
RESEARCH ARTICLE**Optimizing Planting Density and Culture Systems in *Kappaphycus alvarezii*: A Systematic Review of Growth, Carbon Dynamics, and Carrageenan Quality****Sri Mulyani***Aquaculture Study Program, Faculty of Agriculture, Bosowa University, Makassar 90231, Indonesia***Corresponding Author:** Sri Mulyani, **E-mail:** sri.mulyani@universitasbosowa.ac.id

ABSTRACT

Kappaphycus alvarezii is a globally important carrageenophyte underpinning food, pharmaceutical, and biomaterials industries while supporting coastal livelihoods in tropical regions. Despite its economic significance, production remains highly variable, with inconsistent biomass yields and carrageenan quality driven by environmental variability and heterogeneous farming practices. This systematic literature review synthesizes evidence published between 2000 and 2026 on how planting density and culture system configuration including tie-tie/longline systems, tubular nets, vertical columns, and related designs shape growth performance, carbon dynamics, and carrageenan quantity and functional quality in *K. alvarezii* cultivation. Drawing on PRISMA-guided screening, the review integrates findings across four themes: (i) density–growth relationships, (ii) farm configuration as micro-environmental engineering, (iii) carbon dynamics and physiological responses, and (iv) carrageenan yield and quality outcomes. The synthesis reveals a consistent intermediate-density advantage for growth efficiency and physiological stability, strong context dependence mediated by site-specific environmental conditions, and recurring trade-offs between biomass maximization and carrageenan quality. Carbon dynamics emerge as a critical mechanistic link connecting farm geometry to biochemical outcomes. The review highlights persistent challenges related to non-standardized density definitions, heterogeneous outcome metrics, and limited multi-site experimentation. By framing density and configuration as integrated farm-engineering levers, this review advances a multi-objective optimization perspective and proposes evidence-based operational windows and reporting priorities to support resilient, quality-oriented, and scalable *K. alvarezii* aquaculture.

KEYWORDS*Kappaphycus alvarezii*; planting density; culture systems; carbon dynamics; carrageenan quality**ARTICLE INFORMATION****ACCEPTED:** 01 February 2026**PUBLISHED:** 16 February 2026**DOI:** 10.32996/bjbs.2026.6.1.2

1. Introduction

Kappaphycus alvarezii is a cornerstone species in global carrageenan production, supplying a sulfated polysaccharide used as a gelling, stabilizing, and thickening agent across food, pharmaceutical, and emerging biomaterials industries (Ej & Morris, 2018; Laksono et al., 2022; Rupert et al., 2022; Tresnati et al., 2021; Vega et al., 2016).

Beyond industrial relevance, *K. alvarezii* cultivation supports livelihoods in tropical coastal regions by providing accessible, low-input aquaculture income streams (Nurdin et al., 2023; Rantetondok & Latama, 2017). However, production remains highly variable due to environmental stressors and heterogeneous management practices, including disease outbreaks (e.g., ice-ice) and epiphytism (Aris, 2020; Kumar et al., 2020).

Among controllable variables, planting density and culture-system configuration act as practical farm-engineering levers that regulate light interception, water exchange, nutrient delivery, and fouling pressure. Intermediate densities often balance space use and competition, while configurations (tie-tie/longline, tubular nets, vertical/stacked arrays) shape micro-environmental exposure and operational risk (Astriana et al., 2019; Ihsan et al., 2023; Prayudha et al., 2024).

This review synthesizes evidence on how planting density and culture system configuration influence growth/yield, carbon dynamics and physiological responses, and carrageenan quantity and functional quality in *K. alvarezii* cultivation. Four research questions guide the synthesis: (RQ1) density effects on growth and yield; (RQ2) configuration effects on micro-environment and stability; (RQ3) links to carbon dynamics; (RQ4) impacts on carrageenan content and functional quality.

2. Methods

This systematic literature review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and traceability in study identification, screening, and synthesis (Tilaar et al., 2023; Yıldıztekin et al., 2018).

Primary searches were conducted in Scopus, complemented by Web of Science and Google Scholar. Keyword blocks covered species identifiers, planting-density descriptors, culture-system descriptors, and outcome-related terms (e.g., SGR/DGR, carbon metrics, carrageenan yield, gel strength). Backward and forward citation tracking were used to reduce omission bias (Djoundi et al., 2025; Ratnawati et al., 2020).

Eligible studies were peer-reviewed empirical works that explicitly tested planting density and/or culture-system configuration in *K. alvarezii* cultivation and reported at least one outcome relevant to growth/yield, carbon-related indicators, or carrageenan quantity/quality. Studies lacking extractable outcomes or sufficient methodological detail were excluded (Bennett et al., 2023; Kim et al., 2017; Lang et al., 2024).

Figure 1 summarizes the PRISMA-based screening and selection workflow.

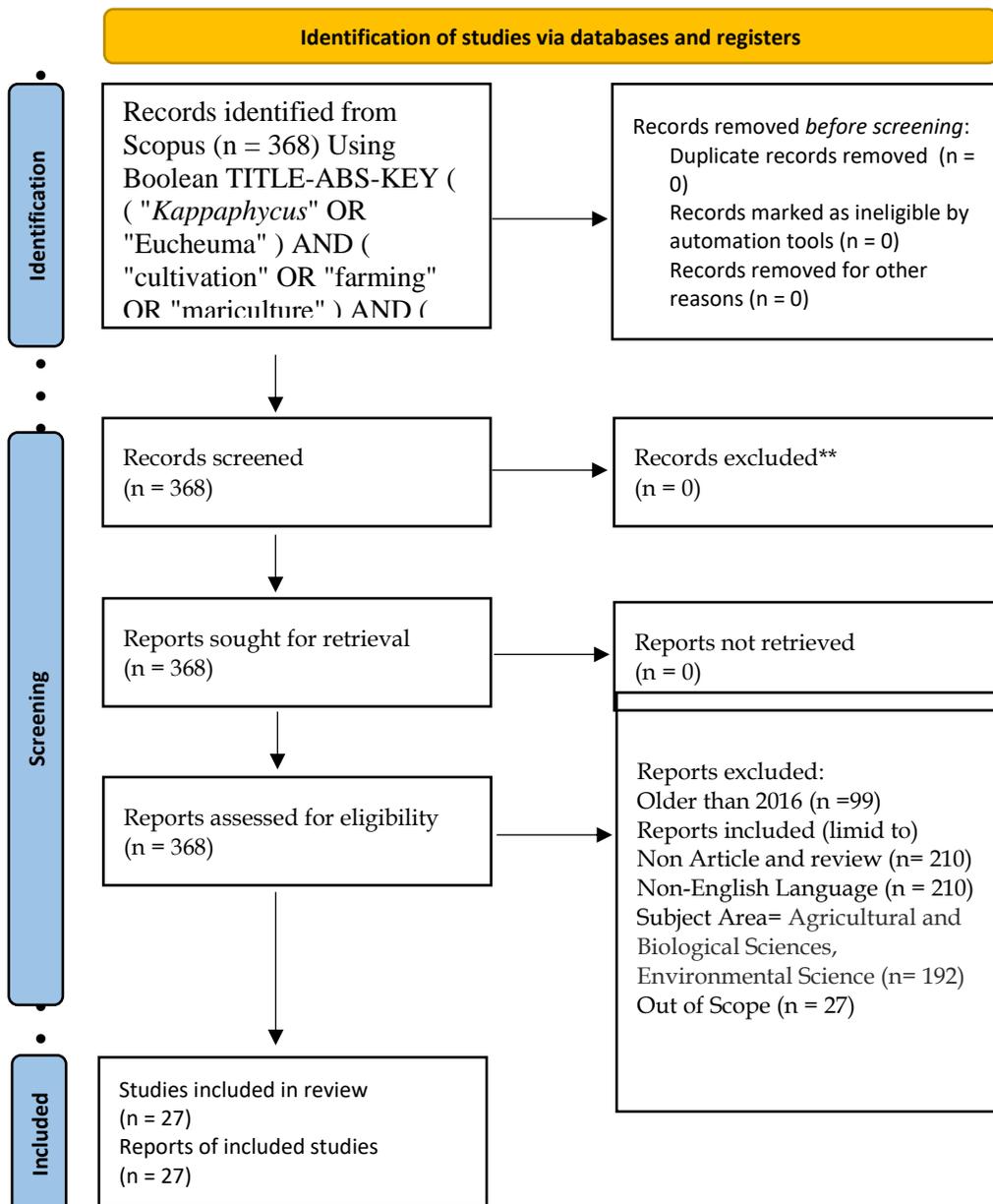


Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature.

[Insert PRISMA flow diagram here]

3. Theoretical Background

Cultivation outcomes in *K. alvarezii* arise from interactions between biological processes and farm geometry. Planting density and configuration regulate micro-environmental conditions (light, hydrodynamics, nutrients), which influence photosynthesis, carbon assimilation, carbon allocation, and carrageenan biosynthesis pathways.

Density-dependent growth theory predicts non-linear responses: increasing density raises standing biomass but can intensify self-shading and nutrient competition, leading to plateaus or declines (Campbell et al., 2019; Sato et al., 2023). Hydrodynamic mass-transfer and boundary-layer theory explain how flow controls nutrient and inorganic carbon delivery to thallus surfaces (Glanzmann et al., 2022; James et al., 2022). Photo-physiological regulation links irradiance and carbon acquisition to biochemical allocation and carrageenan properties (Thien et al., 2016, 2021; Soraya et al., 2024).

Figure 2. Theoretical Framework Linking Density, Configuration, and Carbon Dynamics

[Insert conceptual framework figure here]

4. Review of Findings

4.1 Planting Density Effects on Growth and Yield

Across contexts, evidence indicates non-linear density effects with an intermediate-density advantage for growth efficiency, while higher densities may maximize final yield but increase risk of self-shading, nutrient limitation, fouling, and disease. Heterogeneous density definitions and outcome metrics complicate cross-study comparison; standardized reporting is needed.

Table 1. Empirical evidence linking planting density / seeding biomass to growth and carbon-related outcomes in *Kappaphycus alvarezii*.

Referensi (nama, tahun)	Culture system & location	Study design & duration	Planting density / seeding level(s)	Growth metrics reported	Peak performance (growth/yield)	Carbon / biochemical outcomes	Practical implication for optimization
Mulyani & Cahyono (2025)	Tie-tie cultivation; South Sulawesi (Indonesia)	Controlled experiment; CRD; triplicate; 45-day cycle	25 g/tie, 50 g/tie, 75 g/tie	Biomass yield; SGR	75 g/tie: highest final biomass; 50 g/tie: highest SGR	50 g/tie: stable carbon content; 25 g/tie: higher initial C but lower growth	Trade-off: medium density optimizes growth efficiency/carbon stability; high density maximizes final yield
Megarajan et al. (2024)	Floating HDPE raft with tube-nets; Visakhapatnam coast (India)	Feasibility evaluation; 6 cycles; 45 days per cycle	3, 5, 7.5, 10 kg per tube-net	Daily growth rate; net biomass/raft/crop	5 kg/tube-net: ~3.52% day ⁻¹ ; ~191.11 kg raft ⁻¹ crop ⁻¹	Not reported	Intermediate seeding can outperform under/over-seeding in tube-net systems
Van Oort et al. (2025)	Longline vs tube-nets vs cages; South Sulawesi (Indonesia)	Two field experiments; multi-season; five cycles; bi-weekly sampling	Seedling weight classes: low, medium, high	Yield; losses; ice-ice; epiphytes/fouling; environmental drivers	Medium/high outperformed low (Jun–Oct); longline best (Mar–Jul) under fouling pressure	Not reported	Optimal density interacts with seasonality and configuration; context-specific optimization required

4.2 Culture Systems and Farm Configuration as Micro-Environmental Engineering

Culture systems act as micro-environmental engineering tools by regulating exposure to light, water exchange, and fouling pressure. Evidence suggests context dependence: in favorable conditions, tie-tie and tubular nets can produce comparable growth; vertical systems can increase space-use efficiency but may introduce depth/position variability.

Table 2. Evidence on culture systems / cultivation configurations in *Kappaphycus alvarezii*.

Reference (authors, year)	Location & cultivation period	Culture system / configuration tested	Experimental design & sampling unit	Environmental parameters monitored	Key outcomes (growth & quality)	Operational implications / recommendations
Nursidi et al. (2020)	South Sulawesi, Indonesia; Mar–Nov 2016	Vertical cultivation using four columns	Field trial; compared column positions	Environmental parameters evaluated (site-specific)	SGR and carrageenan differed among columns; Column 2 highest	Vertical systems can improve productivity but need calibration across seasons/depth gradients
Cáceres-Farías et al. (2025)	Coastal Ecuador; 70 days	Tubular nets vs tie-tie; three color strains	Cross-system comparison; 15 thalli per strain	Temp, salinity, DO, turbidity, nutrients (daily)	No significant system difference: tie-tie $4.0 \pm 0.92\% \text{ day}^{-1}$ vs nets $3.8 \pm 0.81\% \text{ day}^{-1}$	Both systems feasible under local conditions; system choice should match hydrodynamics and farming capacity

4.3 Carbon Dynamics and Physiological Responses Under Density and System Choices

Carbon dynamics link farm geometry to biochemical outcomes. Intermediate densities and well-ventilated configurations tend to stabilize carbon assimilation/allocation, while nutrient availability and salinity/irradiance regimes co-regulate physiological responses.

Table 3. Carbon dynamics and physiological responses relevant to planting density and culture-system decisions in *Kappaphycus alvarezii*.

Reference (authors, year)	Carbon-related measure(s) / proxy	Analytical approach	Treatment variable(s)	Physiological outcomes (linked to carbon dynamics)	Mechanistic interpretation (density/system relevance)	Limitations / notes
Mulyani & Cahyono (2025)	Tissue carbon content	Field trial; randomized; triplicate; 45 days	Density: 25, 50, 75 g/tie	50 g/tie highest SGR and stable carbon; 75 g/tie highest final yield	Supports “operational windows”: medium density optimizes carbon stability and growth efficiency	Carbon method detail limited in abstract; external drivers not fully specified
Ventura et al. (2020)	CO ₂ enrichment; starch granules; cell wall thickening; pigments	In vitro; 2+2 week light shift; microscopy/TEM; pigment quantification	CO ₂ addition × irradiance (50–200 μmol photons m ⁻² s ⁻¹)	CO ₂ -enriched thalli: more starch, thicker walls, higher pigments;	Explains why better mixing/flow (reducing boundary-layer limitation) can	Laboratory setting may not capture farm hydrodynamics/fouling

				improved stress tolerance under high light	stabilize carbon allocation	
Long et al. (2024)	Biochemical proxies: soluble carbohydrate/protein, amino acids, proline; MDA	Factorial 21-day experiment; photosynthesis/pigments + biochemistry	NO ₃ -N levels × pCO ₂	Nutrients dominated effects; higher nutrients improved photosynthesis and reduced oxidative stress	High density/low flow that reduces nutrient delivery can constrain carbon assimilation even under high CO ₂	Physiology-focused; not direct farm yields/quality
Siddik et al. (2025)	Proteomic shifts in glycolysis/TCA/carbon fixation pathways	Label-free nano LC-MS/MS; pathway/network analysis	Salinity: 24, 32, 40 psu	Differential abundance of carbon-metabolism proteins; 14-3-3 as key node	System choices affecting salinity exposure (depth/nearshore gradients) can shift carbon fixation capacity	Molecular study; needs field validation
Jalil et al. (2020)	Dissolved CO ₂ monitored as environmental variable	Field measurements + farm trials; multiple culture methods	Longlines vs polyethylene nets vs baskets	Growth differed mainly due to epiphytes; nets/baskets reduced fouling	Configuration that reduces fouling protects light and carbon assimilation	Tissue carbon not measured; limited design detail in abstract

4.4 Carrageenan Quantity and Functional Quality Outcomes

Carrageenan yield and functional properties (gel strength, viscosity) are shaped by interacting effects of configuration, environment, harvest timing, and crop health. Rapid growth does not always translate into superior functional quality; trade-offs are common and site effects can be dominant.

Table 4. Carrageenan quantity and functional quality outcomes in relation to cultivation practice and environment (focus on *Kappaphycus alvarezii*).

Reference (authors, year)	Carrageenan endpoints measured	Extraction / processing & testing	Cultivation variables (management lever)	Environmental covariates reported	Key carrageenan findings	Value-chain / decision implication
Trivedi et al. (2026)	SRC yield; gel strength	SRC extraction; gel strength (g cm ⁻²)	Tube-net farming across 3 sites; 3 cycles	Salinity; phosphate; nitrite (correlations)	SRC 32.97–44.84%; gel 318–636 g cm ⁻² across sites/cycles	Site selection can shift both yield and gel strength substantially
Rajapaksha et al. (2025)	Yield; gel strength; FTIR profile	Extraction + FTIR; gel testing	Method comparison + harvest timing	Site context	Yield highest ~Day 37; gel strength highest ~Day	Harvest timing should match product requirements

			+ morphotypes		45; method differences small	
Muyong & Tahiluddin (2024)	Yield; gel strength	Extraction; gel strength assessed	Nutrient enrichment × method (45 d)	Ice-ice incidence tracked	Enrichment increased yield and gel strength	Fertilizer interventions can be quality-positive where feasible
Faisan et al. (2024)	Yield; viscosity; gel strength	Property testing across seasons	Seed source: tissue-cultured vs farm seedlings	Seasonality linked to disease/epiphytes	Properties largely similar; tissue-cultured improved growth and reduced disease incidence	Domestication via tissue culture can raise productivity without sacrificing quality
Simatupang et al. (2021)	Content; gel strength; viscosity	Standardized farming + lab testing	Location comparison (10 sites)	Site differences implied	Content 26.4% to 8.6–11.7%; gel 735.2 to 291.5 g cm ⁻² ; viscosity 138.8 to 30.0 cP	Quality-aware zoning and seed distribution are critical
Mulyaningrum et al. (2019)	Yield; gel strength	Lab extraction + gel testing	Health status: healthy vs epiphyte-infected	Epiphyte density/species	Healthy: 48.17% & 1130.76 g cm ⁻² vs infected: 42.47% & 958.22 g cm ⁻²	Reducing fouling protects carrageenan quality

5. Discussion

Evidence synthesized across Tables 1–4 indicates that optimization cannot be reduced to single-objective yield maximization. Intermediate planting densities frequently maximize growth efficiency and physiological stability, while higher densities can increase final yield but elevate stress and fouling risks. Configuration choice modifies how density translates into realized exposure conditions, influencing stability and losses.

Carbon dynamics provide a mechanistic explanation for many observed trade-offs: density and configuration shape light and mass-transfer environments, which modulate carbon assimilation and allocation, ultimately influencing carrageenan biosynthesis and functional properties. Nutrient and salinity regimes further co-regulate these outcomes (Long et al., 2024; Siddik et al., 2025). Methodological limitations persist, including inconsistent density definitions, heterogeneous outcome metrics, and limited multi-site factorial experimentation. Standardized reporting of density units, environmental covariates, and carrageenan testing protocols will strengthen comparability and transferability.

6. Conclusion

Optimizing *Kappaphycus alvarezii* cultivation requires integrated decision-making across growth, stability, and carrageenan quality. Intermediate densities most consistently support higher growth efficiency and carbon stability, while configuration acts as micro-environmental engineering that can mitigate or amplify density-related stressors.

Future work should prioritize multi-site factorial trials that jointly test density and configuration across seasons, with standardized metrics for growth, carbon dynamics, and carrageenan quality.

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