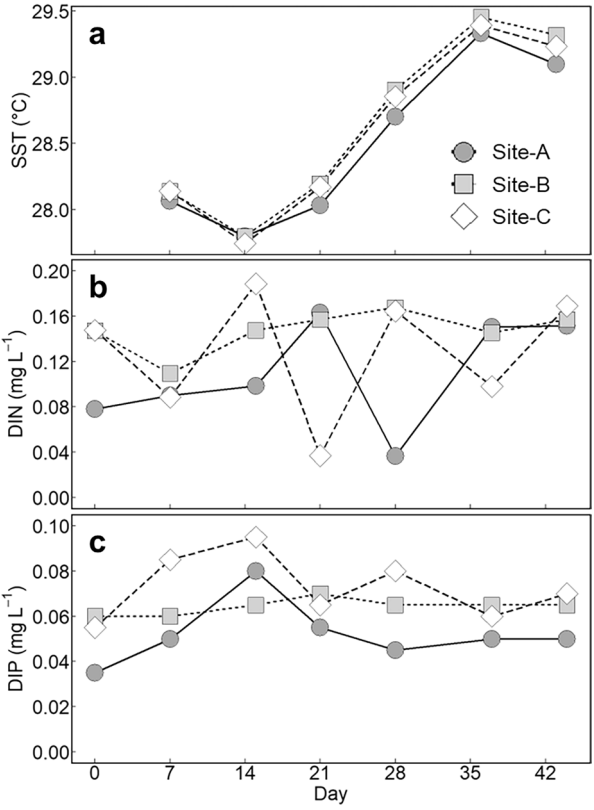


Fig. 3 Environmental parameters in the sea-based experiment. **a** Sea surface temperature (SST), **b** dissolved inorganic nitrogen (DIN), and **c** dissolved inorganic phosphorus (DIP) were measured weekly at each site. Symbols distinguish Site-A, Site-B, and Site-C

specific growth rate (SGR) of *Hypnea* sp. was consistently higher than that of *K. striatus* during the first 28 days (8.57–13.6%), but it gradually declined and became comparable to that of *K. striatus* by day 43 (6.07%) (Fig. 2b). In contrast, the SGR of *K. striatus* remained relatively stable throughout the experiment (6.19–7.07%). This overall trend was consistent across sites, although the biomass of *Hypnea* sp. declined at day 36 and day 43 at Site C and Site A, respectively (Table S5). At Site C, small sea slugs were observed in trays containing *Hypnea* sp. at day 36. This observation may partly explain the biomass loss of *Hypnea* sp. between day 28 and day 36, possibly due to herbivory.

Environmental parameters

The mean sea surface temperatures (SSTs) throughout the whole experimental period were 28.6 ± 1.09 °C, 28.6 ± 1.04 °C, and 28.5 ± 1.00 °C at Site A, Site B, and Site C, respectively, showing no marked differences among sites. The SSTs were high in the second half of the experimental period compared to the first half (Fig. 3a). The mean concentrations of dissolved inorganic nitrogen (DIN) throughout the term were 0.110 ± 0.043 mg L^{-1}, 0.147 ± 0.017 mg L^{-1} and 0.128 ± 0.050 mg L^{-1} at Site A, Site B, and Site C, respectively (Fig. 3b). The mean concentrations of dissolved inorganic phosphorus (DIP) throughout the term were 0.052 ± 0.013 mg L^{-1}, 0.064 ± 0.004 mg L^{-1}, and 0.072 ± 0.014 mg L^{-1} at Site A, Site B, and Site C, respectively (Fig. 3c).

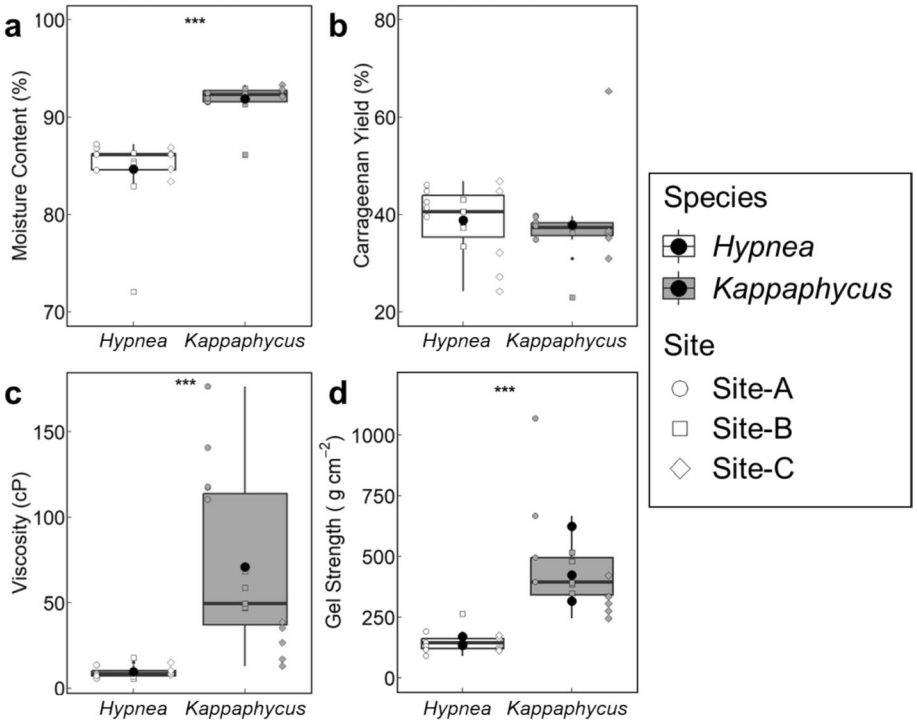


Fig. 4 Carrageenan properties of *Hypnea* sp. and *Kappaphycus striatus* in the sea-based culture experiment. Boxplots show **a** moisture content, **b** carrageenan yield, **c** viscosity, and **d** gel strength. Symbols represent site values, and filled circles indicate means (per species per site, $n = 15$). Data were analyzed using GLMMs with appropriate distributions. Significant differences are indicated by asterisks (***, $p < 0.001$; ns, not significant)

Carrageenan properties

The moisture content was lower in *Hypnea* sp. ($84.7 \pm 3.70\%$) than in *Kappaphycus* ($91.9 \pm 1.69\%$) ($p < 0.001$), indicating the residual biomass containing carrageenan was higher in *Hypnea* sp. than *K. striatus* (Fig. 4a; Table S7). The carrageenan yield did not differ significantly between *Hypnea* sp. ($38.8 \pm 6.83\%$) and *K. striatus* ($37.8 \pm 8.68\%$) on a dry weight basis ($p > 0.05$) (Fig. 4b; Table S7). The viscosity was lower in *Hypnea* sp. (9.52 ± 3.53 cP) than in *K. striatus* (70.9 ± 49.4 cP) ($p < 0.001$) (Fig. 4c; Table S8). Similarly, the gel strength was lower in *Hypnea* sp. (148 ± 41.6 g cm^{-2}) than in *K. striatus* (456 ± 201 g cm^{-2}) ($p < 0.001$) (Fig. 4d; Table S8). The viscosity and gel strength of carrageenan from *K. striatus* varied among sites, whereas those of *Hypnea* sp. were consistent (Fig. 4).

Discussion

The genus *Hypnea* is a cosmopolitan group of red seaweeds that has been utilized as a source of carrageenan in several countries (Ganesan et al. 2006; Yokoya et al. 2020; Pereira et al. 2020, 2021; Mohiuddin et al. 2023). Nevertheless, studies on *Hypnea* spp.

in the Philippines have focused mainly on ecological and taxonomic aspects (Geraldino et al. 2010; Beringuela et al. 2020), with little attention to aquaculture applications. In the present study, *Hypnea* sp., native to the Philippines, demonstrated growth performance in sea surface farming conditions when compared with the conventional aquaculture species *Kappaphycus striatus* (Fig. 2). The semi-refined carrageenan (SRC) extracted from the cultivated *Hypnea* sp. showed distinct properties compared with those of *K. striatus* (Fig. 4). To our knowledge, this is the first study to assess *Hypnea* sp. in the Philippines for aquaculture purposes.

Growth performance

Hypnea sp. and *Kappaphycus striatus* were successfully grown in the IMS (Fig. 1), where previous sea-based culture experiments have also been conducted with *K. alvarezii* (Faisan et al. 2024b). In that study, the specific growth rate (SGR) of *K. alvarezii* was 3.3–8.8% for 30 days and 2.6–6.9% for 45 days during the same season as the present study (February–April). In comparison, the SGR of *K. striatus* in our experiment was approximately 6% day^{-1}, indicating that the sea-based experiment was conducted under appropriate conditions. Under these conditions, *Hypnea* sp. also showed growth performance comparable to *K. striatus* (Fig. 2).

The SGR of *Hypnea* sp. was $8.57 \pm 1.27\%$ over 28 days and $6.07 \pm 0.96\%$ over 43 days (Fig. 2b). After day 28, some trays showed biomass loss. Although there is no direct evidence, small sea slugs were observed on trays containing *Hypnea* sp. at Site C on day 36. This observation may partly explain the biomass loss, possibly due to grazing (herbivory). Nevertheless, those SGR values were relatively high compared with previous reports for other *Hypnea* species (e.g., 5.66% for *H. pseudomusciformis* in Brazil, Pereira et al. 2020; 3.8–10.9% for *H. musciformis* in India, Ganesan et al. 2006; 2–6% for *H. musciformis* in Bangladesh, Mohiuddin et al. 2023). Seaweed growth is influenced by numerous factors, including environmental conditions and culture methods such as culture duration, depth, and stocking density (Hurtado et al. 2008; Ullah et al. 2023). In the present study, seaweeds were maintained inside floating trays, whereas most previous culture experiments employed rope-fixed methods (Ganesan et al. 2006; Pereira et al. 2020; Mohiuddin et al. 2023). The tray method may have helped reduce biomass loss by mitigating wavebreaks and herbivorous fish. However, the SGR of *Hypnea* sp. declined during the later phase (Fig. 2b). Stocking density is known to affect seaweed growth due to self-shading and nutrient competition, a phenomenon referred to as self-thinning (Scrosati 2005; Xiao et al. 2019; Sato et al. 2023; Megarajan et al. 2024). In our sea-based culture, branches of *Hypnea* sp. overlapped within the trays, which may have caused localized light and nutrient limitations and contributed to the reduced growth observed in the later phase.

In addition, this experiment used plastic trays based on their past performance (Faisan et al. 2024b). However, the use of plastics in marine environments has recently attracted attention due to concerns about microplastic pollution. Long-term use of plastic materials may increase the risk of microplastic generation (Luo et al. 2025). Therefore, plastic trays may be less desirable from an environmental perspective, and alternatives such as biodegradable materials warrant evaluation for practical aquaculture.

During the study period, the daily mean sea surface temperature was about 28 °C in the early phase and increased to around 30 °C in the later phase (Fig. 3a, Fig. S5a). Several in vitro culture experiments have shown that rising temperature can promote growth in

species such as *H. brasiliensis*, *H. cervicornis*, *H. spinella* (Nauer et al. 2022a), *H. pseudomusciformis* (Nauer et al. 2022b), and *H. japonica* (Hayakawa et al. 2013). However, most of these species exhibit reduced or no growth above 30 °C, except for *H. pseudomusciformis*, which is thermally tolerant (Nauer et al. 2022b). Conversely, a sea-based culture experiment reported that the growth rate of *H. musciformis* decreased with increasing water temperature (Mohiuddin et al. 2023). In light of these findings, the relatively favorable temperatures in the early phase may have supported the good growth of *Hypnea* sp., while the higher temperatures in the later phase may have constrained its growth (Fig. 2).

Although the growth of *Hypnea* sp. was reduced in the late phase, *K. striatus* maintained stable growth throughout the experimental period (Fig. 2). The strain of *K. striatus* used in this study originated from a seaweed farm where seedlings had been selected and acclimated for cultivation (Faisan et al. 2024a). By contrast, a wild strain of *Hypnea* sp. was used without prior selection or acclimation. The variation observed in the growth of *Hypnea* sp. may therefore reflect the physiological diversity of wildtype strains. For commercial aquaculture, selection and establishment of strains with enhanced growth capacity and carrageenan quality would be necessary.

Hypnea sp. grew more rapidly than *K. striatus* even within a short cultivation period (ca. 1 month; Fig. 2). In coastal areas, unforeseen environmental disturbances such as rough seas and elevated temperatures, occur frequently as a result of typhoons and El Niño events. Under such unfavorable conditions, farmers who cultivate a single seaweed species in the open sea face a high risk of complete crop loss. In this context, the ability to harvest seaweed within a short period represents a major advantage for farmers' livelihoods. In regions with stable climate conditions throughout the year, species exhibiting steady growth (e.g., *Kappaphycus*) may be preferred for continuous farming. However, in areas frequently affected by typhoons, such as the central–northern Philippines, the characteristics of *Hypnea* spp. may provide particular benefits for small-scale farmers engaging in short-term or opportunistic seaweed farming. Further investigation of the environmental factors influencing *Hypnea* growth and of variety selection will support the development of *Hypnea* aquaculture into a viable industry.

Carrageenan properties

Carrageenans have been identified into more than 15 structure types based on the modification of the disaccharide repeating unit by ester sulfate groups and the presence of 3,6-anhydrogalactose (AG), of which three types (λ-, ι-, and κ-carrageenan) are commercially produced (Rafiquzzaman et al. 2016; Tuvikene 2021). In those three types, κ-carrageenan forms strong brittle gels with potassium ions (Necas and Bartosikova 2013). Our observation of the gel formation property of the alkali-transformed extracts indicates that the *Hypnea* sp. used in this study contained κ-carrageenan.

Clear, universal industrial requirements for carrageenan quality are difficult to define because carrageenan is used for diverse applications (e.g., food ingredients, nutraceuticals, pharmaceuticals, and cosmetics), and target viscosity and gel strength can vary with extraction and measurement conditions. However, FAO specifies a minimum viscosity of ≥ 5 cP at 75 °C for carrageenan products (FAO 2014). For yield, although no formal criterion is universally applied, values of $\geq 25\%$ are often used as a practical benchmark (Astuti et al. 2017; Rahmawati et al. 2023). In contrast, reported gel strength spans a wide range (from 1 to 1000 ~ g cm^{-2}) depending on species and methodology (Ohno et al. 1994;

Hurtado-Ponce 1995; Manuhara et al. 2016; Ha et al. 2022; Faisan et al. 2024b). The SRC extracted from *Hypnea* sp. in this study meets these reported ranges (Fig. 4).

Previous studies have reported that *Hypnea* spp. generally contain predominantly κ-carrageenan with small amounts of iota-carrageenan when extracted after alkali treatment (Bi et al. 2006; Arman and Qader 2012; Vázquez-Delfín et al. 2014; Al-Alawi et al. 2011; Al-Nahdi et al. 2019). The gel strength of κ/ι hybrid carrageenans decreases with lower κ-content (van de Velde et al. 2005). Although the chemical composition of *Hypnea* extracts was not determined here, the relatively weak gel properties may reflect a lower κ-content compared with *K. striatus*.

The gel properties of *Hypnea* spp., as well as other carrageenophytes and agarophytes, are known to vary with environmental conditions (Reis et al. 2008; Qari et al. 2018). For instance, the gel strength of *Gracilaria heteroclada* agar was higher during the dry season than in the wet season (Luhan 1992); in *Gelidium pulchellum*, light intensity influences gel strength (Sousa-Pinto et al. 1999); and in *Chondrus crispus*, κ/ι hybrid carrageenan exhibited stronger gels after culture in darkness (Song et al. 2022). In the present study, the strong sunlight conditions of the sea surface may have influenced the gel strength of *Hypnea* sp.

In addition, this study applied an alkali extraction method using 3% and 12% KOH solutions, which had been optimized for carrageenan extraction from *K. alvarezii* (Luhan et al. 2015; Faisan et al. 2024b). Some reports, however, suggest that NaOH treatment may be more efficient for carrageenan extraction from *Hypnea* spp. (Al-Alawi et al. 2011; Castelar et al. 2016). Development of cultivation and extraction methods tailored to *Hypnea* will therefore be needed to improve carrageenan quality.

Interestingly, the viscosity and gel strength of carrageenan from *K. striatus* varied among sites (Fig. 4). Similar variations in gel properties have been reported for *K. alvarezii* in response to changes in salinity, nutrients, and temperature (Periyasamy et al. 2016; Shalvina et al. 2022). The present study did not identify the specific environmental factors affecting carrageenan properties of *Kappaphycus*, which should be clarified in future work.

Issues and future perspectives

The present study demonstrated the potential of *Hypnea* sp., native to the Philippines, as a candidate seaweed for aquaculture, based on its growth and carrageenan characteristics. However, the study focused mainly on comparisons between *Hypnea* sp. and *K. striatus*, and several issues remain for the broader development of *Hypnea* aquaculture, including the improvement of cultivation methods and the identification of suitable applications based on carrageenan properties. Among these, seedling preparation is particularly critical. In the survey area, although *Hypnea* spp. were available at the collection site during the dry season, they were not found during the rainy season. Such seasonal fluctuations are also common in *Kappaphycus* spp. (Hung et al. 2009; Faisan et al. 2024b).

Seasonal variation in biomass has been reported for *H. musciformis* in Morocco (Aziza et al. 2008), Brazil (Caires et al. 2013), India (Maharana et al. 2015), Ghana (Akrong et al. 2022), and Mexico (Vázquez-Delfín et al. 2023), for *H. charoides* in Hong Kong (Kong and Ang 2004), and for *H. japonica* in Japan (Tanaka et al. 2011). Field surveys indicate that *H. musciformis* inhabiting tropical coasts of the North Atlantic and Indian Oceans persists year-round but with greater biomass in the dry season, whereas *H. charoides* and *H. japonica* in the temperate Pacific Ocean disappear completely during summer (August)

and grow mainly from winter to spring (December/January to April/May). The growth pattern of the *Hypnea* sp. from the present collection site resembled that of the temperate Pacific species.

Sea-based cultivation of *H. musciformis* has been achieved year-round in Bangladesh and India (Ganesan et al. 2006; Mohiuddin et al. 2023). By contrast, the *Hypnea* spp. in this study disappeared from the coast at the end of the dry season (May) and reappeared only in January of the following year in Panay. Further ecological studies on seasonal growth patterns are therefore necessary to provide insights into the development of aquaculture techniques in the Philippines.

In addition to ecological issues, accurate species identification remains a challenge. Based on DNA sequences, we detected two *Hypnea* lineages (*Hypnea* sp. and *H. cf. stellulifera*) that have not previously been reported from Panay Island, and definitive identification was not achieved in this study. Recent taxonomic and phylogenetic studies have highlighted the difficulty of classifying *Hypnea* species based on morphology alone and have revealed cryptic diversity using molecular evidence (de Jesus et al. 2023). Currently, 15 species of the genus *Hypnea* are recognized in the Philippines (Lastimoso and Santiañez 2021). While *H. stellulifera* was previously described as a variety of *H. cornuta* and distributed in tropical regions in the Pacific Ocean, including the Philippines (Geraldino et al. 2009), Yamagishi et al. (2003) proposed raising var. *stellulifera* to the rank of species based on the *rbcL* gene. Given the wide distribution of this species in Southeast Asia, it is plausible that *H. stellulifera* occurs in Panay. On the other hand, *Hypnea* sp. requires more detailed taxonomic characterization.

In Panay, only four *Hypnea* species have been listed in an illustrated guide (*H. musciformis*, *H. pannosa*, *H. spinella*, and *H. valentiae*; Hurtado et al. 2006). Because this classification was based on morphology, it should be re-evaluated using DNA sequence data. Conversely, *Hypnea* sp. and *H. cf. stellulifera* were identified based on molecular evidence in this study. Integrating anatomical observations with DNA-based analyses will facilitate robust species delimitation and classification.

Taken together, these limitations indicate that further work is needed, including (i) characterization of carrageenan physicochemical properties (e.g., FTIR-based structural analysis and melting temperature), (ii) optimization of extraction conditions to maximize yield (e.g., alkali type and procedure), and (iii) clarification of ecological and taxonomic questions relevant to the practical application of *Hypnea* sp. in the Philippines.

Conclusion

This study examined the growth performance and carrageenan properties of a *Hypnea* sp. native to the Philippines in comparison with the conventional cultivar *Kappaphycus striatus*. *Hypnea* sp. showed satisfactory growth under sea-based cultivation and contained κ-carrageenan polysaccharides. However, differences in carrageenan properties, particularly gel strength and viscosity, warrant further investigation for practical applications. The present findings provide baseline information supporting the potential utilization of *Hypnea* sp. as a carrageenan-producing seaweed and as a candidate species for aquaculture in the Philippines.

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Author contributions All authors contributed to the conceptualization of the study; Ryuya Matsuda, Joseph P. Faisan Jr., Hananiah Sollesta-Pitogo, and Leobert D. de la Peña implemented the study; Ryuya Matsuda analyzed the data, including the preparation of tables and figures; and all authors reviewed the manuscript.

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Data availability The data supporting the study's findings can be accessed from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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