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SPATIAL AND ECONOMIC ASYMMETRIES IN GLOBAL SEAWEED PRODUCTION AND TRADE: IMPLICATIONS FOR COASTAL DEVELOPMENT AND MARINE SPATIAL PLANNING

Abstract: This study investigates the spatial and economic asymmetries in global seaweed production and trade between 2003 and 2023, highlighting implications for coastal development and marine spatial governance. Using harmonized datasets from FAO FishStatJ, FAO Seaweed Insights, and FAO trade circulars, triangulated with UNCTAD reports and peer-reviewed literature, we analyze six producer categories: China, Indonesia, Republic of Korea, the Philippines, Other Asia, and Rest of World. Three comparative indicators were computed: global production share, export value share, and export value-to-volume ratio (USD/ton), enabling diagnosis of structural disparities and functional upgrading trajectories within the global value chain (GVC). Results reveal extreme spatial concentration: Asia accounts for over 98% of global seaweed output, dominated by China and Indonesia. However, value capture remains disproportionately low for these biomass leaders, reflecting reliance on raw or minimally processed exports. In contrast, Korea and the Philippines achieve higher export intensity through product upgrading (nori and carrageenan derivatives), while Rest-of-World suppliers secure premium markets for agar and specialty extracts. These asymmetries confirm persistent "commodity traps" in major tropical producers and underscore governance challenges associated with volume-driven growth. The discussion links these disparities to coastal development pathways, emphasizing the need for integrated Marine Spatial Planning (MSP), ecosystem-based aquaculture (e.g., Integrated Multi-Trophic Aquaculture), and blue economy strategies that combine downstream processing, spatial zoning, and inclusive finance. Without such interventions, rapid aquaculture expansion risks ecological degradation and social inequality. Conversely, leveraging niche specialization and technological upgrading offers pathways to sustainable, equitable blue growth.

Keywords: international trade dynamics, value chain upgrading, coastal spatial governance, sustainable aquaculture, bioeconomy strategies, ocean-based development

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Introduction

The Food and Agriculture Organization (FAO) of the United Nations has emphasized that marine resources hold a strategic position in current debates on sustainable development, climate change adaptation, and the spatial reconfiguration of coastal economies (FAO, 2024a). Within this broader ocean agenda, the United Nations Conference on Trade and Development (UNCTAD) highlights that seaweed aquaculture has gained global attention for its role in supporting emerging food systems, industrial biomaterials, and climate solutions, while simultaneously generating employment in coastal communities (Kajla et al., 2024; Farghali et al., 2023; Cai et al., 2021). As one of the fastest-growing marine biomass sectors, seaweed links biophysical productivity in nearshore waters with downstream bioeconomy industries, including hydrocolloids, nutraceuticals, packaging polymers, and agricultural inputs (Sekar et al., 2025; Rosenboom et al., 2022).

Seaweed cultivation also offers potential ecosystem co-benefits increasingly cited in blue economy policies: nutrient uptake and improved water quality; habitat structure; contribution to the carbon cycle and potential marine carbon interventions; and and buffer against coastal acidification (Alleway, 2023; Pessarrodona et al., 2024; Waqas et al., 2024). When cultivated within Integrated Multi-Trophic Aquaculture (IMTA) or regenerative coastal production systems, macroalgae can enhance nutrient recovery and reduce the environmental footprint compared to high-input aquaculture (Massocato et al., 2023). These environmental functions strengthen the argument for incorporating seaweed into spatial planning frameworks that align production objectives with ecological constraints. Beyond these ecological benefits, seaweed aquaculture holds substantial socio-economic importance for smallholder farmers and coastal communities throughout the Global South.

At the same time, seaweed aquaculture has significant socio-economic significance for the livelihoods of smallholder farmers and coastal communities throughout the Global South. Women's participation and household labor networks are well-documented in value chain case studies, and the global policy community is increasingly framing seaweed as an instrument for inclusive and gender-responsive blue development (UNCTAD, 2024; Hicks, 2025). National policy reviews emphasize the role of farmer cooperatives, rural employment, and export earnings in scaling up the sector—particularly in Indonesia and the Philippines (Permani et al., 2024; Department of Agriculture, Republic of the Philippines, 2015).

FAO production statistics show that global seaweed production increased from approximately 9.4 million wet tons in 2003 to >36 million tons in 2023, surpassing many other aquaculture commodities over the same period (FAO, 2025; FAO Fisheries and Aquaculture, 2023). This growth is highly uneven spatially: Asia provides the majority of global supply; China remains the long-term production leader; Indonesia surged after 2008 to become the second-largest producer; the Republic of Korea and the Philippines contribute smaller but steady volumes; the “Rest of Asia” adds scattered production; and the Rest of the World - Africa, Europe, the Americas, and Oceania—combined still accounts for <1% of total volume, despite recent expansions seen in Tanzania, Chile, and the Temperate Kelp Initiative (Magobe, 2025; Veenhof et al., 2024). However, this high concentration of production does not necessarily translate into proportional value gains in trade, and the economic geography of seaweed reveals a contrasting structure.

This clustering is enabled by favorable coastal geomorphology, seed supply networks, agricultural infrastructure, and targeted policy instruments, subsidies, seed distribution, export facilitation, and coastal licensing reforms, documented in leading producer countries (Permani et al., 2024; FAO, 2024a; Cai, 2021). However, spatial concentration also increases exposure to ecological risks and conflicts over use: disease outbreaks in dense agricultural clusters, nutrient accumulation, storm and heat stress, gear conflicts with fisheries and tourism, and competition for nearshore space in multi-use coastal zones (Waqas et al., 2024; Ewig et al., 2025). These pressures underscore the need to integrate seaweed expansion into Marine Spatial Planning (MSP) and broader integrated coastal management.

While production geography is well described, the economic geography of seaweed trade reveals a different pattern: biomass dominance does not guarantee value capture. Data compiled for this study show that China and Indonesia, despite commanding global tonnage, capture disproportionately lower shares of export value, consistent with a product mix dominated by raw or minimally processed materials and, for China, large domestic utilization (FAO, 2024b; Kang et al., 2023). By contrast, the Republic of Korea (Pyropia/nori) and the Philippines (carrageenan concentrates) obtain higher export value intensity (USD/ton) due to product and functional upgrading (Ababouch, 2022; Department of Agriculture, Republic of the Philippines, 2015). Premium niches for agar (Chile) and alginate or specialty extract products (selected European processors) further demonstrate that small volumes can command high prices when supported by processing technology, standards, and market differentiation (Farghali et al., 2023; UNCTAD, 2024). This divergence between volume dominance and value capture aligns closely with Global Value Chain (GVC) theory, which distinguishes between scale-driven primary production and higher-margin downstream activities.

These findings resonate with Global Value Chain (GVC) theory, which distinguishes between scale-driven primary production and higher-margin downstream activities, processing, refinement, formulation, branding, that capture a larger share of total value (Gereffi & Fernandez-Stark, 2016). Countries locked into exporting wet or sun-dried raw biomass risk functional lock-in, while those investing in extraction, product quality systems, and branded consumer goods move toward upgrading (Kang et al., 2023; Permani et al., 2024). Understanding where nations sit along this functional gradient is a central question in the economic geography of marine commodities.

While numerous reviews address seaweed technology, environmental services, or market prospects (Farghali et al., 2023; Sekar et al., 2025; Waqas et al., 2024), few integrate cross-regional and multi-decade quantitative data with a comparative spatial-economic perspective to examine how production concentration, export performance, and value intensity intersect with coastal development pathways and marine governance. The existing case literature is often country-specific or commodity-focused, resulting in limited comparative insights into how structural positions within seaweed GVCs reflect geography, policy, and environmental constraints. This analytical gap reduces the evidence base available to planners in emerging producer regions, many of which now view seaweed as an entry point to a diversified blue economy (FAO, 2024a; UNCTAD, 2024).

Guided by the above framing and data, this study pursues three interrelated objectives: (a) to map and quantify spatial patterns in global seaweed production and export value shares across major producer nations and regional groupings (2003–2023); (b) to calculate

and interpret export value intensity ratios (USD/ton) as indicators of product and functional upgrading in the global seaweed value chain; and (c) to relate observed spatial–economic disparities to coastal development pathways and Marine Spatial Planning (MSP), evaluating governance options to reconcile aquaculture growth with ecological integrity and equitable livelihood outcomes in coastal regions.

This research advances the field (Novelty) in three ways. First, it compiles a harmonized 2003–2023 global dataset across major producers (China, Indonesia, Republic of Korea, Philippines) and two comparative aggregates ("Other Asia," "Rest of World") by triangulating FAO FishStatJ extractions, FAO Seaweed Insights visualizations, FAO trade circulars, and UNCTAD sector analyses, cross-checked with peer-reviewed and industry literature. Second, it applies a geographical GVC framework operationalized through three indicators, global production share, global export value share, and export value-to-volume ratio (USD/ton)—to diagnose product/functional upgrading versus low-value lock-in. Third, it draws policy-relevant implications for coastal development and Marine Spatial Planning, identifying leverage points where emerging producer economies can align aquaculture expansion with environmental limits, spatial conflict management, and inclusive livelihood strategies.

Materials and methods

Study Design and Analytical Scope

This study combines quantitative reconstruction of global seaweed production and export value time series (2003–2023) with comparative ratio analysis and interpretive geographic synthesis. The quantitative component aggregates country-level wet-weight production data reported to the Food and Agriculture Organization (FAO) of the United Nations, harmonizes multi-source export value statistics, and computes derived indicators—production shares, export value shares, and export value intensity (USD per tonne). The interpretive component links observed disparities to global value chain (GVC) positioning, national policy trajectories, and coastal spatial governance challenges. The geographic scope is global; however, Asia is treated analytically as the structural core of seaweed aquaculture, with four top producers (China, Indonesia, Republic of Korea, Philippines) reported individually and two composite regional groupings (Other Asia; Rest of World) constructed for comparability across incomplete historical series.

Data Sources

Primary quantitative data were obtained from public FAO fisheries and aquaculture statistical resources and affiliated knowledge platforms:

1. FAO FishStatJ: Global capture and aquaculture production database; 2025 data pull (downloaded 17 July 2025) used to extract historical macroalgae aquaculture volumes (wet weight, tonnes) by country, 2003–2023 (FAO, 2025)
2. FAO Fisheries & Aquaculture / Seaweed Insights Portal: Curated visualization interface providing structured global seaweed production series by country and species group, aligned with FAO underlying data; used to cross-check country aggregates and identify classification logic for "Other Asia" and "Rest of World" (FAO Fisheries and Aquaculture, 2023)

3. FAO Newsroom Brief – Global Fisheries Record High: Contextual production and trade benchmarks cited for cross-validation of global aquaculture trends and consistency checks against FishStatJ totals (FAO, 2024a)
4. FAO Fisheries and Aquaculture Circular: International Markets for Fisheries and Aquaculture Products – Seaweed Trade and Market Potential: Core reference for export value data, market segmentation, product form definitions, and trade code correspondence (HS chapters) used in constructing value series (FAO, 2024b).

Supporting Peer-Reviewed and Sectoral Literature used to (i) validate sudden changes in country reporting, (ii) interpret product/functional upgrading, and (iii) document policy interventions affecting production scale or value capture. Key sources include Gereffi & Fernandez-Stark (2016) on Global Value Chain (GVC) frameworks; Kang et al. (2023) on competitiveness of China's seaweed exports; Farghali et al. (2023) on environmental and bioeconomic benefits of macroalgae systems; and Permani et al. (2024) on Indonesia seaweed industry policy alignment; and related regional/technical studies cited throughout.

Data Acquisition and Extraction Procedures

Production Volumes

Using FAO FishStatJ (2025 data release), we queried aquaculture production (quantities) for all macroalgae (seaweed) taxa reported under the Aquatic Plants production domain. Country totals were exported in wet weight (tonnes). Reported capture (wild harvest) macroalgae were inspected but excluded from country totals unless explicitly categorized as integrated within aquaculture statistics in FAO metadata; this exclusion prevents double counting in regions with mixed systems. Where FAO reported zero or blank values for a given year and country but adjacent years contained positive production and independent literature confirmed continuity of farming (e.g., smallholder Eucheuma in Tanzania), linear interpolation was not applied; instead, missing values were retained and addressed through regional aggregation (Regional Aggregation Rules). This conservative approach avoids imputational inflation.

Export Value Data

Seaweed export value data are scattered across FAO trade statistics, FAO market circulars, national statistical releases, and industry/region-specific value chain studies. We adopted a tiered sourcing hierarchy: (1) FAO Fisheries & Aquaculture Circular CD3717EN (FAO, 2024b) as the primary structured reference for international market valuations and HS code groupings; (2) FishStatJ trade matrices where commodity coding allowed attribution to macroalgae categories; (3) national or regional reports (e.g., National Research and Innovation Agency, Indonesia; CALABARZON Philippines value chain reports) for gap-filling (Department of Agriculture, Republic of the Philippines, 2015); and (4) peer-reviewed literature (e.g., Kang et al., 2023) for cross-checking magnitude and direction of export trends in major producing nations. Nominal values were recorded in current USD as reported by source; no inflation deflation was applied because (i) source heterogeneity made harmonized deflators unreliable across multi-currency inputs, and (ii) the analytical focus is on relative cross-country differences and trends in value intensity.

Literature-Derived Contextual Metadata

Country-level policy shifts, processing capacity build-outs, disease events, and species transitions were extracted from the peer-reviewed and gray literature to qualify interpretation of discontinuities in the quantitative series. These metadata do not alter numeric values in the dataset but inform discussion of structural drivers.

Regional Aggregation Rules

Because several Asian producing countries report intermittent or low volumes that individually fall below presentation thresholds in the Seaweed Insights portal, we constructed two composite groupings:

1. Other Asia: Aggregates all Asian seaweed-producing countries excluding China, Indonesia, Republic of Korea, and Philippines. Countries most consistently represented include (alphabetical): Bangladesh, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, India, Japan, Malaysia, Myanmar, Pakistan, Sri Lanka, Thailand, Viet Nam, and smaller reporting states.
2. Rest of World: Aggregates all non-Asian countries reporting seaweed production (aquaculture and, where reported in the same FAO macroalgae domain, managed harvest) including Africa (e.g., United Republic of Tanzania, Kenya, Madagascar, Mozambique, South Africa), Europe (e.g., Norway, France, Ireland, United Kingdom, Portugal, Spain, Denmark, Iceland), Latin America & Caribbean (e.g., Chile, Mexico, Peru, Brazil, Ecuador), North America (United States, Canada), and Oceania (Australia, New Zealand, Fiji, Papua New Guinea).

Regional totals were computed as the sum of available national records for each year. No imputation was made for non-reporting countries within a region-year; thus, regional series represent reported production rather than modeled production. This conservative rule produces lower-bound estimates but preserves transparency given heterogeneous national statistical capacity.

Data Harmonization and Cross-Validation

To reconcile discrepancies between the FAO FishStatJ extract and the graphical/tabular outputs of the Seaweed Insights portal, we implemented a three-step cross-validation procedure to ensure data consistency and reliability.

First, Direct Match Check: We compared annual raw country totals from FishStatJ against Seaweed Insights downloadable values, where accessible.

Second, Triangulation Adjustment: When the portal displayed aggregate category totals but underlying country-level details were inaccessible, we triangulated using three reference points: (i) the raw FAO FishStatJ extract, (ii) the UNCTAD–FAO An Ocean of Opportunities summary table (UNCTAD, 2024), and (iii) FAO's historical compilation from Zhang et al. (2022). This step was critical for verifying whether observed inflection points (e.g., Indonesia's surge post-2008) represented genuine production shifts or were data artifacts.

Third, Flagging Inconsistencies: Any year exhibiting >10% divergence between FishStatJ and secondary confirmation totals was flagged for review. In all flagged cases, FishStatJ figures were retained as the authoritative quantitative basis, given its status as FAO's primary statistical release.

Indicator Construction

Three derived indicators were constructed to enable cross-country comparison of production scale, global market position, and value-capture efficiency within the seaweed industry. Global Production Share (GPS) and Global Export Value Share (GVS) quantify each country's relative contribution to global aquaculture production and export value, respectively. Both indicators are expressed as the proportion of national values relative to the global total for the same year (FAO Fisheries and Aquaculture, 2023), allowing comparison of each country's production scale and strategic positioning within the international seaweed economy.

Export Value Intensity Ratio (EVIR) measures the export value captured per tonne of production, an indicator of efficiency in downstream processing, product differentiation, and value-added performance. EVIR is calculated as the nominal export value divided by production volume, producing a direct figure in USD per wet tonne (Kang et al., 2023). Because production and export value are consistently expressed in matching "million-scale" units in the working tables, the scalar cancels out, yielding a simplified form:

$$EVIR\ i,t = \frac{Vi,t\ (million\ USD)}{Pi,t\ (\text{million tonnes})}\ [USD/tonne] \quad (1)$$

where V,t is the export value (million USD) and Pi,t is reported production volume (million tonnes) for country i in year t.This indicator forms the basis for comparative assessments presented in Table 3.

Uncertainty, Data Quality, and Sensitivity Checks

Four classes of uncertainty affect cross-country comparability: (1) Reporting Gaps intermittent national submissions to FAO; (2) Moisture & Product Form Variation wet-weight production vs. traded dry, semi-refined, or extract products; (3) Commodity Coding Drift heterogeneity in HS categorization and aggregation of multi-species shipments; and (4) Currency/Price Effects nominal USD reporting without inflation adjustment. We evaluated directional sensitivity by testing EVIR under two hypothetical moisture conversion scenarios (±25% effective dry yield) in a spreadsheet model (results not shown; available on request); country rank order among major exporters remained stable except for marginal swaps between Indonesia and Philippines in high-moisture years, suggesting robustness of comparative interpretation at the order-of-magnitude level. Nonetheless, reviewers are cautioned that absolute USD/tonne values should be interpreted as indicative rather than definitive benchmarks.

Results

Global seaweed production and utilization volume 2003-2023

The search for global seaweed production volumes refers to the Global Production Volumes 2003–2023 data by country on the Seaweed Insights platform by FAO Fisheries and Aquaculture (2023), expressed in tonnes wet weight. Data tabulation was performed indirectly because the site was not fully accessible at the time of manuscript preparation. To this end, a combination of: (i) the concise documentation of Seaweed Insights/HATCH, (ii) the summary of global production statistics presented in the United Nations Conference on UNCTAD–FAO report, An Ocean of Opportunities (United Nations Conference on Trade and Development, 2024), and (iii) the scientific review of Zhang et al. (2022) that compiles

global seaweed production trends based on historical FAO data up to 2019. This triangulation approach allows for the reconstruction of the country aggregation logic used by Seaweed Insights and the mapping of countries into each group.

The “Other Asia” category in Table 1 is used to group all Asian seaweed-producing countries not shown individually in the graph. Based on the list of top producers presented by UNCTAD–FAO and the study by Zhang et al. (2022), countries most likely to fall into this category include: Democratic People’s Republic of Korea, Japan, Malaysia, India, Vietnam, Thailand, Myanmar, Bangladesh, Sri Lanka, Cambodia, Brunei Darussalam, and Pakistan (as well as other Asian countries with smaller volumes recorded in the FAO dataset). Individually, their contributions are relatively small, but collectively, this group—plus the four main countries constitutes nearly all of Asia’s production, which is the center of the global seaweed industry.

The “Rest of World” category includes all countries outside Asia that report seaweed production (farmed or wild-caught) to the FAO. According to the FAO’s latest figures-based Seaweed Insights mapping, the combined contribution of non-Asian regions is far below that of Asia less than 1% of global aquaculture production. Examples of countries in this group include: Africa (United Republic of Tanzania, Kenya, Madagascar, Mozambique, South Africa); Europe (Norway, France, Ireland, United Kingdom, Portugal, Spain, Denmark, Iceland); Latin America & the Caribbean (Chile, Mexico, Peru, Brazil, Ecuador); North America (United States, Canada); and Oceania (Australia, New Zealand, Fiji, Papua New Guinea). The UNCTAD–FAO report specifically places the United Republic of Tanzania, the Russian Federation, and Chile in the top 10 global producers after major Asian countries, highlighting that the rest of the world contributes a very small share of the volume.

Table 1 presents the development of global seaweed production volumes by country and major regional groups over the period 2003–2023, extracted from the Global Production Volumes 2003–2023 by Country dataset (FAO Fisheries & Aquaculture; tonnes wet weight) as published through the Seaweed Insights platform and supported by summary statistics in UNCTAD (2024) and FAO Fisheries and Aquaculture (2023). It should be noted that 2024 data were not yet available at the time of the analysis. The presentation structure separates the four largest producers—China, Indonesia, the Republic of Korea, and the Philippines from two regional aggregates: Other Asia and Rest of World. The volume distribution pattern over the observation period confirms Asia's dominance, particularly by China and Indonesia, while South Korea and the Philippines continue to make important contributions, albeit at smaller volumes. The Rest of Asia group which includes producers such as Japan, India, Vietnam, and Thailand adds the region's collective weight closer to the global total. In contrast, the combined contribution of the Rest of the World (e.g., Tanzania, Chile, Norway, and other coastal countries) remains relatively limited and reflects the early development of the seaweed industry outside Asia. This finding confirms that the global seaweed value chain remains highly geographically concentrated in Asia.

Table 1. Global Seaweed Production Volume 2003-2023

No.	Country	Production (million tonnes wet weight)				
		2003	2008	2013	2018	2023
1	China	7.50	8.74	11.75	17.39	21.65
2	Indonesia	0.23	2.15	9.30	10.32	9.75
3	South Korea	0.41	0.89	1.11	1.66	1.70
4	Filippines	0.99	1.66	1.56	1.48	1.63
5	Other Asia	0.15	1.02	1.14	1.17	1.12
6	Rest of World	0.15	0.14	0.15	0.15	0.30
Global Total		9.43	14.60	25.01	32.17	36.15

Note: 2024 data from the FAO Fisheries and Aquaculture Organization is not yet available.
Source: FAO Fisheries and Aquaculture (2023) and FAO (2025)

Global seaweed production has experienced rapid growth over the past two decades, increasing from 9.43 million tonnes in 2003 to 36.15 million tonnes in 2023, an increase of nearly 283%. China has consistently dominated global production throughout this period. In 2003, China accounted for approximately 79.53% of total production, with a volume of 7.50 million tonnes. By 2023, production had increased to 21.65 million tonnes, although its global share declined to approximately 59.89% (FAO Fisheries and Aquaculture, 2023) in line with significant growth in other producing countries. This dominance reflects China's position as a major hub of the global aquaculture industry (the percentages are presented in Figure 1).

Indonesia ranks second (2008-2023) as the world's largest seaweed producer, with significant growth over the past two decades. Production surged from 0.232 million tons in 2003 to 9.30 million tons in 2013, a nearly 40-fold increase in ten years. In 2013, Indonesia's contribution to global production reached 37.19%, placing it second only to China, compared to only 2.46% in 2003 when it was ranked fourth. This growth continued to reach 10.32 million tons in 2018, before declining slightly to 9.75 million tons in 2023 (FAO Fisheries and Aquaculture, 2023). This surge confirms Indonesia's position as a key player in meeting global seaweed demand, both for food consumption, animal feed, and as raw materials for processing industries such as alginate and carrageenan (The percentages are presented in Figure 1).

Besides China and Indonesia, other producing countries such as South Korea and the Philippines have shown relatively stable trends. South Korea recorded an increase in production from 0.417 million tons in 2003 to 1.70 million tons in 2023, representing an increase of approximately 307% over two decades. In contrast, the Philippines experienced fluctuations, with production peaking at 1.66 million tons in 2008 and declining to 1.63 million tons in 2023. The “Rest of Asia” group, which includes countries such as Japan, India, and Vietnam, contributed approximately 1.12 million tons in 2023, remaining relatively stagnant since 2013. Outside Asia, the contribution of countries such as Tanzania, Chile, and Norway remains very small, accounting for only around 0.30 million tons, or less than 1% of total global production. This fact confirms that the global seaweed industry remains highly concentrated in Asia (FAO Fisheries and Aquaculture, 2023).

The 'Rest of the World' group, which includes Africa, Europe, Latin America and the Caribbean, North America, and Oceania, shows a relatively small contribution to global seaweed production. As shown in Table 1, the production volume of this group reached only 0.148 million tons in 2003 and experienced minor fluctuations until 2018, ranging from

0.143 to 0.151 million tons. However, in 2023, production increased to 0.300 million tons (FAOFisheries and Aquaculture, 2023). Although its contribution accounts for less than 1% of the total global production, the UNCTAD - FAO report (UNCTAD, 2024) highlights several countries within this group such as the United Republic of Tanzania, the Russian Federation, and Chile as producers with potential to increase their capacity in the future. Overall, however, the role of non-Asian regions in the seaweed industry remains in a developmental stage and on a limited scale.

Global drivers and direction of seaweed industry development

According to the FAO Fisheries and Aquaculture (2023) and the UNCTAD (2024) reports, the growth of global seaweed production over the past two decades has been driven by a combination of industry demand, national policy incentives, innovation in cultivation technology, and the sustainable blue economy agenda. From a market perspective, the increasing demand for hydrocolloid raw materials alginate, carrageenan, and agar for the food, pharmaceutical, and cosmetics industries is driving the expansion of large-scale cultivation, particularly in Asia. This demand is reinforced by a consumer shift toward naturally based products and environmentally friendly additives that can replace certain synthetic ingredients.

In line with this, government policies play a key role in accelerating the expansion of the industry. Major producing countries such as China and Indonesia have integrated seaweed farming into coastal aquaculture development strategies, food security initiatives, export enhancement, and local economic empowerment. Policy instruments including input subsidies, the distribution of high-quality seedlings, strengthening of post-harvest supply chains, financial support, and facilitation of raw material exports for hydrocolloid production have helped expand cultivation areas and increase production volumes by engaging small-scale coastal communities. Recent policy analyses emphasize the importance of a national roadmap to harmonize cross-ministerial regulations and foster the coordinated development of the seaweed industry in Indonesia (Permani et al., 2024; FAO Fisheries and Aquaculture, 2023).

Advances in cultivation technology and environmental management have increased productivity while reducing ecological risks. The use of certified, high-growth seeds, more wave-resistant longline and sea raft systems, intensive husbandry, and improved harvesting and drying practices have reduced post-harvest losses and improved the quality of industrial raw materials. The Integrated Multi-Trophic Aquaculture (IMTA) approach, the implementation of quality and biosecurity standards, and life cycle assessment (LCA) are increasingly recognized as prerequisites for sustainable expansion. Scientific evidence demonstrates that seaweed cultivation has a relatively low carbon footprint, potential for nutrient mitigation, and contributes to climate change adaptation (Zhang et al., 2022; Farghali et al., 2023; Waqas et al., 2024; Alleway, 2023).

Downstream and bioindustrial development are expanding global economic prospects beyond traditional dry matter markets. Biorefinery technology now processes seaweed biomass into value-added products biopesticides, biochar, bioplastics, bioenergy, and agroecological inputs that support a circular economy, food security, and a low-carbon transition. This potential is crucial for developing countries seeking to enter global value chains without relying on raw material exports (Sekar et al., 2025; Farghali et al., 2023).

Beyond Asia, growth opportunities are linked to the blue economy agenda, coastal economic diversification, and gender inclusion. The UNCTAD report highlights countries such

as the United Republic of Tanzania, Chile, and even the Russian Federation as candidates for expansion if investment in cultivation, research into adaptive varieties, post-harvest quality improvement, and international market access are available. The FAO (2024a) adds that production expansion into new regions must be accompanied by environmental governance, monitoring of coastal ecosystem health, and producer-industry partnerships to ensure value chains remain sustainable.

Overall, cross-source evidence, such as that reported by Zhang et al. (2022), Permani et al. (2024), and Farghali et al. (2023), suggest that the future of the seaweed industry depends on the synergy between bioindustry-based global demand, inclusive policy support, and innovation in cultivation and post-harvest technologies. Furthermore, the integration of blue economy strategies that link environmental sustainability with coastal socio-economic opportunities is also a key factor (Waqas et al., 2024; Sekar et al., 2025; Alleway, 2023). This combination of factors will determine whether production remains concentrated in Asia or expands more evenly globally in the coming decades.

Global production by seaweed species

More than 12,000 seaweed species have been scientifically described, but only a very small fraction (approximately 0.1%) are commercially cultivated on a significant scale. A HATCH/Seaweed Insights analysis (Hatch Innovation Services, 2023), based on FAO statistics, shows that global aquaculture seaweed production is highly concentrated in a small number of species (Hermans, 2023; Rieve, 2023).

In the FAO Fisheries & Aquaculture production database, there are dozens of algae species listed under the aquaculture category. When microalgae entries are excluded, macroalgae items with no production volume are ignored, and species with very small outputs (e.g., <1,000 tonnes wet weight/year) are excluded, only about a dozen macroalgae species are actually operating at a commercial scale. This group of species, in aggregate, accounts for >95% of the volume and value of global seaweed production (Hatch Innovation Services, 2023; Rieve, 2023).

Seaweed Insights classifies the main cultivated species into five global commodity groups that reflect similar supply chains and industrial applications (Hatch Innovation Services, 2023; Rieve, 2023). First, the Eucheumatoids group includes Kappaphycus alvarezii, Eucheuma denticulatum, and Eucheuma spp. (including elkhorn sea moss and spiny eucheuma). Eucheumatoids are widely used as the primary source of tropical carrageenan. Second, the Saccharina group consists of temperate species such as Laminaria japonica, Saccharina latissima, and Laminaria digitata, which are extensively used as sources of alginate and food. Third, the Undaria group comprises Undaria pinnatifida (wakame), which is commonly consumed as a high-value food and industrial biomass. Fourth, the Pyropia group includes Pyropia yezoensis and Porphyra spp., which are consumed directly and processed into high-value dried products. Finally, the Gracilaria group Gracilaria spp. (including G. gracilis and G. verrucosa) is the primary raw material for agar production.

Collectively, these five groups account for approximately 95% of total global cultivated macroalgae production (FAO Fisheries and Aquaculture, 2023; Cai, 2021). According to Rieve (2023) and Hatch Innovation Services (2023), although these five major commodities have been commercially produced for nearly half a century, volume growth trends remain strong in many regions. Notably, Gracilaria has exhibited rapid volume expansion over the past decade, becoming one of the most aggressively growing groups in the global

market, signaling new opportunities for expansion within the agar supply chain and marine polysaccharide derivative products.

Main directions for seaweed utilization in the world

Globally, seaweed utilization follows three main paths. First, direct consumption as human food is a traditional form of use that still dominates in East and Southeast Asia. Seaweed is consumed in various processed forms, both fresh and dried, and is used in a variety of dishes due to its high nutritional content, distinctive umami flavor, and unique texture. The popularity of seaweed continues to increase with the trend of healthy eating and functional foods, as most species do not contain intrinsic toxins and are therefore safe for consumption (Cai et al., 2021; Rioux et al., 2017).

Second, seaweed is used as direct feed for high-value aquaculture organisms, such as abalone and sea urchins. This utilization plays a crucial role in supporting aquaculture productivity, particularly for species at lower trophic levels. Seaweed provides a natural nutrient source while helping create more sustainable aquaculture systems (FAO, 2018). Third, seaweed biomass is used as a raw material for the hydrocodone industry, producing high-value-added products such as alginate, agar, and carrageenan. These compounds are extracted from the cell walls of macroalgae and are widely applied in the food industry as thickeners, stabilizers, water binders, and gelling agents. They are also used in cosmetics, pharmaceuticals, textiles, printing, and the development of bioplastic materials and sustainable packaging (Kajla et al., 2024; Santana et al., 2024; Rosenboom et al., 2022; Saji et al., 2022; Abdul Khalil et al., 2017).

Seaweed trade value (exporters)

The global trade value of seaweed exports has experienced significant growth over the past two decades, driven by rising demand for hydrocolloid raw materials and biopolymer-based products. Table 2 presents data on export values and global market shares of the five leading exporters, along with the 'Rest of the World' category, for the period 2003–2023. Meanwhile, the distribution of each country group's contribution, expressed as a percentage of total global trade, is visualized in Figure 2 to provide a clearer comparative overview. Together, these data serve as the basis for analyzing market concentration, competitiveness dynamics, and diversification opportunities within the global seaweed value chain.

Table 2. Value of Seaweed Trade (Exports), Global 2003–2023

No.	Country	**Export value (million USD)**				
		2003	2008	2013	2018	2023
1	China (FAO, 2024b; Kang et al., 2023)	94	115	300	585	700
2	Indonesia (FAO, 2024b; National Research and Innovation Agency, 2024)	40	262	430	320	435
3	South Korea (FAO, 2024b; Ababouch, 2022)	80	150	231	310	400
4	Filippines (FAO, 2024b; Department of Agriculture, Republic of the Philippines, 2015)	50	120	195	252	295
5	Rest of World (FAO, 2025; 2024b)	25	50	120	185	290
Global Total		289	697	1276	1652	2120

The global trade value of seaweed exports has surged sharply over the past two decades, rising from USD 289 million in 2003 to USD 2.12 billion in 2023 an increase of more than 633%. A significant jump occurred between 2008 (USD 697 million) and 2013 (USD 1.276 billion), marking a phase of rapid expansion in the Asian seaweed industry and growing global demand for hydrocolloid-based products (alginate, carrageenan, agar). However, growth has leveled off since 2018, reflecting supply capacity constraints and limited product diversification.

China remains the largest exporter, with the highest trade value of USD 700 million in 2023. Its global share has fluctuated, dropping from 32.53% (2003) to 16.50% (2008), then rebounding to 35.41% (2018). This pattern reflects two key dynamics: (1) rising regional competition (particularly from Indonesia) during 2008–2013, and (2) China's strengthened downstream capacity through value-added processing after 2013, which restored its global market share.

Indonesia experienced explosive growth, from USD 40 million (2003) to USD 430 million (2013), before declining to USD 320 million (2018) and rising again to USD 435 million (2023). Its global share peaked at 37.59% in 2008, driven by the dominance of raw material exports (*Eucheuma* sp.) to China. However, the post-2013 decline reveals limited downstream processing and reliance on raw material markets, indicating that Indonesia's competitiveness is highly dependent on global prices and a still-suboptimal value chain structure.

South Korea grew from USD 80 million (2003) to USD 400 million (2023), maintaining a relatively stable share of around 18–21%, linked to its focus on premium processed products (*Pyropia*, gim) for both domestic and high-value export markets. The Philippines, while smaller than Korea, remains a key player with exports of USD 295 million (2023), a 14% share, and a strong position in the processed carrageenan industry.

The 'Rest of the World' category (including Chile, Tanzania, Norway, and others) rose significantly from USD 25 million (2003) to USD 290 million (2023), with its share increasing from 8.65% to 13.68%. This growth is primarily driven by Chile's expansion in the agar industry and the role of East African countries as suppliers of raw materials.

Comparison of export value intensity and production share in the global seaweed trade

Analysis of the global seaweed trade emphasizes not only production volume but also the economic value generated per ton. One indicator used to measure the economic efficiency of this product is the export value per ton ratio, which is calculated by dividing the total export value (in millions of USD) by the production volume (in millions of tons wet weight). This ratio provides an overview of value intensity, or the amount of export revenue generated from each ton of seaweed produced.

This measurement is crucial because, in commodity-based industries, high production volumes do not necessarily correspond to high export values. A country with a large production share may record a low value-per-ton ratio if its products are exported in raw form with minimal added value. Conversely, a country with a smaller production share can achieve a high ratio by focusing on derivative products with a higher degree of processing.

Therefore, comparing the export value-per-ton ratio with production share allows for a deeper analysis of producer countries' strategies within the global value chain and reveals potential shifts in competitiveness from a volume-oriented to a value-added orientation.

The results of this comparative analysis are presented in detail in Table 3, which compares export value-per-ton ratios with production shares for several major producer countries.

Table 3. Export Value-to-Volume Ratio (USD per Ton)

No.	Country	**Ratio (USD/ton)**				
		2003	2008	2013	2018	2023
1	China	12.53	13.16	25.53	33.64	32.33
2	Indonesia	172.41	121.86	46.24	31.01	44.62
3	South Korea	191.85	168.35	208.11	186.75	235.29
4	Filippines	50.76	72.29	125.00	170.27	180.98
5	Rest of World	168.92	349.65	794.70	1275.86	966.67
Global Average		30.65	47.74	51.02	51.35	58.64

The differences in export value per ton ratios between countries reflect the highly variable industry structure within the global seaweed value chain. China, as the largest producer, exhibits relatively low values per ton (USD 12.53–33.64). This pattern indicates the dominance of raw or semi-processed products marketed at low average prices, while high domestic consumption also reduces incentives to increase downstream exports.

In contrast, Indonesia started with a very high ratio in 2003 (USD 172.41) due to limited exports but high commercial value. However, this ratio declined drastically with the surge in production from 2013–2018, reflecting a commodity-driven orientation without a corresponding increase in value-added processing. This situation highlights the risk of "functional lock-in" at the lower end of the value chain, where control is limited to raw material supply.

South Korea consistently maintained the highest ratio among major exporters (168–235 USD/ton), even increasing in 2023. This advantage is related to the dominance of premium processed products such as Pyropia (nori), which is marketed in ready-to-eat form, providing significant pricing leverage. The Philippines showed a significant upward trend (50.76 → 180.98 USD/ton), in line with the strengthening of its processed carrageenan industry for export. Both countries emphasized the importance of domestic processing capacity to optimize export value despite limited volumes.

The 'Rest of the World' group shows the most extreme ratio (USD 168 → >1,200 per ton) despite its small volume contribution. This phenomenon is driven by a focus on niche products such as agar, alginate, pharmaceutical ingredients, and cosmetics targeting premium markets with high quality standards (Europe, North America). This fact reinforces the argument that product specialization and innovation are key drivers of global competitiveness, rather than production scale alone.

Following the examination of variations in export value-per-ton ratios across countries in Table 3, which indicate disparities in downstream efficiency and product strategies, the next analysis focuses on the comparison between production share and global export value share (as presented in Figures 1 and 2). This approach aims to assess the extent to which dominance in production volume translates into control over trade value. This indicator is crucial, as it reveals the structural position of each country in the global value chain whether scale-based advantages align with value contributions, or whether imbalances exist, signaling a functional lock-in at lower value-added segments.

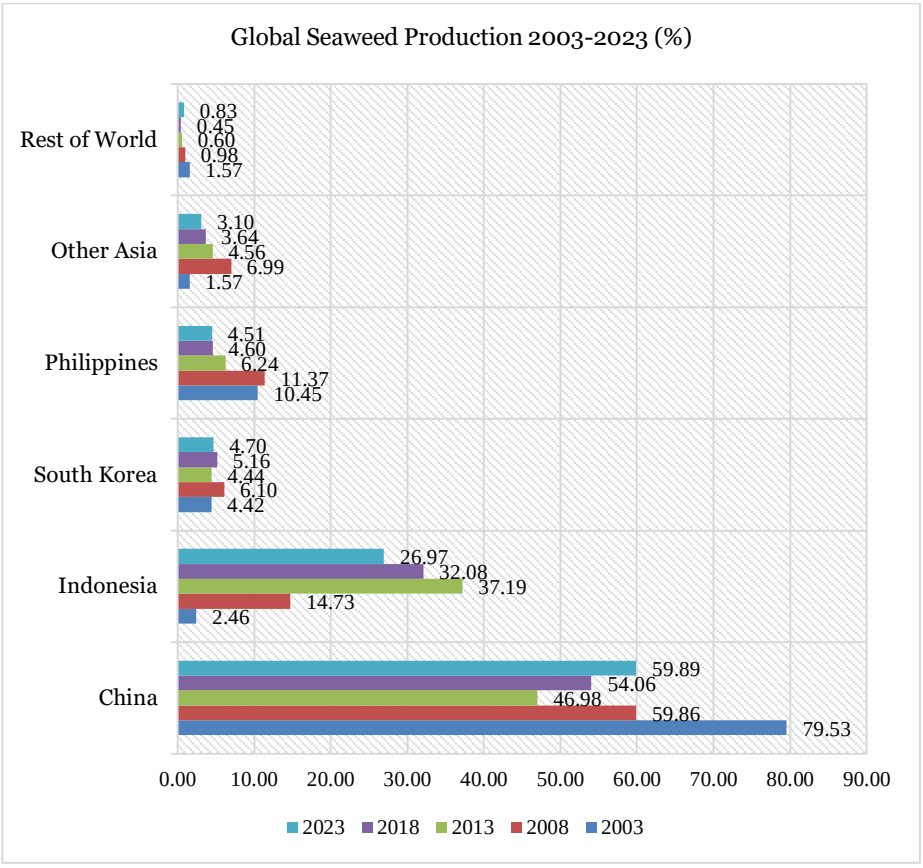


Fig. 1. Percentage of global seaweed production volume 1990-2023 (Source: FAO 2025; FAO Fisheries and Aquaculture, 2023)

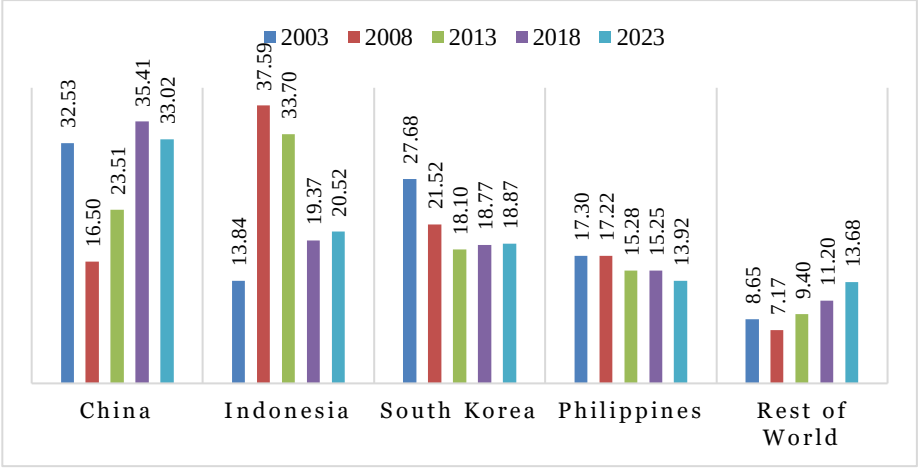


Fig. 2. Percentage of global seaweed trade (exports), 2003–2023

Considering the data presented in Figures 1 and 2, it is found that the comparison of global production share with export value share confirms the existence of a structural imbalance among seaweed-producing countries. China, for example, controlled almost 80% of global production in 2003 and remained dominant (47–60%) throughout the period, but contributed only 16–35% to world export value. This imbalance indicates that biomass scale does not automatically translate into control of trade value—a characteristic of the fragmented GVC of biological commodities, where economic value is created more in the downstream stages (refining, processing, product formulation, branding) than in primary production (Gereffi & Fernandez-Stark, 2016; UNCTAD, 2024). A study by the FAO (2024) also confirmed that China prioritizes domestic consumption and export of low-value raw materials over product differentiation.

Indonesia experienced a dramatic transformation: its share of global production rose from 2.5% (2003) to 37.2% (2013), tying with China for tropical biomass (Eucheuma/Kappaphycus). However, its share in export value did not increase proportionally (33.7% in 2013; down to 19.4% in 2018), indicating commodity-driven expansion without adequate functional upgrading. This phenomenon is related to the dependence on dried seaweed exports to foreign processing centers (FAO, 2024). Policy analysis emphasizes the need for a national roadmap for downstreaming through investment in carrageenan processing, improving raw material quality, and integrating domestic supply chains (Permani et al., 2024).

South Korea's export value share is significantly larger than its production share: only 4–6% of global production, but 18–22% of trade value in most years. This advantage is related to the innovation of ready-to-eat products (Pyropia/nori) and the integration of premium markets (Ababouch, 2022; FAO, 2024). The Philippines follows a similar pattern, with the processed carrageenan industry as a pillar of competitiveness. The decline in production share (10.4% → 4.5%) was not accompanied by a drastic decline in value share (17.3% → 13.9%) because domestic processing remained strong (Cai, 2021). Both cases support the thesis that processing capabilities and product branding determine position in GVCs more than simply production scale.

The 'Rest of the World' countries contributed less than 2% of global production until 2018, yet their value share increased from 8.7% (2003) to 13.7% (2023). Niche product strategies—such as agar and alginate from Chile, cosmetic and pharmaceutical extracts from Europe, and premium-grade materials for North American markets have driven significantly higher prices per ton (>USD 900/t in 2023). Studies by UNCTAD (2024) and Farghali et al. (2023) confirm that market-specific innovation and quality certification can penetrate the dominance of high-volume producers, emphasizing a quality-driven trade model as a source of competitive advantage.

These findings align with the concept of upgrading within the Global Value Chains (GVC) framework as outlined by Gereffi and Fernandez-Stark (2016). Countries that rely on raw material exports tend to experience functional lock-in, a condition in which their trade value share consistently lags behind their production share. This pattern is particularly evident in China and, during certain periods, Indonesia. Conversely, countries that diversify their products and engage in value-added processing such as South Korea, the Philippines, and some 'Rest of the World' countries demonstrate indicators of product and functional upgrading, as reflected in export value shares that consistently surpass their production shares (Waqas et al., 2024; Alleway, 2023).

These insights underscore critical policy implications: to enhance foreign exchange earnings and competitiveness, tropical biomass-producing countries need to accelerate downstream development through the advancement of hydrocolloid extraction technologies, the adoption of international quality standards, and innovation in bioindustry products (Permani et al., 2024; UNCTAD, 2024).

Discussion

Reconstructed cross-source data reveal a pronounced geographical concentration in global seaweed production: China and Indonesia have dominated world volumes throughout 2003–2023, while South Korea and the Philippines maintain important yet significantly smaller roles. Combined non-Asian regions have remained below 1% of global output until the end of the period, although they show recent signs of growth. This pattern reflects a core periphery structure within the global seaweed economy, where biophysical advantages (tropical/subtropical waters, optimal salinity, and coastal land availability) and targeted coastal policy interventions have driven the emergence of large-scale aquaculture clusters in Asia. Indonesia's post-2008 production surge from a small base to becoming the world's second-largest producer underscores how coastal policy incentives, access to seedstock, and export markets can transform rural coastal areas into global commodity production landscapes, while simultaneously increasing exposure to climate risks and price volatility (FAO, 2024a; UNCTAD, 2024).

Despite the large biomass scale, not all producers have successfully translated volume dominance into trade value leadership. A comparison of production data with export values and USD/ton ratios highlights a structural gap: China and Indonesia supply the largest volumes but rank relatively low in value intensity; conversely, South Korea and the Philippines, with smaller volume shares, capture a much larger portion of export value due to their focus on premium processed products (e.g., Pyropia/nori, refined carrageenan) and strong brand positioning in high-value markets. The "Rest of World" category—including Chile, Tanzania, and several niche European producers—shows exceptionally high value-per-ton ratios, reflecting specialization in agar, alginates, pharmaceuticals, cosmetics, and differentiated quality products. This configuration aligns with the Global Value Chain (GVC) framework, which posits that downstream stages (refining, extraction, formulation, branding) absorb the highest share of value, while upstream, volume-based segments risk functional lock-in if upgrading does not occur.

The Indonesian case demonstrates a non-linear transition: the value-per-ton ratio was high in 2003 when exports were still limited, then fell sharply when biomass expansion accelerated without balanced downstreaming. More recently, there has been a resurgence of industrial downstreaming initiatives, factory revitalization, and discussions of a cross-ministerial national roadmap to strengthen domestic processing, quality standards, and market connectivity. Cross-jurisdictional challenges—decentralization, maritime zoning, industrial logistics, and policy coordination—have been identified as key obstacles in recent policy literature; however, machinery support, investment incentives, and international partnerships (with China, Singapore, and development institutions) are beginning to be directed toward reducing dependence on raw material exports (Permani et al., 2024; Indonesia Business Post, 2024).

The volume-value gap is also related to domestic market structure and internal consumption. China maintains a large production base, largely absorbed by the domestic market and/or traded in relatively low-priced forms. The recovery in value share after 2013 is likely related to the expansion of hydrocolloid processing capacity and processed seafood products in the internal market, which then enter exports. The fluctuating movement of China's value share relative to global volume share confirms that production size alone is not a determinant of value competitiveness; downstream industry structure and market integration play a key role (FAO, 2024a; UNCTAD, 2024).

From the perspective of coastal development geography, the spatial–economic asymmetries revealed in this study namely Asia's dominance in production volume but a disproportionate capture of export value raise fundamental questions about the development trajectory of coastal communities in emerging economies. Can resource-based expansion (through increasing cultivation area and biomass tonnage) be transformed into innovation-driven development that enhances local incomes and reduces vulnerability? Escaping the "commodity trap" requires investments in biorefineries, biomaterials, functional foods, biofertilizers, and other health and industrial products that expand downstream margins. Policy experiences in Indonesia and the Philippines highlight the pivotal role of producer cooperatives, quality standardization, and cross-ministerial support in facilitating upgrading (Permani et al., 2024; Department of Agriculture, Republic of the Philippines, 2015). The FAO's Blue Transformation agenda positions social inclusion particularly the participation of women and household enterprises as a prerequisite for ensuring a fairer distribution of seaweed value chain benefits across the Global South (UNCTAD, 2024; Hicks, 2025).

The spatial concentration of cultivation in densely farmed bays and lagoons amplifies ecological pressures and conflicts over marine space. Cross-study evidence points to risks of nutrient accumulation, disease outbreaks, impacts from extreme weather events, and interactions with small-scale fisheries, tourism, habitat conservation, and marine energy infrastructure (Waqas et al., 2024; Ewig et al., 2025). Marine Spatial Planning (MSP)—or data-driven marine zoning offers a framework to align seaweed farming areas with ecological carrying capacity, shipping routes, conservation zones, and community access rights. The integration of site suitability modules (bio-physical and social), measurable nutrient load thresholds, and multi-decade climate change scenarios should become explicit components of MSP in regions experiencing rapid seaweed expansion (Veenhof et al., 2024; Massocato et al., 2023). Practices such as Integrated Multi-Trophic Aquaculture (IMTA) can serve as adaptive zoning instruments, linking extractive macroalgae with higher-trophic species to enhance nutrient uptake while maintaining multi-product economic value.

The climate change dimension reinforces the urgency of spatial planning. Projections of ocean warming, marine heatwaves, and storm variability threaten seaweed farm productivity, raw material quality, and supply chain stability (Pessarrodona et al., 2024; Alleway, 2023). While the carbon storage pathways of macroalgae remain contested in formal accounting, substitution benefits such as reducing synthetic agricultural inputs, lowering methane emissions from livestock feed, and replacing fossil-based polymers can deliver indirect climate value relevant to blue finance mechanisms (Farghali et al., 2023; Rosenboom et al., 2022). Access to innovative financing instruments (e.g., blended finance, blue credits tied to ecosystem services, and climate-linked outcomes) is crucial to closing investment gaps in climate-resilient farming technologies, downstream processing facilities, and environmental verification systems (Hicks, 2025). MSP that integrates climate risk modules

can prioritize sheltered farming sites, spatial rotation, and disaster contingency plans to safeguard the livelihoods of low-income coastal communities.

The recent albeit small rise in value contributions from the "Rest of World" group signals opportunities for geographic diffusion of the seaweed industry beyond Asia. The cases of Tanzania (tropical seaweed for carrageenan), Chile (agar), and mid-latitude kelp initiatives in the North Atlantic illustrate niche upgrading strategies: prioritizing high quality, compliance with strict standards, and premium market access rather than pursuing sheer volume (Magobe, 2025; Veenhof et al., 2024). For coastal planners, this opens pathways for staged development starting with high-value pilot clusters, expanding through regional producer–processor networks, and anchored by MSP frameworks that protect ecosystems and community access rights. A cross-scale approach local, national, and transboundary is essential as seaweed trade chains have become global and are increasingly vulnerable to logistical disruptions and international sanitary regulations (FAO, 2024b; UNCTAD, 2024).

Overall, our evidence suggests that highly concentrated spatial distribution of production does not automatically translate into a balanced distribution of economic value. To avoid "low-value lock-in," biomass-producing countries need to move on four integrated policy fronts: (i) product and function upgrading (processed hydrocolloids, biomaterials, high-value foods); (ii) marine and coastal spatial planning that internalizes ecological boundaries and multi-actor use rights; (iii) inclusive financing and investment incentives for downstreaming and innovation; and (iv) a global collaborative framework open data, quality standardization, socio-environmental certification that empowers small-scale producers and improves the distribution of value margins (Permani et al., 2024; UNCTAD, 2024). This integrated policy direction will determine whether the seaweed industry develops as a vector of ecologically resilient and socially equitable coastal development, or remains a low-value, volume commodity on the fringes of global value chains.

Implications

The dominance of production volumes by a few Asian hotspots combined with export value disparities and signs of functional lock-in among raw biomass suppliers highlights the need for more integrated cross-sectoral national policy interventions. For major tropical producers particularly Indonesia a strategic priority is to align the seaweed industry roadmap with marine spatial planning frameworks (RZWP3K/MSP), provide downstream processing incentives, and expand access to financing for the establishment of domestic processing facilities (e.g., carrageenan, agar, biostimulants, bioplastics, bioenergy) (Permani et al., 2024; Indonesia Business Post, 2024). These measures are key to escaping the low-value trap, as production scale alone is insufficient to enhance global competitiveness.

The spatial concentration of aquaculture in dense clusters also heightens the sensitivity of coastal ecosystems to ecological impacts such as nutrient accumulation, disease outbreaks, and marine space-use conflicts. Therefore, integrating aquaculture data into Marine Spatial Planning (MSP) and implementing Integrated Multi-Trophic Aquaculture (IMTA) must become priority agendas to ensure ecological carrying capacity while improving value chain efficiency (Ewig et al., 2025; Massocato et al., 2023). This approach enables multi-functional GIS-based space allocation and optimizes the biofiltration function of macroalgae to reduce nutrient loads.

In addition, there are opportunities for a measured diversification of global production regions. The rising value contribution from the "Rest of World" group indicates that the

development of high-value niche markets can be pursued in East Africa, Latin America, and temperate latitudes, provided that quality standards, biosecurity measures, and international certifications are met (Magobe, 2025; UNCTAD, 2024). This strategy allows these countries to integrate into global value chains through premium processed products (e.g., agar, alginates, cosmetic ingredients) without having to compete on the same production scale as Asia.

Ultimately, the success of this sector's transformation will heavily depend on an inclusive Blue Economy agenda one that links bioindustry innovation with improvements in coastal household incomes, women's empowerment, and the achievement of cross-cutting SDG targets (food, environment, climate, gender equality) (Hicks, 2025). Global evidence shows that women's participation in the seaweed value chain remains constrained by limited access to technology and capital, making socially just interventions (blue justice) and innovative financial instruments (such as blended finance and blue credits) essential to avoid reproducing entrenched inequalities.

Conclusion

This study reveals that global seaweed production increased significantly from 2003 to 2023, but the distribution of economic benefits remains spatially uneven. Although Asia dominates global biomass supply, particularly China and Indonesia, these countries fail to capture proportional export value due to functional lock-in in low-value-added chain segments. In contrast, countries with smaller production volumes, such as the Republic of Korea and the Philippines, demonstrate higher export value intensity by adopting product and functional upgrading strategies, including hydrocolloid processing and branded nori production. New suppliers from Latin America and Africa also represent opportunities for niche, high-value markets. These dynamics underscore the structural disconnect between production scale and economic returns, highlighting the need for an integrated strategy linking value chain upgrading, spatial governance, and blue economy resilience.

This analysis confirms six key findings. First, Asia remains the global hub of seaweed biomass, while non-Asian regions represent only a marginal share despite recent growth. Second, Indonesia experienced a rapid production surge after 2008, followed by stagnation, with limited progress in functional upgrading. Third, there is a persistent disconnect between the scale of production and the capture of trade value, particularly in China and Indonesia. Fourth, countries with effective industrial upgrading strategies, such as Korea and the Philippines, secure higher export values relative to volume. Fifth, non-Asian suppliers achieve premium prices through quality-oriented niche strategies despite small volumes. Finally, intensive agricultural clusters in coastal Asia pose ecological and spatial risks, reinforcing the need for integrated marine spatial planning (MSP) and an ecosystem-based approach.

These findings suggest that simply increasing production scale is insufficient to achieve sustainable economic benefits. For leading biomass suppliers like Indonesia, policy interventions should prioritize downstream processing, technology upgrading, and market diversification to avoid the low-value commodity trap. Furthermore, coastal production zones need to be integrated into the MSP framework to manage environmental risks and multi-use conflicts, while encouraging innovative systems such as Integrated Multi-Trophic Aquaculture. Developing regions can benefit from quality-based strategies supported by

certification, biosecurity standards, and targeted investments. Finally, inclusive blue economy initiatives, including gender-responsive financial access and cooperative processing models, are crucial to ensure equitable value distribution and socio-economic resilience in coastal communities.

Limitations and future research directions

This study faces several limitations. First, limited data availability necessitated the reconstruction of production series from multiple secondary sources, which may introduce aggregation bias. Second, the absence of the 2024 FAO update limits trend validation, while potential revisions in historical reporting could alter country rankings. Third, export value data comes from heterogeneous sources with different product classifications and conversion factors, affecting comparability. Fourth, inferences about functional improvements rely more on secondary literature than on factory-level verification. Finally, the ecological consequences of seaweed expansion are addressed qualitatively but lack quantitative environmental impact modeling across countries.

Further studies should integrate high-resolution spatial mapping with remote sensing and permitting data to assess coastal production density and ecological vulnerability. Standardizing wet-to-dry conversion factors and harmonizing trade classifications would improve the comparability of volume-value metrics across countries. Longitudinal case studies are needed to track policy instruments enabling value chain upgrading. Furthermore, socioeconomic research should address gender dimensions and community-level benefit sharing in the blue economy. Future research should also utilize coupled human-environment models to evaluate trade-offs between production growth, marine ecosystem services, and spatial governance under climate change scenarios. Finally, quantifying carbon sequestration and the life-cycle benefits of seaweed-based bioproducts could attract blue finance and accelerate the transition to a circular bioeconomy.

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Data Availability: All datasets used in this study are publicly accessible through FAO Fisheries and Aquaculture Statistics and associated portals (FAO, 2023–2025). No proprietary or restricted data were used.

Conflicts of Interest: The authors declare no conflict of interest.

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