

Brief Report

Impact of Transportation Duration on the Growth, Pathological Stress, and Dry Biomass Yield of *Kappaphycus striatus* Propagules

Albaris B. Tahliluddin *, Aldimar S. Bara , Adzhar M. Abduhasad and Nurizna T. Jumaide

College of Oceanography, Fisheries, Environmental Science and Technology, Mindanao State University
Tawi-Tawi College of Technology and Oceanography, Bongao 7500, Tawi-Tawi, Philippines;
aldimarbara@msutawi-tawi.edu.ph (A.S.B.); adzharabduhasad@msutawi-tawi.edu.ph (A.M.A.);
nuriznajumaide@msutawi-tawi.edu.ph (N.T.J.)

* Correspondence: albaristahliluddin@msutcto.edu.ph

Abstract

Seaweed cultivation is a primary economic driver in Tawi-Tawi, Philippines, yet the industry faces significant challenges regarding the physiological integrity of propagules during inter-island transit. This study evaluated the effects of varying transportation durations (0, 12, 24, 36, and 48 h) on the specific growth rate (SGR), occurrence of ice-ice disease, and dry biomass yield of *Kappaphycus striatus* over a 30-day cultivation period using a modified fixed-off-bottom method. The results demonstrated that transportation duration significantly influenced SGR at Day 10 and Day 30 ($p < 0.05$), whereas no significant differences were observed at Day 20. The control group (0 h transport) exhibited the highest growth performance ($4.61 \pm 0.18\% \text{ day}^{-1}$ at Day 10), whereas the lowest growth was recorded in the 48 h treatment group at Day 30 ($0.93 \pm 0.49\% \text{ day}^{-1}$). Pathological assessment indicated that ice-ice disease occurrence was highly significant during the initial recovery phase (Days 1–7) and at Day 20 ($p < 0.05$). Specifically, propagules subjected to 48 h transport reached 100% disease incidence within the first four days post-transplant, while the 36 h group reached 96.67%, highlighting acute transport-induced stress. Although the 48 h group exhibited significantly higher initial ice-ice spot counts ($p < 0.05$), statistical differences diminished between Day 10 and Day 30, suggesting a degree of physiological resilience and recovery capacity. Ultimately, prolonged transportation exceeding 24 h induced severe dehydration stress, resulting in a 62.7% reduction in SGR by Day 30 compared to the control. These findings suggest that seedling transport should be optimized within a 24 h window to preserve thallus vigor and maximize sustainable yields. Future research should investigate post-transport recovery protocols to mitigate the effects of unavoidable shipping delays.

Keywords: *Kappaphycus striatus*; inter-island transport; seaweed cultivation; ice-ice disease; biomass yield; transport stress



Academic Editor: Gary Caldwell

Received: 13 February 2026

Revised: 10 April 2026

Accepted: 20 April 2026

Published: 22 April 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The red seaweed genus *Kappaphycus* is a pillar of the global hydrocolloid industry, accounting for over 90% of the world's carrageenan production [1], a market projected to reach USD 1.32 billion by 2030 [2]. This genus is primarily valued for its *kappa*-carrageenan, a gelling agent indispensable in food processing, pharmaceuticals, and emerging nutraceutical applications [1,3,4]. Among the cultivated species, *Kappaphycus striatus* (locally known

as “sacol”) is consumed as food and supports coastal livelihoods, particularly in the Philippines [5–8].

While often perceived as less commercially attractive than *K. alvarezii* due to its higher susceptibility to disease and intensive maintenance requirements [5,9], *K. striatus* has demonstrated superior performance in certain environments; for instance, growth rates of 2.98% day^{−1} have been recorded compared to 1.98% day^{−1} for *K. alvarezii* in Indonesian waters [10]. Despite this potential, significant declines in productivity and a rising prevalence of disease have been reported over the last decade across major producing regions globally, including Southeast Asia and East Africa [11,12]. While these trends affect *Kappaphycus* spp. broadly, evidence suggests that *K. striatus* populations are increasingly compromised by physiological stress even prior to out-planting [6,13,14]. This pre-planting stress is recognized as a primary driver of cultivation failure, yet the specific impacts of transportation-induced stress on the subsequent growth and health of *K. striatus* remain insufficiently documented.

The success of seaweed mariculture is fundamentally tied to the quality of the propagules [6]. Healthy propagules are essential for optimizing specific growth rates (SGR), maximizing biomass yield, and ensuring resistance to environmental stressors [15]. A primary threat to the stability of the seaweed trade is ice-ice disease—a physiological condition that results in thallus whitening and branch fragmentation [9,11,16]. Triggered by abiotic stress, this condition involves a transition from metabolic disruption to biotic infection, where the seaweed’s defense mechanisms fail, allowing opportunistic bacteria (primarily *Vibrio* and *Cytophaga* species) to invade and degrade cortical tissues [11,12]. The economic impacts are severe, with annual production losses estimated at 15–30% in affected regions, representing millions of dollars in lost export revenue [11,16].

A critical yet frequently overlooked source of such stress is the transportation of propagules. In archipelagic regions like Tawi-Tawi, propagules must often travel vast distances from nurseries to farming sites. While Indonesia utilizes diverse methods—including dry, cold, and waterless systems [4,17]—the dry system remains the standard in Tawi-Tawi due to its simplicity and low cost. Typically, propagules are packed into polypropylene sacks and transported via small pump boats or *lantsa* for anywhere from 6 to 48 h, depending on distance and weather (AB Tahiluddin, Personal Observation). During transit, propagules are subjected to prolonged air exposure, mechanical pressure, and temperature fluctuations, which induce acute dehydration and metabolic disruption [15,18]. Previous research has indicated that transport duration is a decisive factor in cultivation success. For instance, while short transport windows (6–24 h) may allow for physiological recovery, durations exceeding 30 h often result in irreversible tissue damage and significantly reduced regeneration ability [15,18]. However, this physiological threshold has been primarily established using the dominant cultivar, *K. alvarezii*. In contrast, *K. striatus*—an equally important red seaweed due to its kappa-carrageenan content—occupies a distinct ecological niche and possesses a unique thallus morphology that may confer differential resilience to desiccation and physical stress. Understanding this species’ specific response is crucial, as its distinct physiological traits could make it either more vulnerable to transport stress or a more resilient candidate for specific farming environments. Besides, there is a lack of studies on the utilization of *K. striatus* with regard to its potential effect on transport stress.

While recent studies have explored mitigation strategies—such as the use of biostimulants [19] or cold chain logistics [17]—there remains a paucity of field-based data regarding the specific response of *K. striatus* to transportation-induced stress. This species has demonstrated a unique capacity to adapt to adverse habitats, such as mangroves, by forming denser morphologies to resist desiccation [20]. However, the threshold at which

transportation duration transitions from manageable stress to a driver of ice-ice disease and biomass loss remains poorly defined under real-world farming conditions.

This study is of particular relevance to Tawi-Tawi, which was recently declared the “Seaweed Capital of the Philippines” under BTA Bill No. 101 [21]. In this region, seaweed farming is more than a livelihood; it is a fundamental cultural and economic identity [22]. As propagules are regularly transported from island municipalities to the commercial hub of Bongao, ensuring the physiological integrity of these “seeds” is paramount for maintaining the region’s economic output. Therefore, this study aims to evaluate the effects of varying transportation periods on the SGR, ice-ice disease incidence, and dry biomass yield of *K. striatus* over a 30-day field cultivation period. These findings seek to establish evidence-based protocols for propagule handling to enhance the sustainability and productivity of the seaweed industry.

2. Materials and Methods

2.1. Study Site

The study was conducted in the coastal area of Pasiagan, Bongao, Tawi-Tawi, Philippines (Figure 1). The selected cultivation site is characterized by a sandy substrate dominated by seagrass beds (*Thalassia hemprichii*) and a semi-exposed wave regime. At high tide, water depths reach approximately 2.0 m, providing adequate clearance for the cultivation lines. However, tidal variations result in periodic aerial exposure of the propagules; while propagules remain submerged during neap tides, spring tides lead to aerial exposure for intervals of 1–2 h. A moderate current regime prevails in the area, facilitating continuous nutrient exchange and water circulation. Furthermore, the site’s isolation from urban runoff and major riverine discharges effectively eliminates significant freshwater input or local pollution, maintaining stable oceanic conditions throughout the study period.

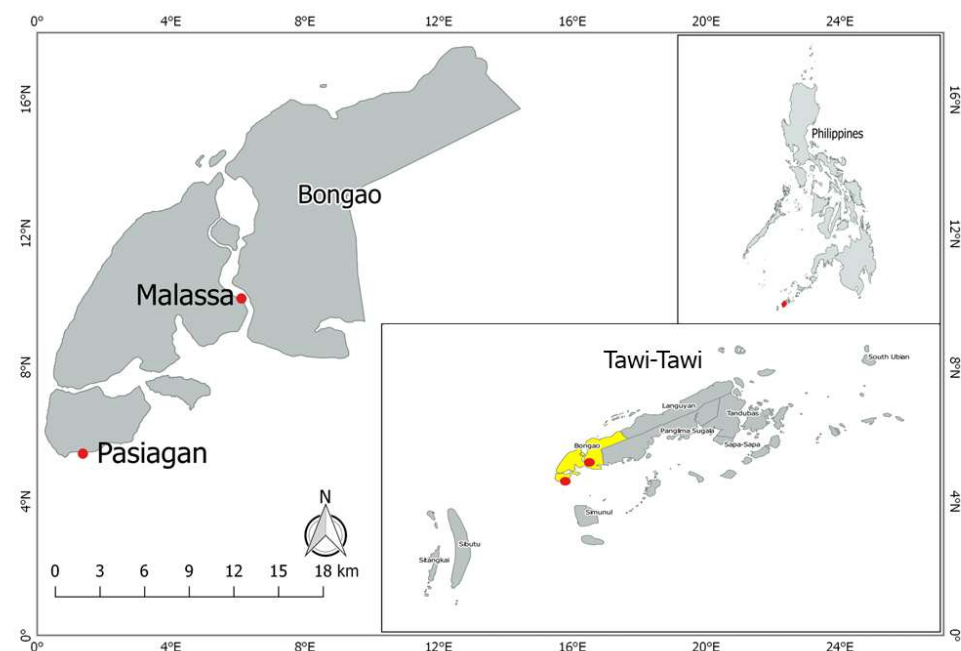


Figure 1. Geographic location of the study area in Bongao, Tawi-Tawi, Philippines. The map indicates the propagule collection site in Malassa and the experimental cultivation site in Pasiagan (red circle dots).

2.2. Experimental Design and Seedling Procurement

A completely randomized design (CRD) was employed, consisting of five treatment groups based on holding durations: 0 h (control), 12 h, 24 h, 36 h, and 48 h. Each treat-

ment was performed in triplicate, with each replicate comprising 15 bundles of seaweed propagules to ensure sufficient biomass for longitudinal monitoring.

The propagules of *Kappaphycus striatus* were sourced from Barangay Malassa, Bongao, Tawi-Tawi. Selection was restricted to healthy specimens, characterized by a vibrant dark brown coloration, firm thalli texture, and the absence of epiphytes or visible tissue whitening (indicative of ice-ice disease). To address initial variability, the fresh weight of individual propagules was maintained within a range of 50 to 70 g.

2.3. Sample Transport and Treatment Protocols

The control group (0 h holding time) was immediately transported to the experimental site in Barangay Pasiagan (approx. 30 min transit) using a 50 L insulated ice chest. To maintain physiological homeostasis, the chest was filled with 30 L of ambient seawater, providing a loading density of approximately 50 g L⁻¹. Given the exceptionally short transit duration and the use of a sealed, insulated container, supplemental aeration and water exchange were not performed. The insulation served to minimize thermal fluctuations and maintain dissolved oxygen levels close to ambient saturation during the brief journey. While continuous monitoring of water parameters was not conducted during the 30 min transit, the immediate deployment of the propagules upon arrival ensured they remained in a high-vitality state prior to out-planting.

Conversely, the experimental groups (12, 24, 36, and 48 h) were subjected to a traditional “dry system” transport simulation to mimic local logistics. Propagules were loosely packed in open polypropylene sacks (45 × 70 cm) at a packing density of approximately 2 kg per sack. To simulate shaded transit, the sacks were arranged in a single layer within a shaded facility, protected from direct sunlight and provided with consistent natural ventilation. An initial ambient air temperature of 31 °C was recorded using a glass thermometer (Nahita, Beriáin, Spain). Due to equipment limitations, continuous temperature logging and relative humidity monitoring were not conducted; however, the laboratory environment was kept stable to minimize extreme fluctuations. This traditional waterless technique is practiced locally to induce a state of metabolic depression or hibernation, theoretically preserving seedling viability during extended inter-island transit [4,15]. Following their respective holding durations, the propagules were transported to the field site (approximately 5–7 min) for out-planting and further observation.

2.4. Field Cultivation and Experimental Setup

The field experiment was conducted using a modified fixed-off-bottom method [23]. Each replicate consisted of ten *K. striatus* propagules, with an initial fresh weight standardized between 50 and 70 g. Ropes were anchored to bamboo stakes at both ends and suspended approximately 30 cm above the substrate.

While the control group was out-planted immediately upon arrival at the site, the experimental groups (Treatments 2–5) were out-planted sequentially as their respective holding durations (12, 24, 36, and 48 h) concluded.

2.5. Growth and Pathological Monitoring

The health and performance of the seaweeds were monitored over a 30-day cultivation period. Observation frequency was intensified during the initial recovery phase (daily for the first week) and continued at 10-day intervals (Days 10, 20, and 30).

2.5.1. Ice-Ice Disease Assessment

The occurrence of ice-ice disease was evaluated by identifying the characteristic whitening of the thallus. Disease incidence was quantified as a percentage using the formula adapted from Largo et al. [24]:

$$\text{Ice – ice disease occurrence(\%)} = \frac{\text{number of infected bunches}}{\text{total number of bunches}} \times 100\%$$

Additionally, the severity of the infection was assessed by recording the mean number of necrotic spots per bunch.

2.5.2. Specific Growth Rate (SGR)

Biomass was recorded at 10-day intervals to determine the SGR (% day^{−1}), calculated according to Luhan et al. [25]:

$$\text{SGR} = \frac{\ln(W_t) - \ln(W_0)}{t} \times 100\%$$

where W_t is the weight at time t (g), W_0 is the initial weight (g), and t is the cultivation duration in days.

W_t was defined as the total fresh weight per bundle, encompassing all attached seaweed biomass regardless of health status (including necrotic or ice-ice affected tissue). This approach was adopted to provide a comprehensive assessment of biomass retention under environmental stress. Prior to weighing, bundles were gently shaken and blotted with a soft cloth to remove excess surface water and epiphytes.

2.6. Dry Biomass Yield

Upon termination of the experiment on Day 30, the total seaweed biomass was harvested. Following the determination of the final fresh weight, the samples were solar-dried until a constant weight was achieved. The dry biomass yield (%) was then calculated as per Tahiluddin et al. [26]:

$$\text{Dry yield(\%)} \text{ biomass} = \frac{\text{Final weight}}{\text{initial weight}} \times 100\%$$

2.7. Environmental Parameters

Water temperature and salinity were monitored in triplicate at multiple points within each treatment plot to account for spatial variability. Temperature was recorded using a precision glass thermometer (Nahita, Beriáin, Spain) (0.5 °C increments), and salinity was measured using a handheld refractometer (Atago Master, Tokyo, Japan) (1.0 ppt increments).

The reported standard deviation of 0.0 for these parameters is a function of instrumental resolution rather than absolute environmental homogeneity. Under the prevailing field conditions, fluctuations fell within the margin of error of the equipment used. Consequently, replicate readings frequently yielded identical values at the scales of 0.5 °C and 1.0 ppt. We acknowledge this as a limitation of field-based reporting resolution and have clarified these instrument sensitivities in the text to provide a transparent representation of the data.

While this study focused on the physiological responses of *K. striatus* during transport, we acknowledge that ice-ice disease expression is a complex process influenced by a broader suite of environmental factors. Parameters such as nutrient availability, dissolved oxygen, turbidity, and irradiance intensity, as well as microbial community dynamics, were not monitored in this study due to logistical constraints. Given that these variables are known to modulate seaweed health and disease susceptibility, their absence represents a limitation in our environmental characterization. Future research should integrate these multi-factorial parameters to provide a more holistic understanding of the synergistic stressors leading to ice-ice outbreaks.

2.8. Statistical Analysis

Data were analyzed using IBM SPSS (v. 20, SPSS Inc., Chicago, IL, USA). Prior to analysis, all datasets were examined for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene’s test. To satisfy these assumptions, percentage-based data (e.g., ice-ice incidence) were subjected to arcsine square root transformation before being processed, while growth data were found to meet the requirements for parametric testing without further modification.

To isolate the effect of transportation duration at specific stages of cultivation, independent one-way analyses of variance (ANOVA) were performed for each sampling interval: Days 1–7, 10, 20, and 30 for disease parameters; Days 10, 20, and 30 for SGR; and Day 30 for dry biomass yield. No statistical comparisons were made between different sampling days (e.g., Day 10 vs. Day 20) to avoid the confounding effects of temporal environmental fluctuations.

For parameters where ANOVA indicated significant differences ($p < 0.05$), post hoc mean separation was performed using Duncan’s Multiple Range Test (DMRT) to identify homogeneous subsets. Given the balanced experimental design with equal sample sizes (per treatment), ANOVA and DMRT are considered statistically robust even under moderate deviations from normality [27]. While a sample size of three replicates is the standard minimum for such trials in seaweed research [23,25,28], the high degree of observed within-group consistency and the clear, dose-dependent trends across treatment durations support the reliability and biological significance of the results.

3. Results

3.1. Specific Growth Rate

Transportation duration significantly influenced the growth performance of *K. striatus*. One-way ANOVA revealed significant differences in SGR among treatment groups at Day 10 and Day 30 ($p < 0.05$), although these differences were not significant at Day 20 ($p > 0.05$; Figure 2). While a 12 h transport duration maintained growth comparable to the control, a clear inverse relationship was observed as durations exceeded 24 h, with SGR declining significantly ($p < 0.05$) in a dose-dependent manner. At Day 10, a substantial reduction in growth (33.6%) relative to the control was observed in the 36 h and 48 h treatment groups. While a transient period of acclimation was noted at Day 20, the 48 h transport group ultimately suffered a severe 62.7% reduction in SGR by Day 30 compared to the control. The control group consistently maintained superior growth, peaking at $4.62 \pm 0.18\% \text{ day}^{-1}$ on Day 10 and remaining at $2.49 \pm 0.09\% \text{ day}^{-1}$ at the conclusion of the study.

3.2. Ice-Ice Percentage Occurrence

Extended transportation periods directly correlated with the rapid onset of ice-ice disease. Statistical analysis indicated highly significant differences in disease occurrence from Day 1 to Day 7, and again at Day 20 ($p < 0.05$; Figure 3). The 48 h treatment group reached 100% infection within the first four days of out-planting, while the 36 h group reached 96.67%. In contrast, the control group maintained negligible disease levels. While significant differences diminished by Day 10 and Day 30 ($p > 0.05$), the 48 h group remained symptomatic throughout the 30-day period.

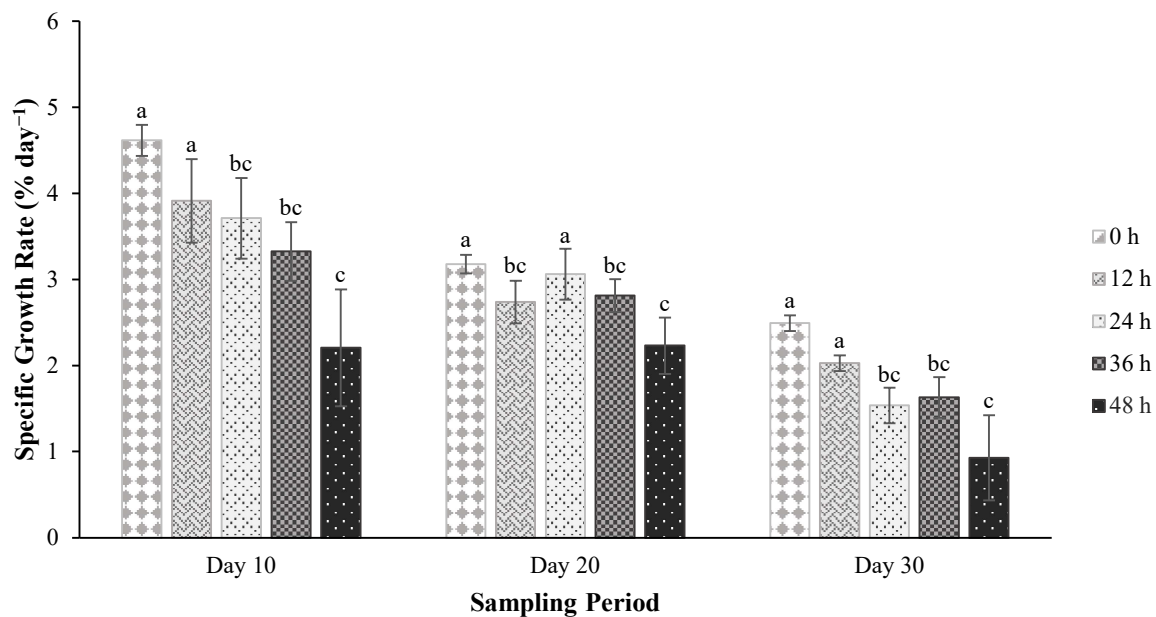


Figure 2. Specific growth rate (SGR, % day⁻¹) of *Kappaphycus striatus* across five transportation durations (0, 12, 24, 36, and 48 h) measured at 10-day intervals. Data are presented as mean $\pm$ SEM ($n = 3$). Mean values within the same sampling day followed by different lowercase letters indicate significant differences according to Duncan's Multiple Range Test ($p < 0.05$).

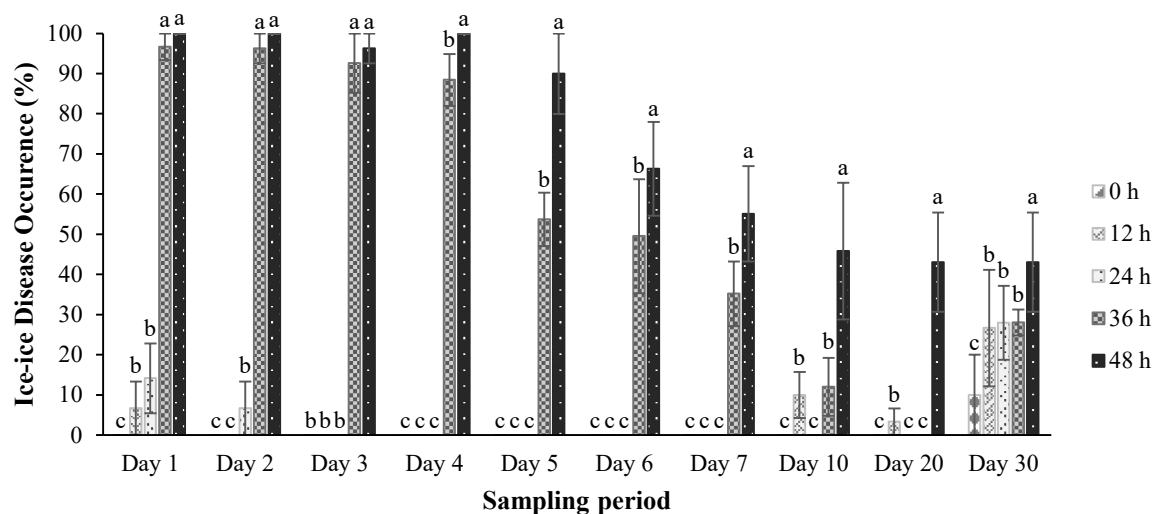


Figure 3. Daily and interval-based occurrence of ice-ice disease (%) in *Kappaphycus striatus* following different transportation durations. Data represent the mean percentage of infected thalli per treatment ($n = 3$). Error bars indicate the standard error of the mean (SEM). Different lowercase letters denote significant differences between treatments within a specific sampling day based on Duncan's Multiple Range Test ($p < 0.05$).

The density of necrotic ice-ice spots mirrored the occurrence patterns, serving as an indicator of disease severity. The 48 h transport group exhibited the highest initial severity, with 50.45 spots per bundle on Day 1 (Figure 4). Severity was significantly higher in the long-duration groups during the first week ($p < 0.05$), but these differences neutralized between Day 10 and Day 30 ($p > 0.05$). The convergence of ice-ice spot density among treatment groups after Day 10 suggests a phase of visual tissue stabilization as the seaweeds acclimated to field conditions. While this trend points toward a reduction in active lesion formation, we acknowledge that these observations are based on morphological markers rather than internal physiological states.

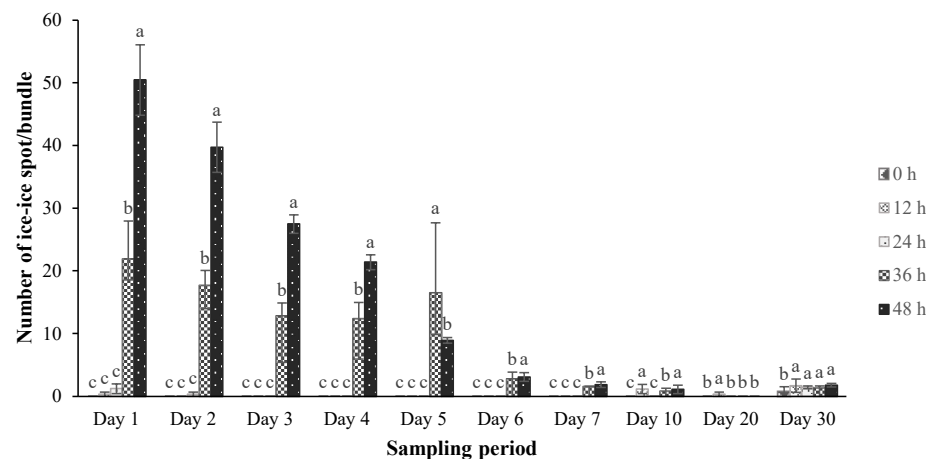


Figure 4. Severity of ice-ice disease in *Kappaphycus striatus* expressed as the mean number of necrotic spots per bundle. Observations were conducted daily during the first week post-transplant and at 10-day intervals thereafter. Data are presented as mean $\pm$ SEM ($n = 3$). Different lowercase letters indicate statistically significant differences between transportation treatment groups within the same observation day (Duncan's Multiple Range Test, $p < 0.05$).

3.3. Dry Biomass Yield

Interestingly, transport duration did not result in a statistically significant reduction in final dry biomass yield ($p > 0.05$; Figure 5). Although the 24 h group showed a numerical peak (16%), it was not statistically distinct from the control or the 48 h group. This stability in dry yield, despite the high incidence of ice-ice disease, suggests that surviving healthy thalli may undergo compensatory growth or that the disease primarily affects fresh weight via moisture loss and fragmentation rather than the total accumulated dry matter.

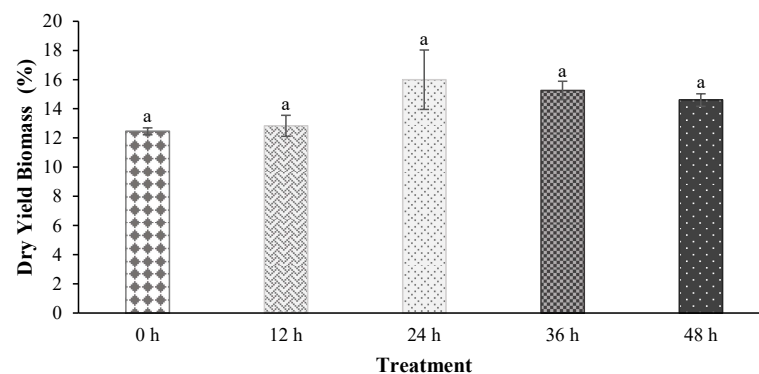


Figure 5. Final dry biomass yield (%) of *Kappaphycus striatus* after 30 days of field cultivation following various transportation durations. Data represent the mean percentage of dry matter relative to initial fresh weight $\pm$ SEM ($n = 3$). The presence of the same lowercase letters above the bars indicates that no statistically significant differences were observed between treatments (One-way ANOVA, $p > 0.05$).

3.4. Environmental Parameters

Physico-chemical monitoring confirmed that the experimental site in Pasiagan provided a stable environment for *K. striatus* (Table 1). Salinity remained constant at 34 ppt, while water temperature generally fluctuated between 27 °C and 33.9 °C. Aside from a transient midday thermal excursion of 33.9 °C on Day 1, these parameters fell within the established optimal physiological ranges for *Kappaphycus* (24–35 ppt; 24–31 °C), ensuring that observed growth variations were primarily attributable to transport stress rather than localized environmental fluctuations.

Table 1. Temporal variations in salinity and temperature at the experimental cultivation site in Pasiagan, Bongao, Tawi-Tawi, Philippines ($n = 3$).

Water Parameters	Sampling Period									
	D1	D2	D3	D4	D5	D6	D7	D10	D20	D30
Salinity (ppt)	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0	34 ± 0.0
Temperature (°C)	33.9* ± 0.0	29.0 ± 0.0	28.0 ± 0.0	27.0 ± 0.0	27.5 ± 0.0	29.0 ± 0.0	29.0 ± 0.0	31.0 ± 0.0	29.0 ± 0.0	28.0 ± 0.0

Note: Values are presented as mean ± SD. A standard deviation of ±0.0 indicates that triplicate measurements were identical within the precision limits of the instruments used (handheld refractometer, ±1 ppt; glass thermometer, 0.5–1.0 °C gradation). Asterisk (*) denotes a transient midday temperature excursion during an unusually warm period on Day 1; all subsequent measurements remained within the optimal range (27–31 °C).

4. Discussion

The findings of this study establish that inter-island transportation duration is a critical pre-cultivation stressor for *Kappaphycus striatus*, with direct, deleterious impacts on disease susceptibility and growth performance. These results corroborate the paradigm that transport logistics represent a primary bottleneck in the seaweed supply chain [15,18]. A clear inverse relationship was observed between transportation duration and the specific growth rate (SGR), aligning with the observations of Oedjoe et al. [15], who noted that while short transport windows (6–24 h) allow *Kappaphycus* to maintain metabolic integrity, durations exceeding 30 h induce severe tissue damage. The 62.7% reduction in SGR observed in the 48 h treatment by Day 30 suggests that prolonged desiccation causes chronic physiological disruptions that persist long after out-planting.

The strong correlation between transport duration and the initial severity of ice-ice disease—evidenced by the peak in spot counts on Day 1—supports the stress-induced infection model [11,12]. Abiotic stress weakens the thallus, facilitating the invasion of opportunistic microorganisms that catalyze tissue softening and whitening [11,12].

However, the subsequent attenuation of significant differences in disease occurrence by Day 10 highlights the notable ecological robustness of *K. striatus*. This recovery capacity is consistent with the findings of Galera et al. [20], who identified the species' ability to adapt to adverse conditions through morphological plasticity. While the resilience of *K. striatus* may be linked to underlying oxidative stress pathways, this remains a speculative framework in the context of the present study. The observed formation of ice-ice lesions is a visible indicator of severe cellular stress potentially induced by desiccation during transport. In the absence of direct biochemical indicators—such as chlorophyll-a content, photosynthetic efficiency, or antioxidant enzyme activity—the precise metabolic nature of this stabilization remains to be fully elucidated. However, the observed trends are consistent with the 'oxidative burst' model in macroalgae, where localized necrotic lesions may represent a programmed cellular response (PCR) to isolate stress-induced damage [29]. This pathway offers a plausible theoretical explanation for the initial appearance of necrotic spots followed by the eventual stabilization of the thalli. Future research incorporating targeted biochemical and microbiological analyses—specifically measuring ROS accumulation and microbial load—is necessary to confirm whether this stabilization reflects a full metabolic return to homeostasis or a state of chronic stress compensation.

Interestingly, although dry biomass yield did not exhibit a statistically significant decline at 48 h, the physiological cost of stress mitigation was starkly evident in the 62.7% reduction in SGR for this group. This apparent paradox—where low-growth plants reach comparable dry weights to the control—suggests a significant shift in the plant's hydration status and resource allocation. While control plants accumulated more fresh biomass through rapid water uptake and turgor-driven elongation, the stressed propagules likely prioritized the maintenance of structural polysaccharides (carrageenan and cellulose) over cellular expansion. This indicates that transport stress primarily affects the seaweed's ability to regulate water and minerals rather than its total carbon fixation. The

stability in dry yield, despite the high incidence of ice-ice disease, further suggests that surviving healthy thalli may undergo compensatory growth or that the disease primarily affects fresh weight via moisture loss and fragmentation rather than the total accumulated dry matter. This suggests a significant metabolic trade-off: energy typically allocated for biomass accumulation is diverted toward cellular repair and defense mechanisms. Furthermore, while the physical volume of the crop may remain stable, the literature suggests that such stressors often compromise the functional properties of the seaweed, specifically carrageenan gel strength and viscosity [30,31]; however, as carrageenan quality was not empirically measured in the present study, this remains a subject for future investigation. Consequently, the “irreversible tissue damage” described in previous laboratory studies [15] may manifest economically through diminished extract quality and reduced commercial value rather than absolute mortality.

5. Conclusions

Transportation duration is a key pre-cultivation determinant of *Kappaphycus striatus* performance. Dry transport exceeding 24 h induced severe dehydration stress, resulting in early, high-incidence ice-ice disease and a persistent reduction in specific growth rate throughout the cultivation period. Our findings identify 24 h as a critical operational threshold; while propagules in the 24 h group remained statistically comparable to the control, durations of 36 h and beyond triggered a significant physiological collapse and near-total disease incidence within the first week. Although final dry biomass yield showed no significant differences—reflecting physiological resilience and compensatory growth—the sustained growth suppression highlights a substantial metabolic cost of stress recovery. These results establish a clear operational threshold for propagule handling: inter-island transport should be limited to within 24 h to maintain thallus integrity and optimize production efficiency. By linking transport duration to growth and disease outcomes under field conditions, this study provides a robust basis for evidence-based logistics management and future refinement of recovery strategies in *Kappaphycus* aquaculture.

Author Contributions: Conceptualization, A.B.T.; formal analysis, A.B.T., A.S.B., A.M.A., and N.T.J.; investigation, A.B.T., A.S.B., A.M.A., and N.T.J.; data curation, A.B.T. and A.S.B.; writing—original draft preparation, A.B.T., and A.S.B.; writing—review and editing, A.B.T., A.S.B., A.M.A., and N.T.J.; supervision, A.B.T. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the Mindanao State University Tawi-Tawi College of Technology and Oceanography.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Rupert, R.; Rodrigues, K.F.; Thien, V.Y.; Yong, W.T.L. Carrageenan from *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae): Metabolism, structure, production, and application. *Front. Plant Sci.* **2022**, *13*, 859635. [CrossRef] [PubMed]
2. Grand View Research. Carrageenan Market (2023–2030) Size, Share & Trends Analysis Report by Processing Technology (Semi-Refined, Gel Press, Alcohol Precipitation), by Function, by Product Type, by Application, by Region, and Segment Forecasts. 2023. Available online: <https://www.grandviewresearch.com/industry-analysis/carrageenan-market> (accessed on 5 April 2026).
3. Hurtado, A.Q.; Neish, I.C.; Critchley, A.T. Developments in production technology of *Kappaphycus* in the Philippines: More than four decades of farming. *J. Appl. Phycol.* **2015**, *27*, 1945–1961. [CrossRef]
4. Iqbal, D.M.; Azis, H.Y.; Tuwo, A.; Zainuddin, Z.; Latama, G.; Syafiuddin, S. Weight Loss of *Kappaphycus striatum* seed reared in Controlled Media after Waterless Transport (A Preliminary Study). In *BIO Web of Conferences*; EDP Sciences: Les Ulis, France, 2025; Volume 185, p. 08004.

5. Ledesma, A.B.B.; Monteclaro, H.M. Farming Systems of Eucheumatoid Seaweeds in Western Visayas, Philippines. *Philipp. J. Fish.* **2025**, *32*, 160–177. [CrossRef]
6. Tahliluddin, A.B.; Roleda, M.Y. Current status of eucheumatoid seaweed farming in Tawi-Tawi, Philippines. In *Biotechnological Interventions to Aid Commercial Seaweed Farming*; Springer Nature: Singapore, 2025; pp. 95–124.
7. Tahliluddin, A.B.; Esmola, F.R.; Abduraup, S.A.; Camsain, A.M.B.; Jamil, W.M.; Bermil, A.B.; Ujing, R.A.; Gunong, A.D.; Damsik, S.U.; Baid, S.D.S.; et al. Seaweed consumption practices in coastal communities of Tawi-Tawi, Philippines. *Phycology* **2025**, *5*, 25. [CrossRef]
8. Tahliluddin, A.B.; Terzi, E. A preliminary study on the effects of seagrass wrack extract as biofertilizer on the growth, ice-ice disease, nitrogen, and phosphorus assimilation and carrageenan quality of eucheumatoid seaweed *Kappaphycus striatus*. *Aquat. Res.* **2026**, *9*, 166–175. [CrossRef]
9. Tahliluddin, A.B.; Eldani-Tahliluddin, M.H.S. Ice-ice disease in cultivated eucheumatoid seaweeds: The perspectives of farmers. *Eur. J. Phycol.* **2024**, *59*, 423–435. [CrossRef]
10. Cokrowati, N.; Nuryatin, N.; Jayusri, J.; Jum'at, M.; Muahidah, N. Growth Performance of *Kappaphycus alvarezii* and *Kappaphycus striatus* cultivated in Ekas Bay, East Lombok Regency, West Nusa Tenggara Province. *J. Aquac. Fish Health* **2024**, *13*, 427–439. [CrossRef]
11. Ward, G.M.; Kambey, C.S.; Faisan, J.P., Jr.; Tan, P.L.; Daumich, C.C.; Matoju, I.; Stentiford, G.D.; Bass, D.; Lim, P.-E.; Brodie, J.; et al. Ice-Ice disease: An environmentally and microbiologically driven syndrome in tropical seaweed aquaculture. *Rev. Aquac.* **2022**, *14*, 414–439. [CrossRef]
12. Tahliluddin, A.B.; Terzi, E. Ice-ice disease in commercially cultivated seaweeds *Kappaphycus* spp. and *Eucheuma* spp.: A review on the causes, occurrence, and control measures. *Mar. Sci. Technol. Bull.* **2021**, *10*, 234–243. [CrossRef]
13. Hurtado, A.Q.; Neish, I.C.; Critchley, A.T. Phyconomy: The extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. *Phycologia* **2019**, *58*, 472–483. [CrossRef]
14. Jiksing, C.; Ongkudon, M.M.; Thien, V.Y.; Rodrigues, K.F.; Yong, W.T.L.; McMarshall, M.O. Recent advances in seaweed seedling production: A review of eucheumatoids and other valuable seaweeds. *Algae* **2022**, *37*, 105–121. [CrossRef]
15. Oedjoe, M.D.; Rebhung, F.; Sunadji. The impact of the transportation of dry systems on the growth and carrageenan content of seaweed (*Kappaphycus alvarezii*) in Batu Bao Water, Kupang District, East Nusa Tenggara, Indonesia. *AACL Bioflux* **2020**, *13*, 1570–1575.
16. Tahliluddin, A.B.; Terzi, E. Ice-ice disease prevalence and intensity in eucheumatoid seaweed farms: Seasonal variability and relationship with the physicochemical and meteorological parameters. *Plants* **2024**, *13*, 2157. [CrossRef] [PubMed]
17. Lukas, A.Y.; Oedjoe, R.; Dj, M.; Tjendanawangi, A. Performance of Seaweed Seed *Kappaphycus alvarezii* Post Cold Transportation Method with Different Transportation Times. *Egypt. J. Aquat. Biol. Fish.* **2025**, *29*, 127–140. [CrossRef]
18. Kavale, M.G.; Veeragurunathan, V.; Jasiwar, S.; Rajai, J.V.; Baraiya, M.; Grace, P.G.; Mantri, V.A. Long-distance translocation of planting material of *Kappaphycus alvarezii* (Doty) Doty ex PC Silva (Rhodophyta) for commercial farming: Assessing metabolic response, viability, and vigor. *Aquac. Int.* **2024**, *32*, 1629–1645. [CrossRef]
19. Yadav, D.S.; Bhojani, A.; Sutariya, J.A.; Kaushik, A.; Rakhasiya, B.; Rajai, J.V.; Bhagiya, B.K.; Grace, P.G.; Habsi, M.; Jaiswar, S.; et al. Effect of *Ascophyllum nodosum* (Phaeophyta) extract on the productivity, performance, and transport stress response on propagules of the commercially important red alga *Kappaphycus alvarezii*. *Discov. Ocean.* **2025**, *2*, 26. [CrossRef]
20. Galera, J.J.M.; Turong, J.A.; Bara, A.S.; Serag-Endonila, K.J.B.; Halun, S.Z.B. Wild *Kappaphycus* cf. *striatus* growing in a mangrove stand in Siasi, Sulu, Philippines. *Philipp. J. Sci.* **2023**, *152*, 673–676. [CrossRef]
21. Bangsamoro Parliament. Bangsamoro Legislators Want Tawi-Tawi to Be the Seaweed Capital of the Philippines. 2023. Available online: <https://parliament.bangsamoro.gov.ph/2023/01/24/bangsamoro-legislators-want-tawi-tawi-to-be-the-seaweed-capital-of-the-philippines/> (accessed on 13 December 2025).
22. Food and Agriculture Organization; Dawnavie, D. *The Seaweed Capital of the Philippines: Sustaining Family Traditions and Livelihood Amidst Economic Shifts*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2025.
23. Tahliluddin, A.B.; Nuñal, S.N.; Santander-de Leon, S.M.S. Inorganic nutrient enrichment of seaweed *Kappaphycus*: Farmers' practices and effects on growth and ice-ice disease occurrence. *Reg. Stud. Mar. Sci.* **2022**, *55*, 102593. [CrossRef]
24. Largo, D.B.; Fukami, K.; Nishijima, T.; Ohno, M. Laboratory-induced development of the ice-ice disease of the farmed red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae, Gigartinales, Rhodophyta). *J. Appl. Phycol.* **1995**, *7*, 539–543. [CrossRef]
25. Luhan, M.R.J.; Avañcena, S.S.; Mateo, J.P. Effect of short-term immersion of *Kappaphycus alvarezii* (Doty) Doty in high nitrogen on the growth, nitrogen assimilation, carrageenan quality, and occurrence of “ice-ice” disease. *J. Appl. Phycol.* **2015**, *27*, 917–922. [CrossRef]
26. Tahliluddin, A.B.; Robles, R.J.F.; Eldani-Tahliluddin, M.H.S. Effects of rainwater on the carrageenan yield and quality and dry yield biomass of eucheumatoid seaweed *Kappaphycus alvarezii*. *Aquat. Bot.* **2025**, *197*, 103837. [CrossRef]

27. Underwood, A.J. *Experiments in Ecology: Their Logical Design and Interpretation Using Analysis of Variance*; Cambridge University Press: Cambridge, UK, 1997; 504p.
28. Sarri, J.H.; Abdulmutalib, Y.A.; Mohammad Tilka, M.E.; Terzi, E.; Tahiluddin, A.B. Effects of inorganic nutrient enrichment on the carrageenan yield, growth, and ice-ice disease occurrence of red alga *Kappaphycus striatus*. *Aquat. Res.* **2022**, *5*, 99–109. [[CrossRef](#)]
29. Hong, Y.; Boiti, A.; Vallone, D.; Foulkes, N.S. Reactive oxygen species signaling and oxidative stress: Transcriptional regulation and evolution. *Antioxidants* **2024**, *13*, 312. [[CrossRef](#)]
30. Hurtado, A.Q.; Critchley, A.T.; Trespoe, A.; Bleicher-Lhonneur, G. Growth and carrageenan quality of *Kappaphycus striatum* var. sacol grown at different stocking densities, duration of culture and depth. *J. Appl. Phycol.* **2008**, *20*, 551–555. [[CrossRef](#)]
31. Failu, I.; Supriyono, E.; Suseno, S.H. Peningkatan kualitas karagenan rumput laut *Kappaphycus alvarezii* dengan metode budidaya keranjang jaring. *J. Akuakultur Indones.* **2016**, *15*, 124–131. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.