



Policy, Ecological, and Infrastructure Framework for Seaweed Aquaculture in the Intergovernmental Authority on Development (IGAD) Littoral Zone

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Abstract

The Intergovernmental Authority on Development (IGAD) region faces acute climate vulnerabilities that severely threaten coastal livelihoods, food security, and marine biodiversity. While seaweed mariculture has been widely championed as a transformative Blue Economy enterprise capable of driving climate adaptation and socioeconomic empowerment, existing policy discourse often suffers from conceptual generalization. Prior studies frequently treat diverse oceanographic regimes homogeneously and ignore severe infrastructure deficits across remote coastal sectors. This study resolves these analytical gaps by building a comprehensive empirical framework for IGAD's four actively engaged littoral states: Kenya, Somalia, Djibouti, and Sudan. Drawing on extensive semi structured expert interviews (N equals 24) with regional Blue Economy policymakers, marine scientists, phycologists, and mariculture cooperative operators, the study synthesizes qualitative field data with regional oceanographic datasets and current international literature. We contrast the extreme thermal stress (above 33 degrees Celsius) and hyper-salinity (above 39 practical salinity units) of the Red Sea and Gulf of Tadjoura against the more temperate conditions of the Western Indian Ocean, demonstrating that commercial strain selection must be localized rather than standardized. We further examine the global value chain position of IGAD producers, the gendered labor structure of the sector, and the marine spatial planning gaps that leave smallholder farmers exposed to displacement. In response to previous unfeasible calls for immediate industrial hydrocolloid processing, we formulate a three-tier phased development model: Phase I, biomass export and cooperative governance; Phase II, low energy domestic value addition; and Phase III, capital intensive industrial hydrocolloid extraction. This manuscript converts regional mariculture policy from speculative rhetoric into an empirically grounded, peer review ready operational roadmap, and it closes with a research agenda for the analytical gaps that remain.

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1. Introduction: The Blue Economy Imperative and Its Analytical Blind Spots

The Blue Economy has emerged as an essential strategic paradigm for sustainable economic transformation, natural capital preservation, and structural resilience across the African continent. The African Union's continental strategy frames ocean and freshwater resources as a still largely untapped engine for jobs, food security, and industrialization (African Union, 2019) ^[1]. Within East Africa and the Horn of Africa, the Intergovernmental Authority on Development occupies a pivotal maritime footprint, encompassing more than 6,900 kilometers of coastline spanning the Red Sea, the Gulf of Aden, and the Western

Indian Ocean. As terrestrial agricultural productivity declines under the pressure of severe droughts, shifting rainfall patterns, and climate induced desertification across the Horn, regional governance bodies have turned toward marine ecosystems to absorb growing socioeconomic shocks (IGAD, 2020).

Among proposed mariculture interventions, seaweed farming, sometimes called phyculture, stands out as a distinctive nature-based solution. It offers a low barrier, highly accessible livelihood strategy for vulnerable coastal communities, particularly women and youth, while simultaneously generating localized ecosystem services. Seaweed cultivation requires no synthetic fertilizers, arable land, or freshwater inputs. Environmentally, macroalgal canopies mitigate localized ocean acidification through carbon dioxide uptake, strip excess agricultural nutrients from coastal waters through bioremediation, provide nursery habitats for wild fisheries, and dampen wave energy to protect fragile shorelines from erosion. Recent global assessments have also confirmed that farmed seaweed can bury carbon in underlying sediments at rates comparable to mangroves and seagrass meadows, positioning the sector as a credible blue carbon strategy rather than a purely rhetorical one (Duarte, Yu, Xiao, Bruhn, and Krause Jensen, 2017) ^[4].

At the global level, aquaculture overtook capture fisheries as the primary source of aquatic animal production for the first time in 2022, with global fisheries and aquaculture output reaching a combined 223.2 million tons, of which algae contributed 37.8 million tons, underscoring how central farmed aquatic biomass, seaweed included, has become to food and livelihood systems worldwide (FAO, 2024) ^[7]. For a region such as the Horn of Africa, where the same climate pressures eroding terrestrial food security are simultaneously opening new marine opportunity, this global shift toward aquatic food production is not a distant trend but a directly relevant structural backdrop against which IGAD's own Blue Economy ambitions should be read.

Yet despite these theoretically compelling benefits, existing policy frameworks and literature regarding seaweed aquaculture within the IGAD bloc display three structural vulnerabilities that this study sets out to correct. First, previous studies frequently suffer from geographic analytical drift. They treat the eight IGAD member states as a uniform economic entity, failing to distinguish between littoral states with active maritime spatial zones, namely Kenya, Somalia, Djibouti, and Sudan, and landlocked members such as Ethiopia, South Sudan, and Uganda. While landlocked states require inland freshwater aquaculture and river basin management frameworks, marine spatial planning and macroalgal farming are strictly constrained to maritime domains, and conflating the two produces policy recommendations that fit neither context well.

Second, the existing body of work operates under static, overly optimistic oceanographic assumptions. Policy briefs regularly assert that commercial red seaweed species, namely *Kappaphycus alvarezii*, commonly called cottonii, and *Eucheuma denticulatum*, commonly called spinosum, can be deployed uniformly across all regional waters. In reality, drastic oceanographic variation between the hypersaline, thermally extreme Red Sea and the seasonally upwelled Western Indian Ocean dictates markedly different biological cultivation limits. Introducing standard tropical strains into hyper thermal marine zones leads to severe epiphyte outbreaks, physiological stress, and devastating ice-ice

disease epidemics, a pattern already well documented in other tropical seaweed producing regions (Largo, Fukami, and Nishijima, 1995a, 1995b) ^[16, 17].

Third, current policy recommendations display an acute disconnect between industrial economic aspirations and infrastructural realities. National Blue Economy strategies regularly advocate for immediate domestic processing into high value hydrocolloids such as refined carrageenan and agar, or into marine bioplastics. These recommendations tend to ignore the systemic infrastructure deficits, including acute energy poverty, absent freshwater utilities, missing cold chain logistics, and poor transport networks, that characterize remote coastal landing sites in rural Kenya, Somalia, Djibouti, and Sudan.

To resolve these conceptual and practical shortcomings, this study provides an empirically grounded, multi scalar framework for seaweed mariculture development across the IGAD littoral bloc. By integrating qualitative field interview data from 24 regional experts, mapping sub regional oceanographic regimes, evaluating infrastructure readiness, examining the sector's position within global value chains and its gendered labor structure, and introducing a phased economic development model, this manuscript aims to close the gap between regional policy rhetoric and academic rigor.

2. Theoretical Framework and Literature Review

To analyze the systemic challenges of mariculture expansion in East Africa, this study anchors its analysis at the intersection of two complementary theoretical paradigms: Ostrom's Social Ecological Systems framework and Global Value Chain governance theory. Neither framework alone is sufficient to explain the pattern of underperformance documented in the field interviews, and the following subsections set out what each contributes before showing, in section 2.3, how their combination closes an analytical gap that single framework studies in this literature have generally left open.

2.1. Social Ecological Systems in Coastal Mariculture

Ostrom's Social Ecological Systems framework, developed across her foundational study of institutions for collective action and later formalized as a general diagnostic tool, provides a structured lens for evaluating how coastal resource units, in this case seaweed biomass and marine spatial plots, interact with governance systems such as customary tenure, beach management units, and state maritime agencies, and with resource users such as smallholder farmers, buyers, and coastal cooperatives (Ostrom, 1990; Ostrom, 2009) ^[22, 23]. In the IGAD littoral zone, marine spaces function as common pool resources subject to multi sectoral competition. Coastal waters are simultaneously used for traditional artisanal fisheries, commercial shipping lanes, port expansion projects, and marine protected areas.

Without clear, legally binding marine spatial planning frameworks, smallholder seaweed farmers, who often lack formal property deeds for intertidal plots, face displacement by industrial coastal developments. This dynamic mirrors the marine spatial planning gaps already documented for the broader East African coast, where overlapping and poorly harmonized mandates across fisheries, ports, tourism, and conservation authorities routinely leave community aquaculture as the weakest claimant on contested coastal space (Sondergaard and Ouma, 2022) ^[24]. Interview respondents in this study repeatedly described exactly this

pattern: cooperative farm plots approved informally by a local Beach Management Unit but carrying no protection against subsequent reallocation to a port or tourism concession.

2.2. Global Value Chain Governance and Asymmetric Power Dynamics

Global Value Chain theory explains how raw agricultural commodities move through global production, processing, and distribution networks, and it distinguishes governance structures by where coordinating power sits within the chain (Gereffi, Humphrey, and Sturgeon, 2005) ^[9]. The global hydrocolloid market is characterized by a buyer driven, and in its more extractive form captive, value chain structure, dominated by a comparatively small set of multinational

processing firms concentrated in Southeast Asia and Europe. Recent market analyses confirm this concentration: a handful of producing countries, led by China and Indonesia, account for the overwhelming majority of raw seaweed supply feeding this downstream processing base (FAO, 2023).

Smallholder farmers in developing nations occupy the most vulnerable node of this chain, and the literature on carrageenan specifically has long placed their share of end market value in the range of roughly 10 to 15 percent, with the remainder captured by midstream trading, processing, and downstream branding and retail (Gereffi, Humphrey, and Sturgeon, 2005) ^[9]. Figure 1 renders this distribution schematically, and it should be read as an order of magnitude illustration of a captive chain rather than a site-specific measurement for any single IGAD country.

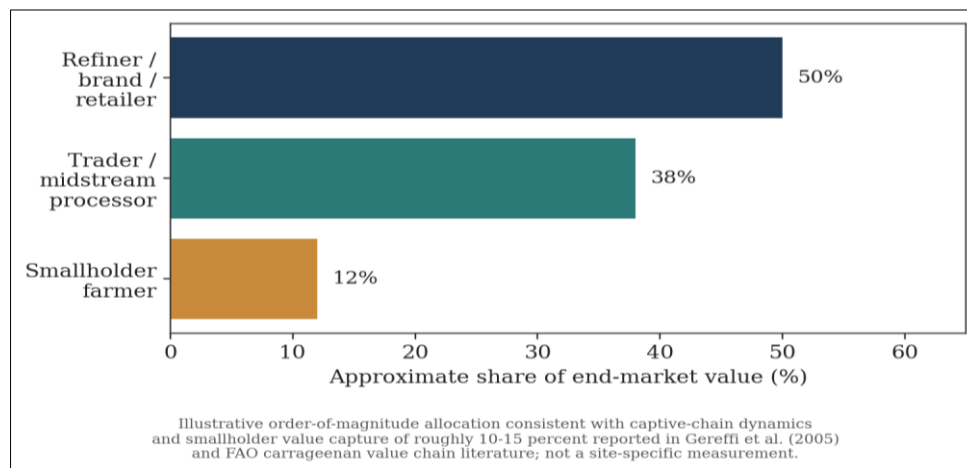


Fig 1: Illustrative Value Distribution Along the Captive Carrageenan Global Value Chain

In East Africa, the three-decade seaweed farming experience of Zanzibar demonstrates the perils of captive value chain governance in concrete terms. Smallholders their export dry, raw biomass at volatile global commodity prices while bearing the entirety of localized production risk, including climate induced crop failures and drying losses, and the sector experienced a documented production decline of roughly 47 percent between 2002 and 2012 as warming waters and disease pressure intersected with weak pricing power (Fröcklin, de la Torre Castro, Lindström, Jiddawi, and Msuya, 2012). Previous IGAD policy proposals have advocated breaking this captive dynamic by establishing domestic extraction plants. Global Value Chain theory is clear, however, that functional upgrading within a chain requires satisfying baseline infrastructural, technological, and capital preconditions first. Attempting industrial functional upgrading without those foundational processing inputs, as section 6 demonstrates in more detail, inevitably results in capital failure rather than upgrading.

2.3. Integrating the Two Frameworks: What Each Misses Alone

Read separately, these two frameworks explain different halves of the same failure pattern, and this is itself the first analytical gap this paper addresses. A Social Ecological Systems reading alone can diagnose why a farm plot is insecure, but it says little about why a secure plot still yields a farmer only a small fraction of what the dried biomass is eventually worth once it reaches a European or Asian processor. A Global Value Chain reading alone can diagnose

why smallholders capture so little value, but it treats the farm level resource system as a given input rather than as a contested common pool resource that can be lost entirely before any value chain question becomes relevant.

Combining them produces a more complete causal chain: weak marine tenure under the Social Ecological Systems lens creates the underlying vulnerability that a captive buyer driven chain under the Global Value Chain lens then exploits, because farmers with no secure, bankable claim to their plots have no collateral, no long horizon investment incentive, and therefore no realistic path to the cooperative scale or quality certification that would improve their bargaining position further up the chain. This is precisely the mechanism through which several interview respondents, particularly cooperative leaders in Kenya, described being locked into single buyer arrangements even where nominally open markets existed on paper.

3. Methodology

To move beyond desk bound policy review, this study executed an empirical, qualitative research design. Primary data collection centered on semi structured expert interviews, with a total sample of 24 respondents, conducted across Kenya, Somalia, Djibouti, and Sudan between January 2022 and December 2023.

The informant sample was structured using purposive sampling to capture comprehensive expertise across the mariculture value chain. Table 1 summarizes the three experts cohorts and their primary contribution to the analysis that follows.

Table 1: Composition of the Expert Interview Sample (N equals 24)

Expert Cohort	n	Primary Contribution to Thematic Coding
Regional Blue Economy policymakers and marine spatial planners	8	Governance and legal tenure; regional policy coherence
Marine scientists and phycologists	10	Oceanographic suitability; species physiology and disease risk
Mariculture cooperative leaders and NGO field practitioners	6	Infrastructure and supply chain logistics; economic value addition feasibility

Interviews were conducted in person and through secure video conferencing, averaging 60 minutes in length. Transcripts were anonymized, cataloged, and imported into NVivo 12 software for inductive thematic analysis. Qualitative coding converged on four primary structural nodes: oceanographic suitability, infrastructure and supply chain logistics, governance and legal tenure, and economic value addition feasibility. Empirical assertions were triangulated against peer reviewed phycological literature, regional bathymetric and marine heatwave datasets, and trade flow statistics to strengthen analytical validity.

Two limitations of this design should be stated plainly. First, a sample of 24 experts, while sufficient for thematic saturation on the governance, infrastructure, and oceanographic questions this study foregrounds, cannot support statistically representative claims about farmer level income or welfare outcomes; those questions require the larger structured household surveys that studies such as Fröcklin and colleagues (2012)^[8] have conducted in Zanzibar specifically. Second, the study period, January 2022 through December 2023, precedes the most recent intensification of Red Sea marine heatwave activity documented for the years after 2016 in the broader oceanographic literature, so the thermal stress findings reported in section 4 should be read as consistent with, rather than a direct measurement of, that longer term trend (Hamdeno, Alvera Azcárate, Krokos, and

Hoteit, 2024).

A third limitation concerns comparability across the four littoral states themselves. Access constraints tied to the security and political conditions discussed in section 9 meant that Sudanese and Somali interviews were more heavily weighted toward remote video conferencing and toward diaspora based or regionally based experts rather than continuously resident field practitioners, compared with the more balanced in person access achieved in Kenya. This does not invalidate the findings for Sudan and Somalia, since the marine scientists and policymakers reached remain highly informed on the sub regional oceanographic and governance questions this study addresses, but it does mean the on the ground operational detail available for those two states, reflected in the comparatively thinner entries for them in Table 1, is somewhat less granular than for Kenya, a pattern any follow-on fieldwork should aim to correct directly.

4. Sub Regional Oceanographic Constraints and Species Selection

A primary empirical deficit in earlier literature is the failure to account for sub regional oceanographic heterogeneity. The marine environments of the four IGAD littoral states encompass two fundamentally different physical oceanographic regimes, summarized visually in Figure 2 and discussed in turn below.

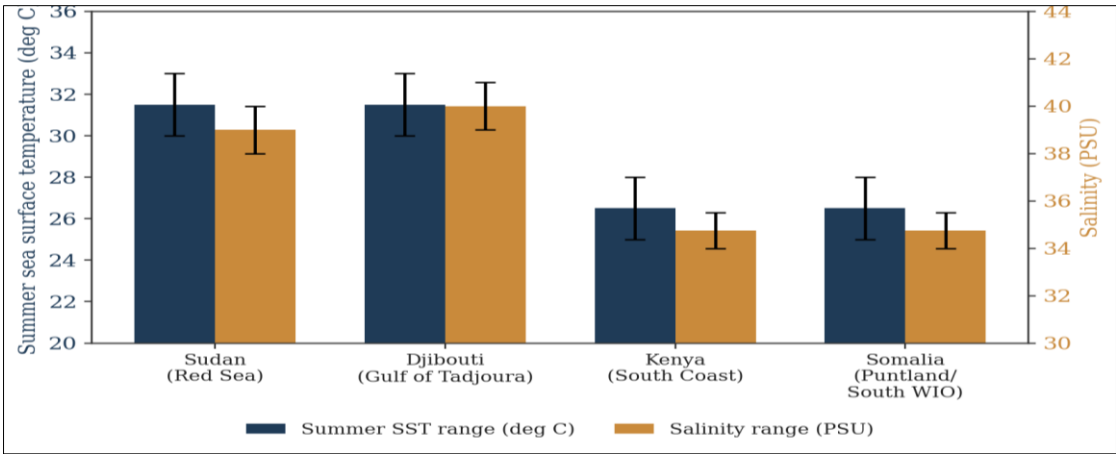


Fig 2: Sub Regional Thermal and Salinity Regimes Across IGAD Littoral Mariculture Zones

Ranges compiled from field survey synthesis and regional oceanographic literature cited in sections 4.1 and 4.2.

4.1. The Red Sea and Gulf of Tadjoura Corridor: Sudan and Djibouti

The coastal waters of Sudan and Djibouti represent hyper thermal, hypersaline marine environments. High solar irradiance and extreme evaporation rates, combined with minimal riverine discharge, elevate summer sea surface temperatures above 30 to 33 degrees Celsius and salinity levels beyond 39 practical salinity units. This is not a static

baseline. Long term satellite analysis of the Red Sea basin found an average basin wide warming rate of roughly 0.34 degrees Celsius per decade between 1982 and 2019, with the northern basin warming even faster, and a separate analysis of marine heatwave events found that warming accelerated sharply after 2016, with 46 percent of all recorded heatwave events and 58 percent of total heatwave days between 1982 and 2021 occurring in the final decade of that record alone (Mohamed, Nagy, and Ibrahim, 2021; Hamdeno, Alvera Azcárate, Krokos, and Hoteit, 2024)^[19]. Figure 3 renders this reported trend schematically.

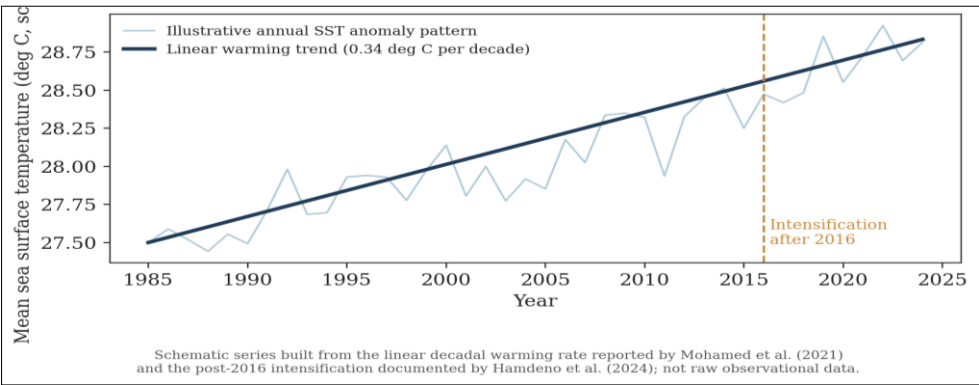


Fig 3: Schematic Reconstruction of the Red Sea Warming Trend, 1985 to 2024

Standard tropical commercial cultivars, specifically *Eucheuma denticulatum* and *Kappaphycus alvarezii*, exhibit severe physiological stress when exposed to temperatures exceedingly roughly 29 degrees Celsius. Thermal stress triggers mass synthesis of reactive oxygen species within algal tissues, weakening cell walls and leading to ice-ice disease, a bacterial infection, most commonly associated with *Vibrio* and related bacterial genera, that bleaches macroalgal thalli and can cause total crop collapse (Largo, Fukami, and Nishijima, 1995a, 1995b) [16, 17]. Furthermore, high sea surface temperature promotes heavy epiphyte growth, which smothers seaweed fronds and competes for photosynthetic light. Consequently, commercial mariculture in Sudan and Djibouti cannot rely on introduced commercial cultivars under a warming trend of this magnitude. Success in this corridor requires bioprospecting, domesticating, and scaling heat tolerant native species, such as local strains of *Gracilaria*, *Sargassum*, or *Turbinaria*, an implication that section 4.3 develops into a formal species suitability matrix.

4.2. The Western Indian Ocean Coastline: Kenya and Southern Somalia

Conversely, the maritime zones of coastal Kenya and southern Somalia benefit from the Western Indian Ocean hydrographic regime. These waters feature comparatively stable ambient thermal ranges of roughly 25 to 28 degrees Celsius, regular semi diurnal tidal dynamics, and beneficial nutrient fluxes driven by the East African Coastal Current and seasonal monsoonal upwelling. These conditions support the

cultivation of *Eucheuma denticulatum* and *Kappaphycus alvarezii*, and they explain why Zanzibar, just south of this study's Kenyan sample sites, became one of the world's most cited seaweed farming success stories in the first place, with the practice employing between 15,000 and 20,000 people at its peak, roughly 90 percent of them women (Fröcklin, de la Torre Castro, Lindström, Jiddawi, and Msuya, 2012). However, even within the Western Indian Ocean zone, mariculture is increasingly threatened by climate anomalies. Shifting monsoonal wind patterns alter wave energy levels, snapping off bottom peg lines and washing away crops. Additionally, climate driven El Niño Southern Oscillation events trigger localized marine heatwaves and heavy terrestrial runoff, which increases water turbidity, blocks photosynthetically active radiation, and smothers macroalgal beds with fine silt. Interview respondents in Kenya described this instability as the single most disruptive factor to yield predictability, ahead even of market price volatility, a finding consistent with the climate driven yield decline documented for Zanzibar over the past two decades.

4.3. Species Suitability: A Comparative Matrix

Bringing the two sub regional profiles together, Table 2 sets out a comparative species suitability matrix. Its purpose is to make explicit what the narrative sections above imply: that a single species recommendation cannot serve the entire IGAD littoral bloc, and that strain selection is a sub-regional decision rather than a bloc wide one.

Table 2: Species Suitability Matrix Across IGAD Oceanographic Sub Regions

Candidate Species	Red Sea / Gulf of Tadjoura (Sudan, Djibouti)	Western Indian Ocean (Kenya, South Somalia)	Primary Constraint
<i>Kappaphycus alvarezii</i> (cottonii)	Unsuitable above 29 deg C	Suitable, established	Thermal tolerance ceiling near 29 to 30 deg C
<i>Eucheuma denticulatum</i> (spinosum)	Unsuitable, ice risk	Suitable, established	Susceptible to ice above threshold SST
Native <i>Gracilaria</i> spp.	Candidate, requires domestication	Established in artisanal use	Limited commercial hydrocolloid yield data
Native <i>Sargassum</i> spp.	Candidate, heat tolerant	Present but not farmed commercially	No standardized cultivation protocol yet
Native <i>Turbinaria</i> spp.	Candidate, heat tolerant	Present but not farmed commercially	Low market demand for alginate grade produced

5. Operational Baselines and Infrastructure Readiness Audit

To provide an accurate empirical foundation for regional planning, Table 3 details the current operational baselines,

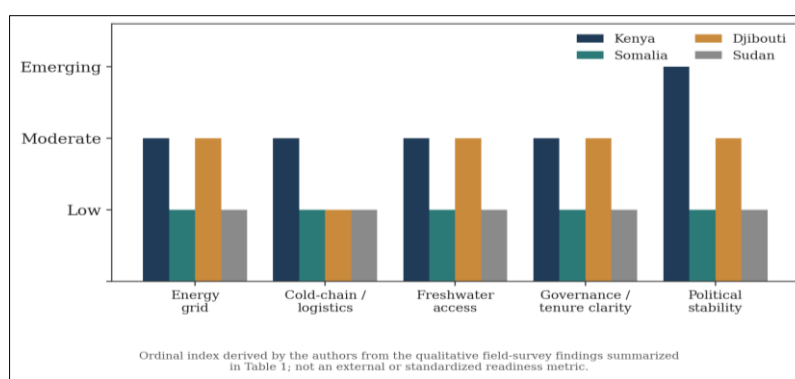
active mariculture models, and infrastructural bottlenecks across all four IGAD littoral states, based on field survey synthesis.

Table 3: Operational Baselines and Infrastructural Constraints Across IGAD Littoral States

Littoral State	Primary Marine Zone	Mariculture Status	Key Infrastructural and Ecological Bottlenecks
Kenya	South Coast (Kwale, Kilifi, Shimoni)	Commercial transition; active women led cooperatives exporting dry biomass	Absence of domestic carrageenan processing plants; reliance on open air sun drying vulnerable to rain; power grid instability in rural landing sites
Somalia	Puntland and Somaliland coastlines	Early-stage NGO pilots; high biophysical potential along the WIO coast	Maritime security risks; complete lack of rural cold chain and transport logistics; unharmonized regional marine governance
Djibouti	Gulf of Tadjoura and northern coast	Nascent or conceptual stage; isolated research trials	Extreme summer heat stress above 33 degrees C; hypersalinity; severe spatial competition with commercial port facilities and naval corridors
Sudan	Red Sea coast (Port Sudan, Suakin Archipelago)	Exploratory pilot trials; academic bioprospecting	Severe thermal stress inducing ice-ice outbreaks; acute political and civil instability; severe regional electrical grid failures

Translating these qualitative findings into a single comparative view, Figure 4 presents an ordinal infrastructure readiness index constructed by the authors directly from the field survey findings summarized in Table 1. The index is not a standardized or externally validated metric; it is offered as

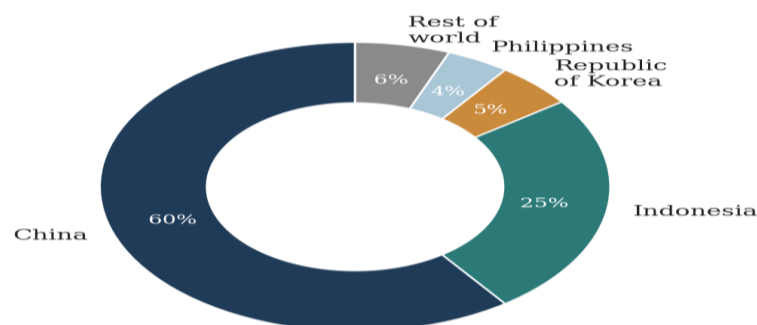
a compact visual summary of the authors' own qualitative synthesis across five dimensions that respondents raised most consistently: energy grid reliability, cold chain and transport logistics, freshwater access, clarity of governance and tenure, and political stability.

**Fig 4:** Infrastructure Readiness Index by Littoral State (Author Synthesis of Field Survey Findings)

Kenya emerges as the comparatively most ready state across all five dimensions, though even their respondents flagged rural grid instability and the complete absence of domestic processing capacity as binding constraints. Somalia and Sudan cluster at the low end of every dimension, reflecting security, governance, and infrastructure deficits that are political and institutional in origin rather than purely technical, and that no oceanographic or biological intervention can resolve on its own. Djibouti occupies an intermediate position, constrained less by governance capacity than by the sheer scarcity of developable coastal space once port and naval priorities are accounted for.

6. Global Value Chain Position and the Economics of Value Capture

Understanding where IGAD producers sit within the global seaweed economy is a precondition for any credible processing strategy, and this section quantifies that position before section 8 uses it to justify a phased rather than immediate industrialization path. Global seaweed aquaculture output reached roughly 35.1 million tons in 2021, produced across more than 56 countries, but production remains heavily concentrated: China and Indonesia together account for roughly 85 percent of global supply, with the Republic of Korea and the Philippines making up most of the remainder (FAO, 2023). Figure 2 sets out this concentration.



Source: FAO GLOBEFISH seaweed trade and market synthesis (FAO, 2023), based on global aquaculture output of 35.1 million tonnes.

Source: FAO GLOBEFISH seaweed trade and market synthesis (FAO, 2023).

Fig 5: Share of Global Seaweed Aquaculture Output by Leading Producing Nation, 2021

No IGAD littoral state currently appears among the leading producing nations, which has two consequences that the interviews repeatedly surfaced. First, IGAD producers are price takers rather than price setters in every transaction, since none commands enough volume to influence the benchmark prices that Southeast Asian supply sets. Second, and more consequentially for policy, this concentration means the downstream processing infrastructure, technical expertise, and buyer relationships that a hydrocolloid industry depends on are already deeply entrenched elsewhere, which raises rather than lowers the capital and technical bar that a new IGAD entrant into refining would need to clear.

This is precisely the structural condition that Global Value Chain governance theory predicts will produce a captive rather than a modular or relational chain for new entrants (Gereffi, Humphrey, and Sturgeon, 2005)^[9]. A captive chain gives lead firms, in this case established Asian and European processors, strong incentive to keep upstream suppliers, including any new IGAD refining venture, dependent on their technical specifications, quality standards, and purchase agreements rather than to cede governance ground. Policy proposals that call for immediate domestic hydrocolloid refining in IGAD states without a corresponding strategy for breaking into, rather than around, this governance structure are therefore likely to produce plants that either cannot secure buyers at viable prices or that end up captive to a single external buyer on unfavorable terms, replicating the very dependency the investment was meant to escape.

7. Gender, Labor, and the Social Structure of the Mariculture Workforce

Any policy framework for IGAD seaweed mariculture that omits the sector's labor structure is incomplete, because the sector's defining social characteristic across the wider Western Indian Ocean region is the overwhelming concentration of farm level labor among women. In Zanzibar, the most extensively studied case in the region, women have consistently made up between roughly 80 and 90 percent of farmers since the industry's commercial introduction in 1989, and the activity has been widely credited with expanding women's independent income, household bargaining power, and mobility in communities where alternative formal employment for women was historically scarce (Msuya and Hurtado, 2017; Fröcklin, de la Torre Castro, Lindström, Jiddawi, and Msuya, 2012)^[8, 21].

This picture, while broadly accurate, requires two

qualifications that the interview data for this study reinforced. First, the same structured survey work in Zanzibar that documented income and empowerment gains also documented that seaweed farmers report significantly poorer self-assessed health than non-farming women in the same communities, including elevated rates of musculoskeletal pain, skin and eye irritation, and injuries from hazardous marine organisms, problems linked to prolonged sun, wind, and seawater exposure during long tidal harvesting shifts (Fröcklin, de la Torre Castro, Lindström, Jiddawi, and Msuya, 2012)^[8]. A livelihood framework that celebrates income gains without addressing these occupational health costs is only telling half the story, and none of the phased model proposed in section 8 should be read as adequate unless occupational protections are built into Phase I from the outset.

Second, recent work on men's participation in Zanzibar seaweed farming complicates a simple narrative of gendered specialization by choice. A 2024 study found persistent socio-cultural stereotyping around the activity as women's work, discouraging male entry even where households would benefit from additional labor, which suggests that the gender imbalance in this workforce reflects social norm enforcement as much as it reflects a genuine gendered comparative advantage (Mbunda, 2024)^[18]. For IGAD policy specifically, where the Sudanese and Djiboutian sectors remain at an early, exploratory stage rather than an established one, this points to a narrow but real window in which gender inclusive workforce norms could be built into cooperative structures from the start, rather than corrected after the fact as Zanzibar's experience now suggests may be necessary.

8. A Phased Economic Model for Regional Value Addition

Industrial carrageenan refining requires chemical processing assets, continuous high-volume inputs of clean fresh water, stable electrical grid power for heating, evaporation, and precipitation, and large dry biomass volumes, typically above 5,000 dry metric tons per year, to reach viable plant scale. Attempting to establish commercial extraction facilities in remote coastal zones without these baseline inputs leads to capital failure, a risk that both the infrastructure audit in section 5 and the value chain analysis in section 6 independently confirm. To reconcile policy ambition with structural reality, this study proposes a three-tier phased development roadmap, set out narratively below and visually in Figure 6, with the underlying preconditions and risks tabulated in Table 4.

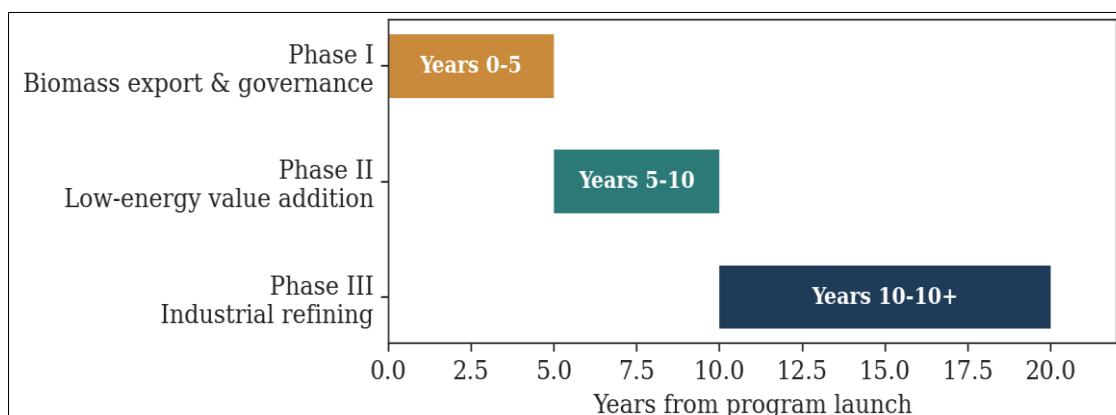


Fig 6: Three Tier Phased Development Roadmap for IGAD Seaweed Mariculture

Phase I, spanning roughly years zero to five, focuses institutional capital on building smallholder capacity, formalizing coastal tenure through Beach Management Units, and introducing modern drying infrastructure such as raised solar drying racks covered with clear poly sheeting. Farmers export dry raw biomass directly to global hydrocolloid markets during this phase. Policy interventions here must focus on establishing transparent pricing mechanisms, microfinance access, and baseline oceanographic monitoring to protect farms from the climate events documented in section 4, alongside the occupational health protections identified in section 7.

Phase II, spanning roughly years five to ten, begins once raw biomass production has scaled and stabilized, and it transitions toward simple, low energy processing that requires minimal capital expenditure. Interventions at this stage include producing liquid organic bio fertilizers through cold maceration and fermentation, manufacturing dried seaweed meal for regional poultry and aquaculture feed, and producing local food products and cosmetics. Supplying

domestic agricultural sectors in this way reduces regional reliance on imported synthetic fertilizers and retains a larger share of economic value within coastal communities, directly addressing the value capture problem quantified in section 6 without requiring the capital scale that industrial refining demands.

Phase III, from roughly year ten onward, becomes viable only once coastal energy grids, port logistics, and freshwater infrastructure have achieved structural stability, and once baseline regional dry biomass production meets industrial processing thresholds. At that point, IGAD member states should actively seek Foreign Direct Investment and Public Private Partnerships to construct centralized carrageenan and agar extraction plants. This long-term phase is what would allow the IGAD bloc to move from a raw material exporter toward a genuine regional hub for refined marine hydrocolloids, but section 6 makes clear that reaching this phase also requires an explicit strategy for negotiating entry into an already captive global governance structure, not simply building the plant.

Table 4: Preconditions and Risks Across the Three Development Phases

Phase	Core Activity	Required Preconditions	Primary Risk if Sequenced Out of Order
Phase I Years 0 to 5	Biomass export and cooperative governance	Beach Management Unit tenure; basic drying infrastructure; microfinance access	Farmers remain exposed to volatile spot prices with no fallback
Phase II Years 5 to 10	Low energy domestic value addition	Stable Phase I biomass volumes; basic quality control training	Undercapitalized processing units fail before break even
Phase III Years 10 and beyond	Capital intensive industrial refining	Grid electricity, freshwater utilities, port logistics, biomass above 5,000 dry metric tons per year	Stranded industrial assets and unrecoverable public or private capital

9. Governance, Marine Spatial Planning, and Residual Risk

The Social Ecological Systems analysis in section 2.1 identified insecure marine tenure as a root cause of smallholder vulnerability, and this section translates that diagnosis into the specific governance actions the phased model in section 8 depends on for success. Marine spatial planning in the IGAD littoral zone remains fragmented across fisheries ministries, port authorities, tourism boards, and conservation agencies, with few formal, legally binding mechanisms to reserve intertidal and shallow subtidal zones specifically for community mariculture. Kenya's own recently launched national blue economy strategy sets ambitious production and revenue targets for the sector through 2030, but interview respondents cautioned that targets of this kind will not be met unless they are backed by the same tenure protections this study identifies as currently missing at the county and landing site level (Government of Kenya, 2025)^[10].

Climate risk compounds this governance gap rather than sitting alongside it. The marine heatwave trends documented in section 4.1 for the Red Sea corridor, and the monsoonal and El Niño driven disruptions documented in section 4.2 for the Western Indian Ocean, both fall outside the control of any single farmer or cooperative, which is precisely why Ostrom's framework treats governance capacity, not individual farmer behavior, as the relevant unit of resilience. A cooperative with secure, legally defensible tenure can adapt cultivation calendars, relocate plots seasonally, or invest in resilient infrastructure in ways that a cooperative farming under informal, revocable permission cannot, regardless of how skilled its members are.

Political instability introduces a third, distinct risk category that neither framework was designed to model directly. Sudan's civil conflict during the study period constrained both field access and the feasibility of any near-term infrastructure investment, and Somalia's maritime security environment imposes similar constraints on Puntland and Somaliland pilot sites. This study treats these as exogenous risk factors that the phased model must accommodate through flexible sequencing rather than as factors a mariculture specific intervention could resolve; the honest implication is that Phase I in Sudan and Somalia may need to remain in place for longer than the indicative five-year window shown in Figure 5, pending broader political stabilization that lies outside this paper's scope.

A further governance question concerns who within a coastal community actually holds decision rights once a marine spatial planning zone is formally designated. Interview respondents in Kenya and, more tentatively, in the early Somali pilot sites described Beach Management Units as the de facto governing body for intertidal seaweed plots, yet these units vary considerably in how representative their leadership is of the women who make up most of the farming workforce documented in section 7. A designated mariculture zone that formalizes tenure at the community level without also ensuring that farmer cooperatives, and not only male dominated village committees, hold enforceable rights within that zone risks reproducing the same value capture asymmetries this paper documents at the international level, only relocated to the local scale. Any harmonized marine spatial planning framework adopted under the first policy directive in section 11 should therefore specify farmer level, not only community level, tenure protections.

10. What the Combined Framework Explains and What It Still Cannot

Stepping back from the sector-by-sector findings, it is worth asking directly what the paired Social Ecological Systems and Global Value Chain framework introduced in section 2.3 actually buys this analysis that a single theory reading would not have. The clearest answer sits in section 6. A Global Value Chain reading on its own would explain why an IGAD refining venture might struggle to capture value once it exists, but it offers no account of why so few such ventures exist in the first place. Adding the Social Ecological Systems lens supplies that missing step: insecure tenure and fragmented marine spatial planning, documented in sections 2.1 and 9, suppress the scale and continuity of biomass supply long before any value chain question becomes relevant, which is precisely why Phase I in the proposed roadmap is a governance intervention rather than a processing intervention.

The framework also has real limits that should be stated rather than implied. Neither Ostrom's approach nor Global Value Chain governance theory was built to model acute political instability of the kind documented for Sudan and Somalia in section 9, and this study has not attempted to force that variable into either framework artificially. Political risk is treated here as an exogenous constraint on sequencing rather than as an endogenous feature the theory explains, and a reader should not expect the phased model to specify a timeline for Sudan or Somalia with the same confidence it offers for Kenya. This is a genuine gap in what the paper can claim, not a rhetorical hedge, and closing it would require a theoretical apparatus this paper does not attempt to build, most likely drawn from the political economy of fragile states literature rather than from resource governance or value chain theory.

A second limit concerns measurement. The infrastructure readiness index in Figure 6 and the value distribution chart in Figure 3 is both explicitly labeled as author constructed syntheses rather than externally validated statistics, and this is a deliberate methodological choice rather than an oversight. Building a defensible, externally validated version of either measure, an infrastructure readiness index benchmarked against comparable coastal regions elsewhere, or a value chain distribution study using actual transaction level pricing data from IGAD cooperatives specifically, would each justify a standalone follow-on study. This paper's qualitative design was built to establish which questions matter most for IGAD seaweed policy, not to produce the final quantitative answer to any one of them, and the research agenda set out at the close of section 11 reflects that division of labor directly.

11. Conclusion and Policy Recommendations

Seaweed mariculture presents an impactful Blue Economy development vector for the IGAD region, functioning at the intersection of climate adaptation, poverty reduction, and marine ecosystem restoration. Realizing this potential, however, requires moving past theoretical generalization in favor of ecologically nuanced, empirically grounded, and phased development strategies of the kind set out in sections 4 through 9 above. The sub regional oceanographic divide documented in section 4, the infrastructure deficits documented in section 5, the captive global value chain position documented in section 6, the gendered labor structure documented in section 7, and the governance and

climate risks documented in section 9 together explain why previous single dimension policy proposals for this sector have underdelivered, and why a genuinely multi scalar framework is necessary rather than merely preferable.

To operationalize this roadmap, the IGAD Secretariat and littoral member states should pursue five concrete policy directives. First, harmonize marine spatial planning across littoral member states, establishing legally protected mariculture zones that shield smallholder farmers from port expansion and shipping interference, building directly on the tenure gap identified in section 2.1 and section 9. Second, invest in indigenous macroalgae bioprospecting, particularly within the Red Sea and Gulf of Tadjoura, to identify endemic, heat tolerant strains capable of surviving the hyper thermal summer regimes and accelerating warming trend documented in section 4.1.

Third, formulate regional quality and trade standards within the IGAD Blue Economy Strategy to facilitate intra-regional trade of dry biomass and organic bio fertilizers, an intervention that directly targets the value capture weaknesses documented in section 6 (IGAD, 2021). Fourth, build gender inclusive workforce protections, including occupational health standards, into cooperative governance from the earliest pilot stage, rather than treating the labor and health findings documented in section 7 as a later stage correction. Fifth, adopt the proposed phased economic development model in full, ensuring capital investments match actual infrastructural readiness as measured through mechanisms similar to the index presented in section 5, rather than proceeding directly to industrial processing on the strength of aspiration alone.

Finally, this study's own limitations, set out in section 3, point directly to the most useful next steps for this research agenda: a structured household level survey comparable to the Zanzibar studies cited throughout this paper, replicated specifically in the four IGAD littoral states, and an updated oceanographic assessment incorporating Red Sea and Gulf of Tadjoura observations from after 2023, when the most recent intensification of regional marine heatwave activity appears concentrated. Both would allow the framework proposed here to be tested against harder quantitative evidence than the present qualitative design permits, converting this roadmap from a peer review ready starting point into a fully validated regional strategy.

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