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Green Gold of the Ocean: Unlocking the Potential of *Caulerpa* in Global Seaweed Markets – A Review

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ABSTRACT

Seaweeds support food, health, and sustainability, yet global production is dominated by red and brown taxa. The green macroalga *Caulerpa* ("sea grapes"/"green caviar") remains underutilized despite notable nutritional and functional potential. This review synthesizes current knowledge on *Caulerpa* taxonomy, biology, distribution, cultivation, utilization, and sustainability. As siphonous, coenocytic algae, *Caulerpa* spp. are prevalent in tropical–subtropical waters, with some lineages invasive outside native ranges. Farming spans traditional lagoon culture in Southeast Asia to modern aquaculture and IMTA. Post-harvest advances (e.g., brining, UV-C, improved packaging) extend shelf life, though quality trade-offs remain. Nutritionally, *Caulerpa* provides proteins, polysaccharides, PUFAs, minerals, and vitamins; bioactives (e.g., sulfated polysaccharides, caulerpin, caulerpenyne) exhibit antioxidant, anti-inflammatory, and metabolic activities primarily in experimental models. Applications include foods, nutraceuticals, cosmetics, fertilizers/feeds, and bioenergy. Key constraints are short shelf life, variable cultivation standards, limited market acceptance beyond Asia, and ecological/biosecurity risks. Priorities include standardized cultivation and post-harvest protocols, selective breeding, toxicology and exposure assessments, and enabling harmonized policies. With sustainable management, *Caulerpa* could evolve from niche product to "green gold of the ocean," aligning ecological responsibility with economic opportunity.

INTRODUCTION

The global seaweed industry is experiencing robust growth. The market was valued at approximately USD 17 billion in 2023 and is projected to expand significantly in the coming decade. According to UNCTAD, emerging seaweed markets, including textiles, biopackaging, and biofuels, represents a potential USD 11.8 billion in additional value by 2030. Academic analyses estimate global seaweed production reached 34–36 million tonnes in 2019 **(Janke, 2024)**. Despite this growth, the sector is dominated by red and brown macroalgae, notably *Eucheuma, Kappaphycus, Gracilaria, Saccharina, Undaria*, and *Pyropia* **(Hurtado *et al.*, 2019; Arias-Echeverri *et al.*, 2022; Khan *et al.*, 2024; Mantri *et al.*, 2024)**. In contrast, green macroalgae (Chlorophyta), including *Caulerpa*, remain underrepresented, constituting less than 1% of global seaweed biomass production **(Moreira *et al.*, 2021)**.

Among green seaweeds, species such as *Caulerpa* (commonly known as "sea grapes" or "green caviar") stand out for their unique texture and growing regional popularity **(Stuthmann *et al.*, 2023)**. It has attracted attention for its unique sensorial qualities and rich nutritional profile, containing dietary fiber, proteins, polyunsaturated fatty acids, vitamins, and essential minerals such as calcium, magnesium, and iron **(du Preez *et al.*, 2020; Zhang *et al.*, 2020a)**. Traditionally consumed in Southeast Asia and Oceania, *Caulerpa* is now attracting growing attention in global food markets. Within these regions, eight species have been reported, including *C. lentillifera, C. peltata, C. racemosa, C. scalpelliformis, C. serrulata, C. sertularioides, C. taxifolia,* and *C. verticillata* **(Abdul Razak *et al.*, 2020; Syakilla *et al.*, 2022; Stuthmann *et al.*, 2023)**. Recent studies confirm that *Caulerpa* is rich in polyunsaturated fatty acids (PUFAs), minerals, dietary fiber, and various bioactive compounds, including influential antioxidants that confer health-promoting properties **(Tanna *et al.*, 2018; Manoppo *et al.*, 2022; Nurkholis *et al.*, 2023)**, and several bioactive compounds such as sulfated polysaccharides, known for their antioxidant, antihyperglycemic, anticoagulant, and immunestimulatory effects **(Tesvichian *et al.*, 2024)**. These properties position it not only as a functional food but also as a promising candidate for nutraceutical formulations. Other species, such as *C. racemosa* and *C. prolifera*, are similarly consumed in coastal Asia and the Mediterranean, where they are integrated into traditional diets or valorized for their secondary metabolites, including caulerpenyne and caulerpin, with potential antimicrobial, anticancer, antioxidant, and antidiabetic **(Belkacemi *et al.*, 2020; Permatasari *et al.*, 2022; Lau *et al.*, 2024; Ouhabi *et al.*, 2025)**. Moreover, nutritional profiling across different populations demonstrates notable protein, sugar, and ash content, with variations linked to geographical and environmental factors **(Zhou *et al.*, 2025)**.

Despite this growing evidence, *Caulerpa* remains a niche genus in global seaweed markets. Cultivation is restricted mainly to smallholder farms in Southeast Asia and Japan, often lacking standardized farming methods and robust supply chains. Critical challenges continue to constrain its commercialization, including short post-harvest shelf life, variable quality across regions, and limited consumer awareness outside Asia-Pacific markets **(Estrada *et al.*, 2021; Pan-utai, 2023)**. Furthermore, while bioactive properties have been identified, comprehensive toxicological assessments, yield and nutrient optimization breeding programs, and systematic post-harvest innovations remain limited. Given these gaps, a comprehensive review is needed to synthesize current understanding of *Caulerpa* across its taxonomy, biology, global distribution, cultivation techniques, nutritional and functional properties, and market prospects. This review highlights the opportunities and ecological trade-offs of expanding *Caulerpa* cultivation, evaluates its role in sustainability and ecosystem services, and identifies future research and policy priorities. By positioning *Caulerpa* as a potential "green gold of the ocean," this paper underscores its untapped role in diversifying global seaweed markets and contributing to climate-smart aquaculture, functional food development, and blue economy innovation.

MATERIALS AND METHODS

This review synthesizes recent knowledge on the taxonomy, biology, cultivation, nutritional and bioactive properties, market trends, and sustainability challenges of *Caulerpa* spp., with emphasis on *C. lentillifera* and *C. racemosa*. We searched Scopus and Web of Science (WoS) for English-language records published during 2015–2025 (last search: 30 September 2025). Searches targeted titles, abstracts, and keywords (Scopus: TITLE-ABS-KEY; WoS: Topic/TS). Core query: "*Caulerpa*" combined with AND/OR terms: "taxonomy," "cultivation," "nutritional composition," "bioactive compounds," "applications," "sustainability," and "market trends". Example: *Caulerpa* AND (taxonomy OR cultivation OR "nutritional composition" OR "bioactive compounds" OR sustainability OR "market trends").

After de-duplication, titles/abstracts were screened to remove (i) studies not centered on *Caulerpa*; (ii) items not indexed in Scopus or WoS; (iii) non-English items; and (iv) non-article/non-review formats (e.g., conference abstracts, editorials, theses). Records lacking experimental data or review-based synthesis relevant to our themes were excluded. Approximately ~100 eligible articles were retained for full-text analysis **(Mengist *et al.*, 2020)**.

Data were extracted into thematic matrices aligned with the review structure and synthesized narratively. All figures (morphology schematics, flowcharts, value-chain and SWOT diagrams, roadmap) were created de novo by the authors from the reviewed sources to ensure clarity and originality.

RESULTS

Taxonomy, biology, and global distribution

Taxonomy and morphology

The genus *Caulerpa* (*Caulerpa*ceae; Bryopsidales) is a diverse clade of siphonous, coenocytic green macroalgae, each thallus comprising a single multinucleate cell lacking cross walls. Recent revisions recognize ~104 accepted species arranged across multiple subgenera and sections, reflecting substantial morphological and phylogenetic complexity **(Lagourgue *et al.*, 2024)**. These green algae belong to the order Bryopsidales, characterized by a siphonous, coenocytic structure, wherein each organism consists of a single multinucleate cell without cross walls, allowing them to attain large sizes while maintaining cytoplasmic continuity **(Ranjan *et al.*, 2015)**. The morphology of *Caulerpa* can be seen in Fig. (1).

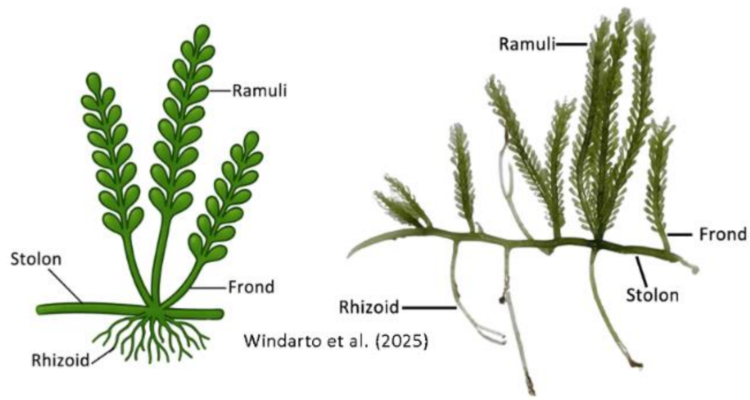

Fig. 1. Morphology of *Caulerpa*

Caulerpa species share a creeping stolon anchored by rhizoids, from which erect assimilatory fronds arise. Fronds typically bear a central axis (rachis) with lateral branchlets (ramuli) whose shapes (e.g., vesiculate, clavate, falcate) and arrangements (e.g., distichous, verticillate) vary among taxa **(Zubia *et al.*, 2020; Lagourgue *et al.*, 2024)**. In *C. lentillifera*, the stolon–rhizoid–frond architecture underpins rapid clonal spread and structural integrity **(Arimoto *et al.*, 2019)**. Pronounced morphological plasticity, long recognized in the genus, has complicated species delimitation; many ecads (environmentally induced morphotypes) were historically described as distinct forms. Integrative taxonomy that couples morphology with molecular markers continues to refine species boundaries.

Global distribution

Caulerpa species occur throughout tropical to warm-temperate coasts worldwide, with high diversity and abundance across the Indo-Pacific (e.g., Southeast Asia, Pacific Islands, northern Australia) and notable presences in the Mediterranean and Caribbean–West Atlantic regions **(Schembri *et al.*, 2015; Lagourgue *et al.*, 2024)**. *C. prolifera* is broadly distributed in the Mediterranean, eastern Atlantic, and western Atlantic, including parts of the Americas **(Fraissinet *et al.*, 2025)**.

Several species are established outside their native ranges. *C. taxifolia* spread widely in the Mediterranean and was also detected and subsequently eradicated in coastal California, USA; ongoing management is required in other localities. *C. racemosa* sensu lato, now treated as *C. cylindracea* in the Mediterranean, has expanded extensively in the basin, illustrating strong dispersal and ecological plasticity **(Mannino *et al.*, 2019)**. Originally Indo-Pacific, *C. brachypus* has been recorded as invasive in Florida (USA), the Caribbean, and New Zealand **(Wells & Bieler, 2020)**. The global distribution of *Caulerpa* can be seen in Fig. (2).

Fig. 2. Global distribution hotspots of *Caulerpa* spp.

Worldwide, there are hotspots of *Caulerpa* distribution and invasiveness, including the Indo-Pacific (Indonesia, Philippines, Japan), Mediterranean Sea (site of *C. taxifolia* invasion), Caribbean Sea, southern Australia, and California. Native ranges highlight *Caulerpa*'s prevalence in tropical and subtropical ecosystems, while invasion records underscore its ecological risks.

Ecological significance

Caulerpa plays dual ecological roles, both beneficial and potentially detrimental. The thriving benthic macroalgae contribute to habitat complexity, substrate stabilization, and nutrient cycling, supporting biodiverse marine communities. Their rapid vegetative propagation through fragmentation enables them to recolonize disturbed habitats efficiently **(Herawati *et al.*, 2021; Parreira *et al.*, 2021; Fraissinet *et al.*, 2025)**.

Conversely, *C. taxifolia* and *C. cylindracea* (*C. racemosa*) exhibit invasive behavior when introduced into non-native ecosystems with minimal predator pressure. Their invasiveness can lead to ecological disruptions, including the displacement of native seagrasses and alterations of benthic habitats, especially in the Mediterranean, where habitat and environmental balance are particularly sensitive **(Montefalcone *et al.*, 2015; Mannino *et al.*, 2019)**.

Cultivation and processing

Traditional farming techniques

In the Indo-Pacific region, especially in the Philippines and Indonesia, *Caulerpa* species have been traditionally harvested from the wild. Still, over time, shallow pond and lagoon farming have been adopted to support local communities. Techniques such as bottom-planting, off-bottom culture, floating long lines, and land-based raceways (Fig. 3) are used to cultivate *C. lentillifera* ("sea grapes") for fresh consumption, capitalizing on its high demand for local and export markets **(Islam *et al.*, 2023)**.

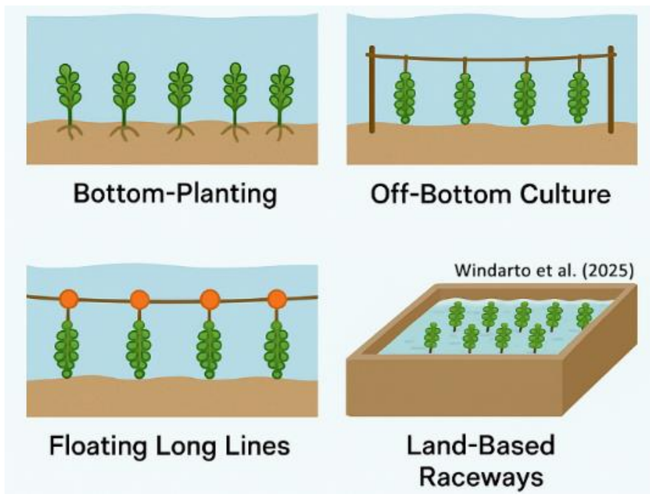

Fig. 3. Farming techniques of *Caulerpa* cultivation

Modern techniques

Efforts to integrate *C. lentillifera* into modern integrated multi-trophic aquaculture (IMTA) systems, where seaweeds serve as extractive species to utilize nutrients from fed organisms, have shown mixed success. In one trial in Southern Cebu, baskets in open-water IMTA failed to support *C. lentillifera* effectively, highlighting challenges in adapting the species to such systems **(Largo *et al.*, 2016)**. Meanwhile, broader developments in IMTA models, particularly in land-based pond systems, demonstrate high nutrient removal efficiencies, reinforcing the potential to include *Caulerpa* as a biofilter in these eco-friendly aquaculture models **(Yang *et al.*, 2025)**.

Beyond biofiltration, *C. lentillifera* can act as a productive substrate that upgrades feed quality. In co-culture, the 60 g m^{-2} substrate level yielded the best outcomes for L. vannamei fed *P. pacifica* grown on that substrate: RGR 34.98%, length gain 1.97 cm, biomass 0.0104 g (per individual), survival 96%, grazing rate 23.034 ind. day^{-1}; the feed contained 62.15% protein, 8.04% fat, EPA 7.95%, and lysine 11.95% **(Herawati *et al.*, 2021)**. These results position *C. lentillifera* as both a controllable nutrient scrubber in land-based IMTA and a substrate that enriches intermediate trophic culture for shrimp grow-out.

Recent trials indicate that low-cost, plant-derived PGRs can enhance *C. racemosa* growth and quality under culture. Combinations of coconut water (*Cocos nucifera*) and shallot crude extract (*Allium cepa* L.) have been reported to stimulate stolon extension, ramuli density, and overall biomass **(Ghani *et al.*, 2023)**. Additional studies using natural PGRs similarly show gains in specific growth rate and selected nutritional attributes (e.g. proximate composition) for *C. racemosa* **(Windarto *et al.*, 2023; Windarto *et al.*, 2024)**. In practice, these extracts are applied via short immersion or periodic dosing in tanks/raceways at empirically optimized concentrations and frequencies; outcomes are typically monitored via SGR, thallus/ramuli metrics, chlorophyll-a, and proximate/nutrient profiles. For deployment at scale, including basic safeguards, standardizing extract preparation, verifying the absence of contaminants, tracking residues where relevant, and documenting batch conditions are important to support reproducibility, food safety, and exporter documentation.

Regional practices and production hotspots

C. lentillifera is prominently cultivated in regions such as Okinawa (Japan) and Mindanao (Philippines), where it holds cultural and economic value. Although cross-regional productivity statistics remain limited, its distinctive texture and niche demand position it differently from staple carrageenophytes such as *Kappaphycus* or *Gracilaria* **(Stuthmann *et al.*, 2023)**.

In the Philippines, *C. racemosa*, locally “ar-arusip”, is commonly harvested alongside *C. lentillifera*. A multi-region socio-economic survey identified Mactan (Cebu) as a top producer, with peak dry-season harvests of ~42 tonnes per month and estimated annual incomes near PHP 2.26 million (≈USD 47,700) **(Estrada *et al.*, 2021)**. These findings underscore the genus’s economic role and cultural integration in Southeast Asia and the Pacific, while highlighting persistent constraints: reliance on wild harvests, limited standardized cultivation, short post-harvest shelf life, and uncertain site carrying capacity.

Priority needs include: (i) development and dissemination of sustainable farming protocols tailored to local conditions; (ii) post-harvest innovations to extend shelf life and stabilize quality; and (iii) community-based value-chain strengthening to improve market access and resilience **(Estrada *et al.*, 2021; Stuthmann *et al.*, 2023)**.

Post-harvest and preservation

A primary constraint to commercialization of *C. lentillifera* is its short shelf life, typically ~3–5 days at ambient temperature, driven by high water content and rapid microbial spoilage **(Toyen *et al.*, 2025)**. Preservation efforts have focused on brining: *C. lentillifera* can retain acceptable nutritional quality for up to ~12 weeks, though with perceptible color and firmness changes; maintaining salt concentrations below ~30% (w/v) helps preserve sensory attributes **(Pan-utai *et al.*, 2023)**. Recent work also explores UV-C irradiation to suppress microbial growth and extend freshness during short-term storage **(Toyen *et al.*, 2025)**. The flowchart of post-harvest and preservation of *Caulerpa* can be seen in Fig. (4).

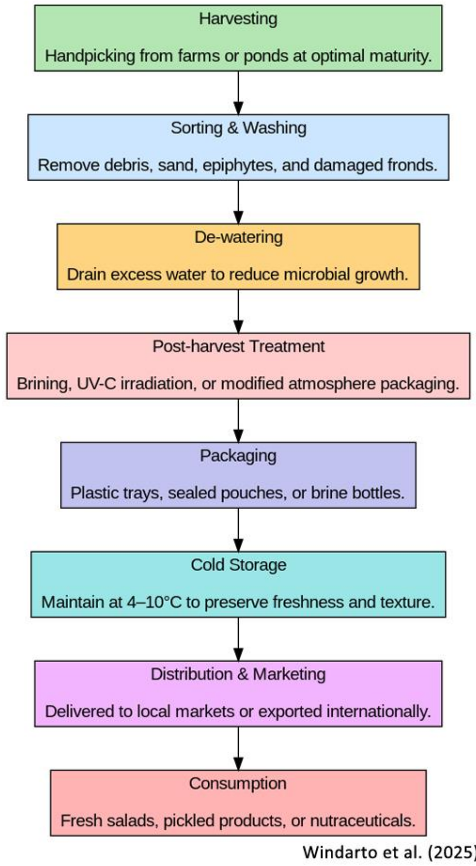

Fig. 4. Post-harvest and preservation of *Caulerpa*

C. racemosa presents similar challenges owing to delicate tissues and high moisture, leading to rapid quality loss post-harvest. Although species-specific studies remain limited, broader analyses of green seaweeds indicate that brining, controlled dehydration, and temperature management can stabilize texture and extend shelf life **(Zhu *et al.*, 2021)**. Metabolite profiling of *C. racemosa* under varied handling suggests several secondary metabolites remain stable under mild processing, supporting the feasibility of gentle preservation strategies **(Taslim *et al.*, 2024)**.

Nutritional, functional, and industrial applications

Nutritional composition

C. lentillifera is a nutrient-rich green macroalga. Dry-weight analysis reveals it contains approximately 7% protein, 14% lipid, 17.5% dietary fiber, and 44% carbohydrates, indicating a robust macronutrient profile supportive of human nutrition **(de Preez *et al.*, 2020)**. *C. racemosa*, or in Indonesia locally known as "Latoh", contains 6% of ash, 0.5-0.7% of fat, 1-1.5% of fiber, and 6-8% of protein **(Windarto *et al.*, 2023;**

Windarto *et al.*, 2024). Furthermore, *Caulerpa* showed a high level of polyunsaturated fatty acids (PUFAs) **(Brix da Costa *et al.*, 2025)**.

Comparative studies across regions such as Hainan, Shandong, Sabah, and Thailand show high levels of polysaccharides (up to ~59%) and proteins (up to ~19%), along with notably high contents of calcium (3,300– 3,700mg/ 100g), magnesium (6,700– 8,100mg/ 100g), iron (500– 2,000mg/ 100g), selenium, and zinc **(Zhang *et al.*, 2020a)**. *C. racemosa* from Jepara, Indonesia, showed a high Na (2.740 mg/100g), Si (1.630mg/ 100g), Cl (4.5mg/ 100g), and Ca (1.960mg/ 100g) **(Windarto *et al.*, 2025a)**. These figures underscore *Caulerpa*'s potential as a vibrant source of essential minerals and macronutrients.

Bioactive compounds

Beyond its impressive nutritional profile, *C. lentillifera* also harbors significant bioactive compounds. Research highlights the presence of sulfated polysaccharides exhibiting immune-enhancing and anti-inflammatory properties **(Tesvichian *et al.*, 2024)**. Experimental extracts of *C. lentillifera* have demonstrated antioxidant, anti-hyperglycemic, and anti-hypercholesterolemic effects *in vivo*, likely via modulation of oxidative stress and metabolic pathways **(Manoppo *et al.*, 2022)**. Furthermore, treatment of inflammatory macrophages (RAW 264.7 cells) with *C. lentillifera* extract led to decreased production of pro-inflammatory cytokines such as IL-6, IL-1β, and TNF-α, indicating strong anti-inflammatory activity **(Yoojam *et al.*, 2021)**. *C. racemosa* contains sulfated polysaccharides, alkaloids, flavonoids, and terpenoids with diverse bioactivities. Sulfated polysaccharides (SPCr) enhance AMPK and SIRT1 expression while reducing mTOR signaling, supporting anti-aging and metabolic regulation **(Nurkolis *et al.*, 2023)**.

Food and nutraceutical applications

Across Southeast Asia, *C. lentillifera* ("sea grapes"/"green caviar") is commonly eaten fresh (salads) or lightly salted, valued for its crisp texture and briny flavor **(Stuthmann *et al.*, 2023)**. Beyond fresh use, compositional profiles and bioactives support development of functional foods and dietary supplements.

For *C. racemosa*, techno-functional measurements indicate water-holding capacity ≈2.16 g/g, swelling capacity ≈6.56 mL/g, and oil-holding capacity ≈1.15 g/g, suggesting applicability as a texture/moisture modifier and emulsion stabilizer **(Windarto *et al.*, 2025a)**. Fermented products (e.g., *C. racemosa* kombucha) have been explored for "anti-ageing" positioning, though substantiation remains preliminary **(Permatasari *et al.*, 2021)**.

Sulfated polysaccharides isolated from *C. racemosa* (SPCr) show pancreatic-lipase inhibitory and anti-inflammatory activities in experimental models, indicating anti-obesity potential **(Mayulu *et al.*, 2023; Inoubli *et al.*, 2025)**. Metabolomic and bioassay studies report antioxidant and cytotoxic effects, including growth inhibition of breast-cancer cell lines **(Taslim *et al.,* 2024)**. Broader screenings identify terpenoids, alkaloids, sterols, and other secondary metabolites with reported antihypertensive, antihyperlipidemic, antimicrobial, antidiabetic/antihyperglycemic, anti-inflammatory, and antioxidant activities, primarily demonstrated *in vitro* or in animal models **(Iveša *et al.,* 2024)**. Translation to human health outcomes requires controlled clinical studies and robust safety/toxicology assessments. The summary of bioactive compounds and nutraceutical functions of *Caulerpa* can be seen in Table (1).

Table 1. *Caulerpa* species and their nutraceutical functions

Species	Bioactive Compounds	Applications	References
C. lentilifera	Sulfated polysaccharides	Anti-inflammatory, immunomodulatory, antioxidant, anti-obesity, anti-viral, anti-diabetic	**Sun *et al.*, (2018)**; **Tian *et al.*, (2019)**; **Khairuddin *et al.*, (2020)**; **Sun *et al.*, (2020)**; **Le *et al.*, (2022)**; **Manoppo *et al.*, (2022)**; **You *et al.*, (2022)**; **Tesvichian *et al.*, (2024)**;
C. lentilifera	Polyphenols, carotenoids, flavonoids, peptides, PUFAs	Antioxidant, anti-hyperglycemic, anti-hypertensive, anti-inflammatory, anti-diabetic, antiobesity	**Yoojam *et al.*, (2021)**; **Syakilla *et al.*, (2022)**; **Lin *et al.*, (2022)**; **Nurkolis *et al.*, (2022)**; **Sommer *et al.*, (2022)**; **Koodkaew *et al.*, (2024)**; **Montolalu *et al.*, (2024)**; **Kurniawan *et al.*, (2025)**
C. lentilifera	13-sophorosyloxydocosanoic acid, jubanine, cysteinyl-tyrosine, polyphenols	Antioxidant, anti-cancer	**Manmuan *et al.*, (2025)**
C. lentilifera	dl-2-phenyltryptophane	reduce hepatic lipid	**Sangpairoj *et al.*,**

	and benzoic acid	accumulation	**(2024)**
C. sertularioides	Caulerpin, difucol, quercetin, phenol, flavonoids, carotenoids, sulfated polysaccharides	Antioxidant, anti-cancer	**Anjali *et al.*, (2022)**; **Agena *et al.*, (2023)**
Caulerpa spp	Caulerpin, monomethyl caulerpinate, and caulersin	Anti-cancer (in silico)	**Olgun *et al.*, (2022)**
C. racemosa	Caulerpin, bioactive peptides, squalene, carotenoids, phenolic content, fatty acids	Antifungal, anti-cancer, antioxidant, anti-inflammatory	**Shanura Fernando *et al.*, (2018)**; **Permatasari *et al.*, (2022)**; **Palaniyappan *et al.*, (2023)**; **Nursidika *et al.*, (2024)**; **Permatasari *et al.*, (2024)**; **Taslim *et al.*, (2024)**
C. racemosa	Bioactive peptides, ADM, flavonoids, phenolic content	Antioxidant, anti-hypertensive, anti-viral (in silico), antimicrobial	**Abdul-Razak *et al.*, (2020)**; **Pangestuti *et al.*, (2021)**; **Tassakka *et al.*, (2023)**; **Purwati *et al.*, (2024)**; **Windarto *et al.*, (2025b)**
C. taxifolia	Heptadecane, Hexadecanoic acid, ester derivatives, phenolic, Ag NPs, caulerpenyne	Antimicrobial, antioxidant, anti-cancer, antitumor	**Akbar *et al.*, (2023)**; **Zhang *et al.*, (2020b)**; **Sfecci *et al.*, (2017)**
C. prolifera	Vanillin, p-coumaric acid, sinapic acid, 7,3′,4′-flavon-3-ol, and kaempferol, di-(2-ethylhexyl) phthalate, β-sitosterol, erucic acid, nervonic acid	Antioxidant, antidiabetic, antiaging	**Ouhabi *et al.*, (2025)**; **Rosa *et al.*, (2025)**

C. peltata	Heptadecane, Hexadecanoic acid, ester derivatives, phenolic, alkaloid, terpenes, caulerpin, manomethyl caulerpinate	Antimicrobial, antioxidant, anti-inflammatory, and immunostimulatory activity	**Hao *et al*., (2019)**; **Akbar *et al*., (2023)**; **Nayaka *et al*., (2020)**

Cosmetics and industrial uses

Although specific cosmetic applications of *Caulerpa* remain exploratory, related green seaweeds are known for their antioxidant and hydrating properties, making them desirable in anti-aging and skin-care formulations **(Peñalver *et al*., 2020)**. Additionally, the genus *Caulerpa* has shown promise in bioremediation and biofilter, while certain extracts are under investigation for uses in animal feed and bioplastic or bioenergy technologies **(Margono *et al*., 2021; Landi *et al*., 2022; Natsir *et al*., 2022; Borazjani *et al*., 2025)**. Moreover, *C. racemosa* has also been found to be a promising antimicrobial edible film for active packaging of food **(Rusli *et al*., 2024)**.

Market trends

Although precise market data for *Caulerpa* remain limited, the Asia-Pacific region, particularly the Philippines, Japan, and parts of Southeast Asia, dominates its production and consumption, with established value chains for fresh and lightly processed forms **(Zhang *et al*., 2020; Stuthmann *et al*., 2023)**. The growing popularity of *C. lentillifera* globally signals increasing potential for export, functional food, and bioproduct innovation.

Sustainability, environmental impact, and challenges

Sustainability in aquaculture

C. lentillifera has significant potential in climate-smart aquaculture, notably through its integration into Integrated Multi-Trophic Aquaculture (IMTA) systems. While studies specific to *Caulerpa* are limited, broader IMTA approaches, where seaweeds act as nutrient sinks, are recognized for their environmental benefits. These approaches enable nutrient recycling, eutrophication control, and diverse co-culture productivity **(Loayza-Aguilar *et al*., 2023; Alam *et al*., 2024)**.

In an experimental setting, *C. lentillifera* demonstrated high nutrient uptake capacities (nitrogen and phosphorus) when cultured with fish effluent, suggesting its utility as a biofilter in sustainable aquaculture **(Bambaranda *et al*., 2019a, b)**.

Ecosystem services

Caulerpa enhances carbon sequestration by fixing CO_2 during photosynthesis, contributing to "blue carbon" storage and helping offset greenhouse gas emissions **(Farghali *et al*., 2023; Pessarrodona *et al*., 2024)**. Moreover, *C. lentillifera* has proven effective in water purification, notably in the removal of nitrogenous waste (e.g., nitrate, phosphate), crucial for ameliorating aquaculture effluent impacts **(Bambaranda *et al.*, 2019a, b)**.

Invasiveness and trade-offs

Some *Caulerpa* species pose ecological risks in non-native habitats. For example, *Caulerpa cylindracea* (formerly *C. racemosa* var. cylindracea) has aggressively invaded the Mediterranean, outcompeting native benthic species and altering local ecosystems **(Brewton & Lapointe, 2023)**. Balancing *Caulerpa*'s utilization and ecological caution requires stringent cultivation protocols and targeted deployment to minimize accidental spread.

Cultivation and market challenges

Commercial cultivation of *C. lentillifera* faces significant hurdles, particularly post-harvest perishability and shelf-life constraints. Fresh “sea grapes” are highly perishable due to their succulent, high-moisture tissues, which rapidly degrade when exposed to ambient conditions or oxidative stress. In a seasonal quality study of Taiwanese seagrapes, storage without seawater led to substantial 20–40% water loss, 70–90% lipid peroxidation (MDA production), and drastic reductions in total phenolics and chlorophyll within just a few days, underscoring the difficulty in preserving freshness under typical storage conditions. However, treatment with an alternating current electric field (ACEF) extended shelf-life by up to 12 days by mitigating physicochemical deterioration (e.g., maintaining chlorophyll and phenolic content) in spring-harvested samples **(Sulaimana *et al.*, 2021)**.

Another challenge lies in market development, particularly in Western regions. Consumer acceptance of seaweed products depends heavily on awareness and nutritional positioning. A 2024 consumer psychology study found that sharing information about nutritional benefits significantly improves Western consumers' acceptance and sensory perception of seaweed-based foods **(Moss *et al.*, 2024)**. The roadmap for *Caulerpa* development is illustrated in Fig. (5).

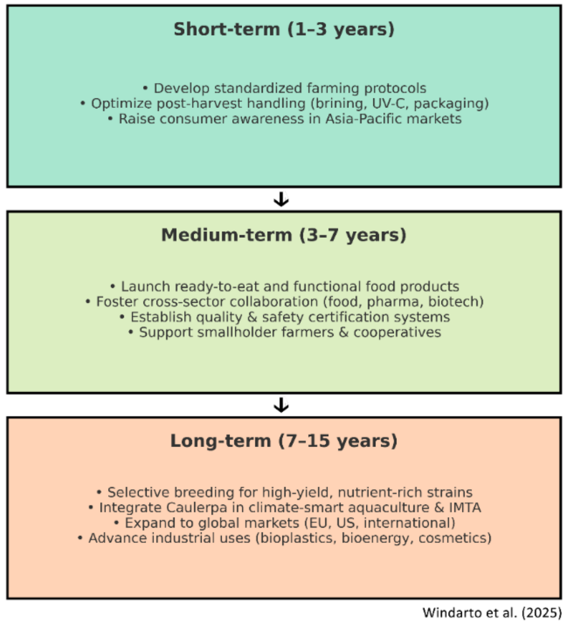

Fig. 5. Roadmap for *Caulerpa* development

Future outlook and recommendations

Caulerpa's market growth will depend on (i) product innovation, especially ready-to-eat formats and standardized functional extracts (e.g., sulfated polysaccharides; alkaloids such as caulerpin), and (ii) cross-sector collaboration among aquaculture, food, pharma, and biotech to translate experimental bioactivities into regulated products with validated safety and quality profiles. Structured reviews for *C. lentillifera* already document workable post-harvest solutions (e.g., brining ranges) and premium fresh positioning that can extend to shelf-stable functional foods and nutraceuticals **(Stuthmann *et al.*, 2023)**.

At the policy/regulatory level, harmonized cultivation, food-safety, and export standards (contaminants, allergens, labeling, traceability) are needed for seaweeds; proactive risk assessment for offshore/novel farming should be embedded into permitting and guidance, elements that *Caulerpa* value chains can adopt to access higher-value markets while protecting consumers **(Banach *et al.*, 2020)**.

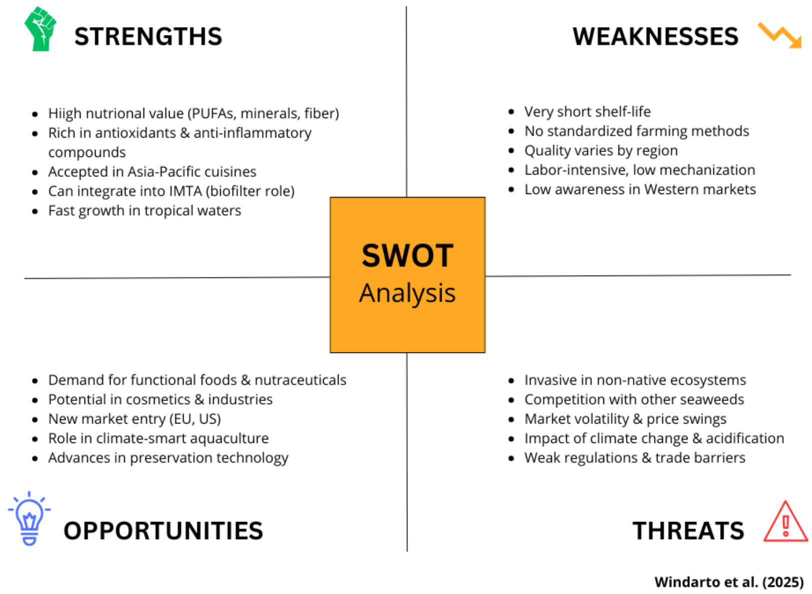

Fig. 6. SWOT analysis of *Caulerpa*

To translate *Caulerpa*'s promise into reliable products and supply, the next phase needs targeted R&D that closes known technical gaps while generating decision-grade safety and quality data. The following priorities are the most actionable near-term levers:

1. Breeding & domestication: Select high-yield, nutrient-dense, and morphology-optimized strains suited to mechanization, following macroalgal selective-breeding frameworks **(Charrier *et al.*, 2015)**.
2. Post-harvest technologies: Validate brine concentration–time–temperature windows; assess emerging physical treatments (e.g., UV-C) for quality and safety; develop packaging that limits oxidation and texture loss **(Pan-utai *et al.*, 2023; Stuthmann *et al.*, 2024)**.
3. Safety/toxicology: Establish dose–response and exposure data for key metabolites (e.g., caulerpenyne, caulerpin) across intended uses (food, cosmetic, pharma); emerging in vivo data suggest low acute toxicity for caulerpin at dietary-relevant levels, supporting further development under GMP **(Russo *et al.*, 2024; dos Santos, 2025)**.

Commercial traction will come from matching product formats to the most ready markets while building credibility through standards and documentation. The steps below stage investments from existing hubs toward new regions and channels:

1. Near term (Asia–Pacific): Consolidate existing hubs with best-practice cultivation and post-harvest SOPs; deploy cooperative/certification schemes to stabilize quality and pricing.

2. New regions: Build evidence-based narratives with standardized quality metrics (moisture, ash, contaminants, bioactives), validated processes, and importer-aligned documentation.
3. Platforms: Position *Caulerpa* as (a) premium fresh produce, (b) functional ingredients (fiber/texture modifiers, extracts), and (c) co-products in IMTA/blue-economy initiatives **(Sultana *et al.*, 2023; Khan *et al.*, 2024)**.

CONCLUSION

Caulerpa, particularly *C. lentillifera* and *C. racemosa*, is an underutilized but promising genus for diversified seaweed value chains. Its nutrient density, bioactive-rich profile, and suitability for fresh, functional-food, nutraceutical, and cosmetic applications position it as a strategic resource for climate-smart aquaculture and blue-economy development. Current barriers, short shelf life, limited and non-standardized farming, low consumer awareness outside Asia, and ecological/biosecurity risks, constrain scale.

Realizing this potential requires coordinated action: (i) validated post-harvest technologies (e.g., optimized brining, emerging physical treatments, fit-for-purpose packaging) to extend shelf life and stabilize quality; (ii) selective breeding and domestication targeting yield, texture, and nutrient traits; (iii) harmonized standards for cultivation, safety, and trade (contaminants, labeling, traceability); and (iv) cross-sector partnerships to translate experimental bioactivities into regulated, market-ready ingredients. With these steps, *Caulerpa* can credibly progress from regional "sea grapes" to globally recognized "green gold of the ocean," contributing meaningfully to future seaweed markets.

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