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REVIEW: AN ECOCENTRISM PERSPECTIVE IN DEVELOPING SEA GRAPES (*Caulerpa* spp.*)* AS A NATURAL, SUSTAINABLE FOOD PRESERVATIVE

Review: Perspektif Ekosentrisme dalam Mengembangankan Anggur Laut (*Caulerpa* spp.*)* Sebagai Pengawet Alami Pangan yang Berkelanjutan

Moegiratul Amaro[1,2*], M Sarjan[3], Siska Cicilia[1,2], Mutia Devi Ariyana[1,2], Ida Ayu Widhiantari[1,2] Hanifah Ayu[1,2], Sudarli[1,4], Gunawan[1,5], Amrullah[1,6], Husnul Jannah[1,7], Aida Muspi'ah[1,8]

[1]Doctoral Program in Sustainable Agriculture, University of Mataram, [2]Faculty of Food Technology and Agroindustry, University of Mataram, [3]Faculty of Agriculture, University of Mataram, [4]Department of Education and Culture of Sumbawa Regency, NTB, [5]PT. Dredolf Indonesia Jakarta, [6]Faculty of Animal Husbandry and Fisheries, Samawa University, [7]Faculty of Science, Technology and Applied Sciences, Mandalika University of Education, Mataram, [8]Faculty of Mathematics and Natural Sciences, University of Mataram, Mataram, NTB

Majapahit Street No.62, Mataram, NTB

*Coressponding Author: moegiratulamaro@unram.ac.id

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ABSTRACT

The increasing concerns over the health and environmental risks of synthetic preservatives have driven interest in natural alternatives derived from marine resources. Sea grapes (Caulerpa spp.) are recognized for their rich bioactive composition, including minerals, phenolics, flavonoids, and sulfated polysaccharides. This study employs a systematic literature review to synthesize findings related to the biochemical characteristics, phytochemical constituents, antioxidant activity, and ecological implications of Caulerpa racemosa as a sustainable food preservative. Data were collected from peer-reviewed journals and institutional reports using a structured search strategy across major scientific databases. Biochemical analysis shows high mineral content (total ash 48.41%), moderate protein levels (12.64%), and considerable nitrogen-free extract (27.26%). Phytochemical screening confirms the presence of terpenoids, steroids, tannins, phenols, and alkaloids predominantly in polar extracts. Antioxidant assays reveal strong radical-scavenging activity, with methanol extracts demonstrating IC_{50} values of 86.33 µg/mL (DPPH) and 54.51 µg/mL (ABTS), approaching the effectiveness of vitamin C. These properties highlight the potential of Caulerpa as a natural agent to inhibit oxidation and microbial spoilage. From an ecocentric perspective, Caulerpa cultivation within Integrated Multi-Trophic Aquaculture (IMTA) systems supports environmental restoration by functioning as a biofilter that absorbs excess nutrients and improves water quality. The review concludes that Caulerpa-based preservatives offer promising benefits for food safety, ecosystem sustainability, and coastal community livelihoods, although further research is required on safety, standardization, and sensory impacts to support broader application.

Keywords: Caulerpa spp., ecocentrism, food sustainability, natural preserves, Sea grapes.

ABSTRAK

Meningkatnya kekhawatiran terhadap risiko kesehatan dan lingkungan dari penggunaan pengawet sintetis mendorong pencarian alternatif alami yang berasal dari sumber daya laut. Anggur laut (*Caulerpa* spp.) dikenal kaya akan senyawa bioaktif seperti mineral, fenolik, flavonoid, dan polisakarida tersulfatasi. Penelitian ini menggunakan metode systematic literature review untuk mensintesis temuan terkait karakteristik biokimia, kandungan fitokimia, aktivitas antioksidan, dan implikasi ekologis *Caulerpa racemosa* sebagai pengawet pangan yang berkelanjutan. Data dikumpulkan dari jurnal ilmiah dan laporan lembaga melalui strategi pencarian terstruktur pada berbagai basis data ilmiah. Analisis biokimia menunjukkan kandungan mineral yang tinggi (total abu 48,41%), kadar protein sedang (12,64%), dan nitrogen-free extract yang cukup besar (27,26%). Uji fitokimia menegaskan keberadaan terpenoid, steroid, tanin, fenol, dan alkaloid terutama pada ekstrak polar. Uji antioksidan menunjukkan kemampuan penangkapan radikal yang kuat, di mana ekstrak metanol memiliki nilai IC_{50} sebesar 86,33 µg/mL (DPPH) dan 54,51 µg/mL (ABTS), mendekati efektivitas vitamin C. Temuan ini menyoroti potensi *Caulerpa* sebagai agen alami untuk menghambat oksidasi dan pembusukan mikroba. Dari perspektif ekosentris, budidaya *Caulerpa* dalam sistem *Integrated Multi-Trophic Aquaculture* (IMTA) mendukung restorasi lingkungan dengan berfungsi sebagai biofilter yang menyerap nutrien berlebih dan meningkatkan kualitas air. Kajian ini menyimpulkan bahwa pengawet berbasis *Caulerpa* menjanjikan manfaat bagi keamanan pangan, keberlanjutan ekosistem, dan penghidupan masyarakat pesisir, meskipun riset lanjutan terkait keamanan, standardisasi, dan dampak sensori tetap diperlukan.

Kata kunci: Anggur laut, *Caulerpa* spp., ekosentrisme, keberlanjutan pangan, pengawet alami.

INTRODUCTION

The modern food industry still relies heavily on synthetic preservatives such as nitrites/nitrates, benzoates, and sorbates to extend shelf life and suppress the growth of spoilage microorganisms. However, various studies have shown that excessive consumption of synthetic preservatives is associated with an increased risk of cancer, metabolic disorders, allergies, and cardiovascular problems, and can also form toxic compounds such as nitrosamines in processed meat products (Shi et al., 2024; Sharma & Rajput, 2023).

As consumer awareness of health and sustainability increases, there is a major shift towards organic food and the use of natural preservatives from plants, animals, microorganisms and algae (El et al., 2025; Pinto et al., 2023). This demand is driven not only by health concerns, but also by the desire for a more environmentally friendly food system that contributes to reducing waste and the ecological footprint (El et al., 2025; Karnwal & Malik, 2024).

In this context, sea grapes (Caulerpa spp.) emerge as an interesting candidate. Sea grapes such as Caulerpa racemosa and Caulerpa lentillifera are known to be rich in antioxidant and antimicrobial bioactive compounds, and their potential as natural preservatives and functional food ingredients has been studied (Palaniyappan et al., 2023; Yap, et al., 2019; Syakilla et al., 2022; Seaweed et al., 2022). From an ecocentric perspective that views moral values not only in humans but in the entire ecological community, the development of sea grape-based preservatives should be assessed not only from its benefits to humans, but also from its impacts on marine ecosystems, nutrient cycles, and socio-ecological sustainability.

Ecocentrism is a view of environmental ethics that places intrinsic value on the entire ecosystem, including species, communities, and ecological processes, rather than solely on human interests (anthropocentrism). In this regard, good food technology is not only safe and beneficial to humans, but also maintains ecosystem integrity and biodiversity, reduces pollution and waste, and respects the reciprocal relationship between humans and nature (co-flourishing) (El et al., 2025; Pinto, et al., 2023). The development of sea grape-based natural preservatives from an ecocentric perspective means prioritizing raw material sources from cultivation that

restores the ecosystem (restorative), for example an integrated aquaculture system that absorbs waste (Elisabeth et al., 2023; Jongjaraunsuk et al., 2025; Rahmadani and Muahiddah, 2024), reducing dependence on synthetic chemicals that have the potential to pollute the environment (El et al., 2025; Shi et al., 2024) and ensure that economic benefits for coastal communities do not sacrifice the health of marine ecosystems (Rahmadani and Muahiddah, 2024; Langford, 2023; Yunus et al., 2024). The purpose of this study is to analyze and synthesize the potential for developing natural food preservatives based on sea grapes (Caulerpa spp.) sustainably using an ecocentric perspective as the main framework.

RESEARCH METHODS

Research Approaches and Types

This research uses a qualitative approach with a systematic literature review type (Langford, 2023; Rahmadani & Muahiddah, 2024). This approach was chosen because the aim of the research is to conduct an in-depth synthesis of various scientific disciplines including food science, marine biology, ecology, fisheries socio-economics, and environmental ethics in order to build a coherent conceptual argument. A systematic literature review allows for the structured identification, evaluation, and interpretation of all available relevant research related to the formulated topic (Rabia, 2025).

Time and Place of Research

Literature data collection was conducted online from September to November 2025. The research site was virtual, providing access to various scientific databases, university repositories, and publication portals of both national and international government agencies.

Data Sources and Types

The data used in this study are secondary data derived from Primary Data sources (in the context of literature studies), namely international and national scientific journal articles that have gone through a peer-reviewed process. Additional Secondary Data comes from books, book chapters, technical reports from government agencies (such as the Ministry of Maritime Affairs and Fisheries/MMAF), non-governmental organizations, and international bodies (such as the FAO), as well as review articles relevant to the blue economy, ecocentric ethics, and food security (Langford, 2023; Yunus et al., 2024; Rahmadani & Muahiddah, 2024).

Data Collection Procedures

Data collection was carried out systematically through three main stages:

Step 1 : Database Determination:Literature searches were conducted on reputable scientific databases, such as Scopus, Web of Science, ScienceDirect, Google Scholar, and the Garuda portal for national publications (Langford, 2023).

Step 2 : Keyword Determination:Keywords were arranged in three groups to ensure comprehensive search coverage. Group A (Species): "Caulerpa spp.", "Caulerpa racemosa", "Caulerpa lentillifera", "sea grapes", "sea grapes". Group B (Preservative Applications): "natural food preservative", "natural preservative", "antimicrobial", "antibacterial", "antioxidant", "edible coating", "food preservation". Group C (Ecocentric & Sustainability Context): "ecocentrism", "ecocentrism", "IMTA", "biofilter", "sustainable aquaculture", "sustainable aquaculture", "blue economy", "blue economy".

Step 3 : Literature Selection Based on Inclusion and Exclusion Criteria:The articles found are then filtered based on predetermined criteria to ensure relevance and quality.

Data Analysis Techniques

Data collected from selected literature was analyzed using thematic content analysis (Langford, 2023). This analysis process involved three main activity streams. Data Reduction: The process of summarizing, selecting, and focusing data from each article on key points relevant to the research question. Key information regarding bioactive composition, antimicrobial/antioxidant activity test results, nutrient uptake efficiency in the IMTA system, and socio-economic impacts was extracted and summarized (Langford, 2023). Data Presentation: The reduced data were then grouped and presented into key themes that had been previously identified. These themes include: The bioactive potential of Caulerpa spp. as natural preservatives (antioxidants and antimicrobials). Sustainable cultivation models aligned with ecocentric principles (IMTA, biofilters). Opportunities and socio-economic impacts for coastal communities. Challenges and risks (caulerpine toxicology, standardization, sensory impacts, and invasive species issues).

RESULTS

Bioactive Potential of Sea Grapes (Caulerpa spp.) as a Natural Preservative

1. Chemical composition and bioactive content of sea grapes (Caulerpa spp.)

Various studies have shown that Caulerpa spp. contains various secondary metabolites such as flavonoids, phenols, tannins, steroids, and alkaloids (including caulerpine) (Santosa et al., 2024;Palaniyappan et al., 2023), sulfated polysaccharides (SPs) such as galactomannan and ulvan-like which are rich in rhamnose, uronate, and xylose (Landi & Esposito, 2020; Nurkolis et al., 2023; Pangestuti et al., 2021), Polyunsaturated fatty acids (PUFA) and pigments such as chlorophyll and carotenoids which have antioxidant activity (Brix & Kunzmann, 2025;Syakilla et al., 2022).

Table 1. Biochemical constituents analysis of *Caulerpa racemosa.*

Biochemical Constituents	*Caulerpa racemosa*
Moisture	7.04%
Crude protein	12.64%
Crude fiber	2.85%
Ether extract	1.80%
Total ash	48.41%
Nitrogen-free extract	27.26%
Gross energy	2089 Kcal/kg

Source: (Palaniyappan et al., 2023)

The biochemical composition of ***Caulerpa racemosa*** exhibits distinctive characteristics as a mineral-rich green seaweed, reflected in its very high total ash value (48.41%), thus potentially serving as a source of important inorganic compounds that play a role in biofunctional activities, including antimicrobials. Its protein content of 12.64% indicates the presence of peptides and amino acids that may contribute to the stability and biological activity of the extract. The relatively high nitrogen-free extract content (27.26%) also indicates the presence of non-fiber carbohydrates, particularly sulfated polysaccharides known to have antioxidant and antimicrobial activities. Meanwhile, its low water content (7.04%) and relatively small fat content (1.80%) support the stability of the material during storage and facilitate the extraction of active compounds. Overall, this nutritional profile confirms the potential of C. racemosa as a candidate raw material for the development of value-added products, including natural preservatives in the food industry.

Table 2. Phytochemical analysis of various extracts of Caulerpa racemosa. "+"indicates presence of phytochemicals. "–" indicates the absence of phytochemicals.

No	Test	Methanol	Ethanol	Acetone	Ethyl Acetate	Petroleum Ether	Hexane
1	Saponins	+	+	-	-	-	-
2	Terpenoids	+	+	+	+	-	+
3	Steroids	+	+	+	+	-	-
4	Phytosterol	+	+	+	+	-	-
5	Tannins	+	+	+	+	+	+
6	Flavonoids	+	+	+	+	-	-
7	Phenol	+	+	+	-	-	-
8	Phenolic	+	+	+	-	-	-
9	flavonoids	+	+	+	-	-	-
10	Alkaloids	+	+	-	-	-	-

Source: (Palaniyappan et al., 2023)

Phytochemical test results indicate that Caulerpa racemosa extract contains a high diversity of bioactive compounds, especially in polar to semi-polar solvents such as methanol, ethanol, acetone, and ethyl acetate. The presence of saponins, terpenoids, steroids, phytosterols, flavonoids, phenols, and alkaloids in polar solvents confirms that most secondary metabolites in C. racemosa are polar and easily extracted with alcohol. Meanwhile, tannins were detected in all types of solvents, including petroleum ether and hexane, indicating that these compounds have a wide solubility range. Non-polar solvents (petroleum ether and hexane) only extracted a small number of compounds, especially tannins and certain terpenoids, indicating that the lipophilic components in this seaweed are relatively low. Overall, this phytochemical profile strengthens the potential of C. racemosa as a source of multifunctional bioactive compounds that can be developed as antioxidants, antimicrobials, and natural preservatives in the food industry.

Caulerpa lentillifera extract is reported to contain sulfated polysaccharides (CLGP4) with high anti-inflammatory and antioxidant activities, including the ability to inhibit free radicals and modulate immune responses (Landi & Esposito, 2020; Damayati et al., 2024). *Caulerpa racemosa* extract is rich in phenolics, flavonoids, and tannins; for example, the methanol extract showed a total phenolic content of ~12 mg GAE/g and flavonoids of ~33 mg QE/g (Palaniyappan et al., 2023).

2. Antioxidant activity

Table 3. IC50 values of Caulerpa racemosa extracts of DPPH & ABTS radical scavenging activity

Extracts of *Caulerpa racemose*	DPPH Assay (µg/mL)	ABTS Assay (µg/mL)
Vitamin C (standard)	36.79	32.06
Methanol	86.33	54.51
Ethanol	104.46	75.10
Acetone	102.52	73.64
Ethyl acetate	111.59	74.41
Petroleum ether	124.41	69.92
Hexane	173.21	76.28

Source: (Palaniyappan et al., 2023)

The results of the antioxidant test showed that Caulerpa racemosa extract has a radical scavenging ability that varies depending on the type of solvent, with the best activity shown by the methanol extract (DPPH 86.33 µg/mL; ABTS 54.51 µg/mL), approaching the effectiveness of vitamin C as a standard. Polar solvents such as methanol and ethanol generally produce lower IC50 values than non-polar solvents, indicating that the dominant antioxidant compounds in C. racemosa are polar, especially phenols and flavonoids. Antioxidant activity decreased in the petroleum ether and hexane extracts, indicating a low content of lipophilic compounds that play a role in the redox mechanism. Overall, this pattern strengthens the finding that the polar fraction of C. racemosa is a potential source of antioxidants, relevant for the development of natural preservatives or oxidative protective agents in food and health applications.

Antioxidants are important in food preservation because they can inhibit lipid oxidation and prevent rancidity and nutrient degradation. Caulerpa extracts show strong antioxidant activity in various tests such as methanol extract of *C. racemosa* has DPPH radical scavenging activity of ~ 54% and ABTS of ~ 77% at certain concentrations, with IC_{50} values competitive with synthetic antioxidants (Palaniyappan et al., 2023). A comparative study of five food macroalgae showed that *C. racemosa* has the highest antioxidant activity (up to 277 mmol Trolox Equivalents/100 g dry weight) and the highest total phenolic content (~ 157 mg GAE/100 g DM) compared to other species (Brix & Kunzmann, 2025).

Caulerpa sp. extract from Sapudi Island also showed antioxidant activity, although it was influenced by the drying method; air-drying gave an IC_{50} of around 200 ppm, while sun-drying was around 492 ppm (Damayati et al., 2024). Sulfated polysaccharides from C. racemosa and C. lentillifera (SPCr and SPCl) isolated from Indonesian waters showed antioxidant EC50s even stronger than Trolox in several assays (DPPH, ABTS, FRAP), confirming their potential as natural antioxidant sources (Nurkolis et al., 2023)

3. Antimicrobial activity

An ideal natural preservative also has antimicrobial properties against spoilage bacteria and food pathogens. Various evidence supports the antimicrobial activity of Caulerpa spp., namely C. racemosa extract showing a clear inhibition zone against fish and food pathogenic bacteria, the tannin and phenolic content is thought to play a role by damaging cell membranes and membrane enzymes (Palaniyappan et al., 2023). Studies on C. racemosa and C. lentillifera from Malaysia showed that the chloroform extract of C. racemosa had the highest phenolic content (13.41 mg GAE/g), the best antioxidant activity (EC50 0.65 mg/mL), and the strongest antibacterial effect against MRSA (reduction of up to ~98%) and *E. coli* K1 (Yap, et al,, 2019). LC–MS indicates that this antibacterial activity is related to a combination of PUFAs, terpenes, and alkaloids such as caulerpine, as well as several new, uncharacterized compounds (Yap et al., 2019). Research in Jepara found 14 isolates of symbiotic bacteria from C. racemosa and C. lentillifera, mostly Pseudomonas and Pseudoalteromonas, all of which exhibited enzymatic and antibacterial activity; this combination of algal metabolites and symbiotic bacteria is considered to have potential as a source of natural preservatives (Santosa Et Al., 2024). Sulfated polysaccharides from Caulerpa spp. have also been shown to possess antimicrobial, immunostimulant, antiurolytic, antinociceptive, and gastroprotective activities in various in vitro and in vivo models, thus conceptually serving a dual role as both a preservative and a functional food component (Landi & Esposito, 2020).

DISCUSSION

Sea Grape Based Preservative Product Design

1. Extract as a preservative in food products

Technically, sea grape extract can be applied as a co-preservative in meat, fish, or bakery products to suppress oxidation and microbial growth. It is also a functional food fortification ingredient with additional antioxidant/anti-inflammatory claims. For example, the addition of C. racemosa powder to semi-sweet biscuit formulations increases the protein, fiber, and antioxidant capacity of biscuits, as well as improving several functional properties of the dough (water/oil absorption, solvent retention) (Kumar et al., 2017). This indicates the potential of C. racemosa as an ingredient that also acts as an antioxidant and preservative in bakery products. In wet food products (e.g., fish, meat), the concept is similar to the use of plant extracts, namely phenolic compounds and Caulerpa polysaccharides can inhibit the growth of spoilage bacteria and delay chemical changes (El et al., 2025; Pinto et al., 2023).

2. Edible coating and active packaging based on sea grape polysaccharides

An increasingly important approach from an ecocentric perspective is the use of biopolymer-based films/edible coatings. Seaweed polysaccharides (agar, carrageenan, alginate, ulvan) have been widely used as biodegradable film matrices with the ability to act as gelling/thickeners and carriers of antimicrobial/antioxidant compounds (Qasim et al., 2024). Ulvan (a polysaccharide from Ulva, a green algae) was successfully extracted with high yields and exhibited antimicrobial activity. Ulvan and similar polysaccharides have the potential to be used in packaging films that release bioactive compounds (Ashour et al., 2025).

Conceptually, Caulerpa spp., which also contain similar sulfated polysaccharides (Landi & Esposito, 2020; Nurkolis et al., 2023), could be a source of film polymers (after purification) combined with alginate/pectin/carrageenan, carrying Caulerpa phenolic/alkaloid extracts within the film matrix. This model mimics the success of alginate/pectin films containing cranberry and grape seed extracts that were able to inhibit microbial growth and biogenic amine formation in herring (Šipailien, 2023). Films similar to sea grape extract have the potential to reduce the rate of fish/meat spoilage by inhibiting bacterial growth and lipid oxidation, partially replacing the use of plastics and synthetic preservatives. Encapsulation and nanoemulsion technologies, already widely used for essential oils and plant phenolics, can also be adapted to maintain the stability and control the release of *Caulerpa* bioactive compounds in food matrices and active packaging (El et al., 2025;Singh et al., 2024; Pinto et al., 2023).

Environmental Sustainability: Sea Grape Cultivation in an Ecocentric Framework

1. Caulerpa as a biofilter and component of IMTA (Integrated Multi-Trophic Aquaculture)

From an ecocentric perspective, preservative raw materials must come from production systems that do not damage the ecosystem, and ideally, they should be restorative. Various studies have shown that Caulerpa lentillifera and C. racemosa have a high capacity to absorb nitrogen and phosphorus from aquaculture waste. C. lentillifera is used as a biofilter in Recirculating Aquaculture Systems (RAS) and IMTA systems, capable of reducing ammonia, nitrite, nitrate, and phosphate from fish and shrimp aquaculture effluents, while simultaneously producing marketable biomass (Stuthmann et al., 2023; Jongjaraunsuk et al., 2025). The integration of *C. lentillifera* with whiteleg shrimp or grouper aquaculture improves water quality, enhances shrimp/fish growth, and results in a daily seaweed growth rate of 0.5–4% per day (Stuthmann et al., 2023; Jongjaraunsuk et al., 2025). *C. racemosa* is also effective in reducing organic matter in semi-intensive tiger shrimp ponds, significantly reducing total organic matter and sediment organic matter and showing the highest specific growth rate (~1.37%/day) compared to *Sargassum* and Gracilaria (Irawan, Permatasari, & Attaqi, 2024).

IMTA (Integrated Multi-Trophic Aquaculture) itself was introduced as an environmentally friendly aquaculture model that utilizes organic/inorganic waste from fed species (fish/shrimp) as nutrients for extractive species (seaweed, shellfish, sea cucumbers) (Rahmadani & Muahiddah, 2024). This system reduces the waste load to the surrounding environment, maintains water quality and ecosystem function, and produces several commodities simultaneously, thereby increasing land and economic efficiency. By incorporating *Caulerpa* as a biofilter and source of preservative raw materials, we create a cycle that aligns with the ecocentric principle: potentially polluting nutrients are converted into useful biomass and reduce pressure on wild ecosystems.

2. Ecological risks: invasive species and caution

However, an ecocentric perspective also requires caution. Several non-endemic *Caulerpa* species, such as *Caulerpa cylindracea* (often called *C. racemosa* var. cylindracea), have become invasive species in the Mediterranean, altering the structure of benthic communities and interacting complexly with local herbivores (Rizzo & Fernández, 2023).

On the one hand, this invasive biomass can be utilized as a bioactive raw material for pharmaceuticals and nutraceuticals, so its commercial exploitation can help control its spread (Landi & Esposito, 2020; Landi & Esposito, 2020; Rizzo & Fernández, 2023). On the other hand, unregulated utilization can inadvertently encourage the spread or strengthen economic dependence on invasive species. Therefore, sea grape cultivation for food preservatives should prioritize local/non-invasive species (e.g., local *C. racemosa* and *C. lentillifera* in the Indo-Pacific) (Stuthmann et al., 2023;Brix & Kunzmann, 2025), implementing strict biosecurity to prevent the introduction or release of invasive strains into new areas, assessing the carrying capacity of local ecosystems before large-scale expansion (Rahmadani & Muahiddah, 2024).

Socio-Economic Dimensions and Ecological Justice

Ecocentrism does not negate human interests, but rather places them as part of a broader ecological community. The development of sea grape-based preservatives offers opportunities for economic empowerment of coastal communities through seaweed cultivation and processing (Yunus et al., 2024), contributing to Indonesia's "blue economy" with high value-added commodities based on renewable resources (Hasbullah, et al, 2024), business diversification for seaweed farmers who have so far been more dependent on Kappaphycus/Eucheuma, which produces carrageenan (Langford, 2023).

Caulerpa cultivation has become an important livelihood in various regions of Indonesia; for example, lawi-lawi (Caulerpa sp.) is developed as a mainstay commodity in South Sulawesi and is able to absorb labor and increase the income of coastal households (Hasbullah, et al, 2024). The downstreaming program for sea grape products in Lamongan and Maluku also shows that processing into food, snacks, and other processed products can increase local added value (Mahmudah et al., 2024;Fitriatno et al., 2025).

Within the framework of ecological justice, it is crucial to ensure that the economic benefits of the sea grape preserves value chain benefit not only downstream industries but also farmers/cultivators as direct managers of coastal ecosystems (Langford, 2023). Cultivation practices must respect local communities' rights to marine space and not lead to spatial conflicts or habitat degradation that harms other communities and species (Langford, 2023).

Challenges and Opportunities

1. Food safety and toxicology

Although numerous studies have demonstrated beneficial biological activities, Caulerpa also produces caulerpin alkaloids, which can accumulate in the tissues of fish that feed on Caulerpa and are suspected of affecting their lipid and PUFA metabolism (Landi &

Esposito, 2020). This raises several issues, such as the need to determine safe limits for caulerpin consumption in humans. Extraction for food preservatives may require minimizing caulerpin content if it is potentially toxic, or conversely, utilizing it in controlled doses for specific functional effects after thorough safety assessments. Regulation of natural preservatives also requires data on toxicology, stability, and interactions with food matrices, as emphasized for other plant extracts (Pinto et al., 2023; Karnwal & Malik, 2024).

2. Composition variability and standardization

The content of bioactive compounds in Caulerpa is greatly influenced by species and strain, location and harvest season, cultivation method (indoor/outdoor, sediment type, light intensity) (Stuthmann et al., 2023;Brix & Kunzmann, 2025). Studies have shown significant differences in the levels of minerals, pigments, and nutrient components of C. lentillifera between indoor and outdoor cultivation, as well as between different geographic locations (Stuthmann et al., 2023). Similar differences may occur for phenolics, caulerpin, and SPs. Therefore, preservative development programs should develop cultivation protocols to stimulate the production of target compounds (e.g., light exposure to enhance antioxidants) (Stuthmann et al., 2023), and establish quality standards (marker compounds, IC_{50}/antimicrobial activity range) for raw extracts.

3. Impact of processing and formulation

Drying and extraction methods affect yield and antioxidant activity. Air-drying versus sun-drying results in differences in moisture, ash, fat, carbohydrate, and antioxidant activity levels in Caulerpa sp. from Sapudi (Damayati et al., 2024). Subcritical water extraction in other green algae (Ulva, Caulerpa), it increases the yield of protein, sugar, phenolic compounds, and antioxidant capacity compared to conventional hot water extraction (Pangestuti et al., 2021). The preservative formulation (free vs. encapsulated extract, in film vs. directly on food) will determine stability, release, and sensory impact. Further research is needed on the effect of Caulerpa extract on the color, aroma, and flavor of food products (as sulfate and pigment components can affect sensory) (El et al., 2025; Karnwal & Malik, 2024). Dose optimization to achieve a balance between antimicrobial/antioxidant effectiveness and consumer acceptance.

4. Economies of scale and infrastructure

Studies on natural preservatives highlight that although they cost more than synthetic preservatives initially, the long-term benefits of reduced food waste, premium prices, and market acceptance can offset these costs (El et al., 2025; Singh et al., 2024). The development of sea grape preservatives requires an economic feasibility analysis (costs of cultivation, extraction, formulation) on an industrial scale, integration with regional development programs, for example seaweed clusters in Nusa Tenggara, Sulawesi, and Maluku, in order to utilize existing infrastructure and networks (Langford, 2023).

CONCLUSION

Sea grapes (Caulerpa spp.) have great potential as a natural preservative due to their bioactive compounds that inhibit oxidation and the growth of spoilage microbes, making them a safer alternative to synthetic preservatives. Furthermore, their use in edible coatings and active packaging offers opportunities for the development of more environmentally friendly food products. From an ecocentric perspective, the use of sea grapes should not be solely oriented towards human needs but should also ensure the sustainability of the marine ecosystem as a whole with intrinsic value. Caulerpa cultivation using the IMTA (Integrated Multi-Trophic Aquaculture) approach demonstrates that this algae can act as a biofilter that absorbs nutrient

waste, improves environmental quality, and simultaneously restores coastal ecosystems. However, the precautionary principle must be applied to potentially invasive species to prevent ecological disruption. From a socio-economic perspective, the development of a sea grape-based value chain can strengthen the economy of coastal communities and support Indonesia's blue economy. However, the success of this innovation still requires ensuring consumption safety, production standardization, sensory studies, extraction technology support, and clear regulations. Taking all these aspects into consideration, utilizing sea grapes as a natural preservative can be a strategic solution that not only promotes human health but also respects the sustainability of the ecosystem and provides justice for the entire ecological community. This approach reflects the essence of ecocentrism: humans thrive alongside nature, not at its expense.

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