CHAPTER 07

Marine Food Security Challenges and Policy Responses in Developing Countries: Comparative Evidence from Indonesia, India, and Tanzania

La Ode M. Aslan[1],*, Tamrin[2], Wa Kuasa Baka[3], Siti Aida Adha Taridala[4], Usman Rianse[5], Yusuf Sabilu[6] & Ratna Diyah Palupi[7]
[1] Department of Aquaculture, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Kendari 93232, Indonesia
[2] Department of Food Science and Technology, Faculty of Agriculture, Halu Oleo University, Kendari 93232, Indonesia
[3] Department of Oral Tradition, Faculty of Cultural Sciences, Halu Oleo University, Kendari 93232, Indonesia
[4] Department of Agribusiness, Faculty of Agriculture, Halu Oleo University, Kendari 93232, Indonesia
[5] Department of Agribusiness, Faculty of Agriculture, Halu Oleo University, Kendari 93232, Indonesia
[6] Public Health Study Program, Faculty of Public Health, Halu Oleo University, Kendari 93232, Indonesia
[7] Department of Marine Science, Faculty of Fisheries and Marine Sciences, Halu Oleo University, Kendari 93232, Indonesia
***Corresponding author's email:** laodemaslan@uho.ac.id

Abstract

Marine food systems are a critical component of global food and nutrition security, providing essential animal protein, micronutrients, livelihoods, and economic opportunities for hundreds of millions of people, particularly in developing coastal and island nations. Despite their significance, they remain underrepresented in conventional food security assessments, which are largely centered on terrestrial agriculture. Growing demand for nutrient-rich "blue foods" and the relatively low environmental footprint of aquatic foods have increased the strategic importance of marine resources in sustainable food system transitions. However, marine food systems face mounting challenges from overfishing, habitat degradation, pollution, climate change, and weak governance structures that undermine sustainable resource management and equitable access. Climate-induced changes in ocean temperatures and fish distribution patterns, combined with illegal, unreported, and unregulated (IUU) fishing, further threaten food security and livelihoods, particularly in the Global South. Comparative evidence from Indonesia, India, and Tanzania highlights shared structural constraints, including ecological stress, institutional weaknesses, and unequal access to marine resources, despite differing national contexts. At the same time, ecosystem-based fisheries management, improved aquaculture governance, climate adaptation strategies, and the expansion of sustainable seaweed farming offer promising pathways toward resilience and inclusive blue economy development. This chapter proposes the Global Marine Food Security Index (GMFSI) as an integrated conceptual framework linking ecological sustainability, nutritional outcomes, and socio-economic dimensions to better assess and guide marine food security policies. Ensuring the long-term sustainability of marine food systems will require coordinated, cross-sectoral governance approaches that prioritize environmental integrity, climate resilience, and social equity.

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1. Introduction

Food and nutrition security remains one of the most persistent and structurally complex challenges in global development. Despite long-term gains in agricultural productivity and sustained international interventions, progress toward eliminating hunger and malnutrition has been uneven and insufficient. Current estimates indicate that approximately 673 million people, about 8.2% of the global population experienced hunger in 2024, while more than 2.3 billion faced moderate or severe food insecurity (FAO, IFAD, UNICEF, WFP, & WHO, 2025). These figures expose a structural imbalance in global food systems in which aggregate availability coexists with persistent inequities in access, affordability, and nutritional adequacy. Reinforcing this concern, nearly one-third of the global population remains unable to afford a healthy diet, underscoring that food insecurity is increasingly driven by economic constraints and distributional inefficiencies rather than absolute production shortfalls (FAO *et al*., 2025).

The burden of malnutrition further complicates this picture. Undernutrition, micronutrient deficiencies, and overweight and obesity now coexist within countries and even within households, particularly across low- and middle-income settings. Deficiencies in essential micronutrients including iron, zinc, iodine, vitamin A, and vitamin B12 continue to undermine cognitive development, immune function, and labor productivity (Development Initiatives, 2024). At the same time, demographic expansion is placing additional pressure on food systems, with the global population projected to reach 9.7 billion by 2050 (United Nations, 2024). Depending on dietary trajectories and socioeconomic pathways, global food demand may increase by 35–56% by mid-century (van Dijk *et al*., 2021), intensifying pressure on already constrained land, water, and ecosystem resources.

Terrestrial food systems, which dominate global supply, are increasingly approaching ecological limits. Agricultural expansion and intensification continue to drive deforestation, biodiversity loss, freshwater depletion, and greenhouse gas emissions, contributing to widespread transgression of planetary boundaries (Campbell *et al*., 2017; Crippa *et al*., 2021). Climate change further exacerbates these pressures by altering temperature regimes, disrupting precipitation patterns, and increasing the frequency of extreme events. The Intergovernmental Panel on Climate Change (IPCC, 2023) confirms that yields of major staple crops such as rice, wheat, and maize are already declining in vulnerable regions. Collectively, these dynamics highlight the diminishing capacity of conventional land-based systems to sustain future food demand.

Within this context, aquatic food systems commonly referred to as “blue foods” have gained recognition as a critical complement to terrestrial production. These include finfish, shellfish, crustaceans, mollusks, and seaweeds derived from marine and freshwater ecosystems. Relative to many terrestrial animal protein systems, aquatic foods often require less land and freshwater and generate lower greenhouse gas emissions across several production pathways (Costello *et al*., 2023). Nutritionally, they are rich in highly bioavailable protein, essential amino acids, omega-3 fatty acids, and key micronutrients such as iron, zinc, iodine, calcium, selenium, and vitamin B12 (Hicks *et al*., 2019; Golden *et al*., 2021), making them particularly relevant for addressing persistent “hidden hunger.”

This importance is reflected in global production trends. In 2022, fisheries and aquaculture output reached 223.2 million tonnes, with aquaculture surpassing capture fisheries as the dominant source of fish for human consumption (FAO, 2024). This shift signals a structural transformation in global food systems and positions aquaculture as a central pillar of future food security. Beyond nutrition, the sector supports the livelihoods of approximately 600 million people through employment and value-chain activities, while small-scale fisheries remain especially vital for food security, income generation, and social cohesion in developing regions (Béné *et al*., 2016).

These developments have catalyzed broader “blue economy” approaches that integrate ecological sustainability with economic and social objectives. Evidence suggests that well-managed expansion of aquatic food systems can improve nutritional outcomes while reducing environmental pressures associated with terrestrial agriculture (Golden *et al*., 2021; Costello *et al*., 2023). However, realizing this potential requires addressing persistent governance deficits, ecological degradation, and structural inequalities that continue to constrain marine food systems, particularly in developing countries.

Within the Global South, marine food systems occupy a strategically central role. Indonesia, India, and Tanzania illustrate this dependence in distinct but complementary ways: Indonesia as a leading archipelagic seaweed producer, India as a rapidly expanding aquaculture economy, and Tanzania as a coastal system reliant on small-scale fisheries and seaweed farming. Despite contextual differences, these countries face converging challenges, including climate impacts, resource overexploitation, governance limitations, and heightened coastal vulnerability (Allison *et al*., 2009; IPCC, 2023). Comparative analysis therefore offers a robust basis for identifying transferable policy insights.

In this framework, marine food security is conceptualized as a multidimensional construct encompassing nutritional adequacy, ecological sustainability, economic viability, and institutional resilience. This integrated perspective underpins the proposed Global Marine Food Security Index (GMFSI), designed to support comparative assessment and evidence-informed policymaking across marine food systems.

1.1. Why Marine Food Security Matters for Developing Countries

Marine food security has become increasingly important for developing countries because of its direct contribution to food availability, nutrition, employment, poverty alleviation, and economic development. Across much of the Global South, marine and aquatic resources constitute a fundamental component of national food systems and support the livelihoods of hundreds of millions of people. Unlike many industrialized countries, where aquatic foods often represent a relatively small proportion of dietary intake, developing countries frequently rely on fisheries and aquaculture as primary sources of animal protein, essential micronutrients, employment opportunities, and household income (FAO, 2024; Béné *et al*., 2016). Consequently, the sustainability and resilience of marine food systems are closely linked to broader development objectives, including food security, poverty reduction, economic growth, and social stability.

The significance of marine food security is particularly evident in countries with extensive coastlines and large coastal populations. Approximately 40% of the global population lives within 100 km of the coast, with a substantial proportion residing in developing countries across Asia, Africa, and Latin America (United Nations, 2021). Coastal communities often depend directly on fisheries, aquaculture, and related marine industries for their livelihoods. In many regions, fishing activities serve not only as a source of food but also as a critical economic safety net, particularly where alternative employment opportunities are limited. The health and productivity of marine ecosystems therefore have direct implications for household welfare, income generation, and community resilience.

Marine resources are particularly important in developing countries because they provide highly nutritious foods that contribute significantly to dietary quality and public health. Fish and other aquatic foods contain high-quality protein, essential amino acids, omega-3 fatty acids, vitamins, and minerals that are vital for human growth and development (Golden *et al*., 2021). These nutritional benefits are especially important in low- and middle-income countries, where micronutrient deficiencies remain widespread and where access to diverse and nutrient-rich foods is often constrained. Aquatic foods are rich sources of iron, zinc, iodine, calcium, selenium, and vitamin B12, nutrients that are essential for cognitive development, immune function, maternal health, and child growth (Hicks *et al*., 2019; Thilsted *et al*., 2016). As a result, fisheries and aquaculture contribute not only to food security in quantitative terms but also to nutrition security by improving the quality of diets.

Recent evidence suggests that the role of aquatic foods in addressing malnutrition has been underestimated in conventional food security frameworks. Hicks *et al*. (2019) demonstrated that improved management and distribution of global fisheries resources could substantially reduce micronutrient deficiencies affecting vulnerable populations. Similarly, Golden *et al*. (2021) identified aquatic foods as one of the most promising yet underutilized solutions for addressing the interconnected challenges of malnutrition, environmental sustainability, and livelihood security. These findings are particularly relevant for developing countries, where dietary deficiencies often coexist with limited access to healthcare and other social services.

Beyond their nutritional contribution, fisheries and aquaculture represent major sources of employment and income. According to FAO (2024), approximately 62 million people were directly engaged in fisheries and aquaculture production worldwide in 2022, while hundreds of millions more depended on associated value chains involving processing, transportation, marketing, and trade. Importantly, around 90% of those directly employed in capture fisheries work in small-scale fisheries, the vast majority of whom are located in developing countries (FAO, 2024). The sector therefore plays a crucial role in supporting rural and coastal livelihoods, particularly among economically vulnerable populations.

Small-scale fisheries occupy a central position within marine food systems throughout the Global South. These fisheries are characterized by labor-intensive operations, relatively low capital investment, and strong links to local food systems and community livelihoods. Although frequently overlooked in national economic statistics, small-scale fisheries contribute significantly to food security, employment, and cultural identity in many developing countries (HLPE, 2014). They provide a substantial share of fish consumed domestically and often supply local markets with affordable and nutrient-rich foods. Furthermore, small-scale fisheries support social cohesion and community resilience by maintaining traditional knowledge systems and fostering local resource stewardship.

The importance of small-scale fisheries extends beyond direct food production. They serve as critical livelihood buffers during periods of economic instability, environmental shocks, and agricultural failures. In many coastal regions, fishing households rely on diversified livelihood strategies that combine fishing with agriculture, aquaculture, trading, and seasonal labor. This diversification enhances household resilience and reduces vulnerability to external shocks (Allison & Ellis, 2001). Consequently, strengthening small-scale fisheries can contribute simultaneously to food security, poverty reduction, and climate adaptation objectives.

Marine food systems also play a significant role in reducing poverty across developing countries. Fisheries and aquaculture generate income opportunities for some of the world's poorest populations, including small-scale fishers, fish farmers, processors, traders, and transport workers. Béné *et al*. (2016) argue that fisheries contribute to poverty reduction through three principal pathways: direct income generation, provision of affordable food, and broader economic multiplier effects within coastal economies. Income generated from fisheries activities supports household expenditures on food, education, healthcare, and housing, thereby contributing to improved welfare outcomes.

In many developing countries, marine resources also represent important sources of foreign exchange earnings and economic growth. Fish and seafood products are among the most widely traded food commodities globally, generating substantial export revenues for coastal nations. Aquaculture has emerged as one of the fastest-growing food production sectors worldwide and is increasingly recognized as a strategic component of sustainable economic development (FAO, 2024). Similarly, seaweed farming has become an important source of employment and export income in several countries, particularly in Indonesia (Aslan *et al*., 2018; Rahim *et al*., 2019; Ya'la *et al*., 2022) and in Tanzania (Charisiadou, . *et al*. (2022); Msuya and Hurtado, 2017; Tobisson, E. *et al*. 2021; World Bank, 2022). The expansion of sustainable aquaculture and seaweed industries therefore offers significant opportunities to strengthen marine food security while supporting inclusive economic growth.

Despite these contributions, marine food systems in developing countries face mounting pressures from climate change, overfishing, habitat degradation, pollution, and governance challenges. These threats disproportionately affect poor and marginalized coastal communities whose livelihoods depend heavily on marine resources (Allison *et al*., 2009; IPCC, 2023). Rising ocean temperatures, changing fish distributions, extreme weather events, and declining ecosystem health are increasing the vulnerability of fisheries-dependent populations and threatening the long-term sustainability of marine food supplies. Strengthening marine food security therefore requires integrated policy approaches that simultaneously address environmental sustainability, socioeconomic development, and institutional resilience.

Taken together, these considerations highlight the central role of marine food systems in the development trajectories of countries across the Global South. Fisheries, aquaculture, and other marine-based activities provide food, nutrition, employment, income, and economic opportunities for millions of people while supporting broader goals related to poverty reduction, social inclusion, and sustainable development. As pressures on terrestrial food systems intensify and demand for nutritious foods continue to grow, marine food security will become increasingly important as a pillar of resilient and sustainable food systems in developing countries.

1.2. Comparative Rationale: Indonesia, India, and Tanzania

The selection of Indonesia, India, and Tanzania as comparative case studies provides a valuable opportunity to examine the diverse challenges and opportunities associated with marine food security across the Global

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South. Although these countries differ considerably in terms of geography, population size, economic structure, governance capacity, and levels of technological development, they share a common dependence on marine and aquatic resources for food security, employment, income generation, and socioeconomic development. Collectively, they represent three distinct yet interconnected marine socio-ecological systems in Southeast Asia, South Asia, and East Africa, thereby offering important insights into how developing countries can strengthen marine food security under conditions of environmental change, population growth, and increasing resource pressures (Allison *et al*., 2009; FAO, 2024).

A comparative approach is particularly valuable because marine food security is shaped by multiple interacting factors, including ecological conditions, fisheries productivity, aquaculture development, governance effectiveness, market integration, and social vulnerability. By examining countries with different resource endowments and policy experiences, it becomes possible to identify both context-specific challenges and broadly applicable policy solutions. Comparative analysis also facilitates cross-country learning regarding sustainable fisheries management, aquaculture expansion, climate adaptation, blue economy development, and community-based resource governance (Cinner *et al*., 2012; World Bank, 2017).

Indonesia: A Global Maritime Nation and Seaweed Powerhouse

Indonesia represents one of the world's most significant marine nations. As the largest archipelagic state, the country comprises 17,380 islands (Badan Informasi Geospasial, 2024) and possesses one of the longest coastlines globally, extending approximately 108,000 km ((Badan Informasi Geospasial, 2018). Its marine territory encompasses highly productive ecosystems, including coral reefs, mangroves, seagrass meadows, estuaries, and extensive coastal waters that support exceptional marine biodiversity (Ministry of Marine Affairs and Fisheries, 2024).

The fisheries sector plays a crucial role in Indonesia's economy and food system. Indonesia consistently ranks among the world's largest fish-producing countries, contributing substantially to both capture fisheries and aquaculture production. According to FAO (2024), Indonesia remains one of the leading global producers of aquatic foods, supplying domestic markets while also generating significant export revenues. Fish consumption has increased steadily over the past two decades, reflecting the growing importance of aquatic foods in improving national nutrition and food security.

Indonesia is also recognized as the world's leading producer of tropical seaweed, particularly species belonging to the genera *Kappaphycus* and *Eucheuma*, which are widely ued in carrageenan production. Seaweed farming has become a major livelihood activity in many coastal communities (Aslan e al., 2022; 2024), generating employment opportunities, supporting export earnings, and contributing to poverty reduction in rural coastal areas (FAO, 2024). The strategic importance of seaweed extends beyond economic benefits, as it represents a highly sustainable source of nutritious food and an important component of emerging blue food systems. Nevertheless, Indonesia continues to face significant challenges related to overfishing, illegal, unreported and unregulated (IUU) fishing, habitat degradation, climate change impacts, and governance complexities associated with managing vast marine territories (OECD, 2023).

India: Expanding Fisheries Production and the Blue Economy Agenda

India represents another critical case study because of its large population, extensive coastline, and rapidly growing fisheries and aquaculture sectors. With a coastline approximately 11,098 km (Government of India, 2025) and a population surpassing 1.4 billion people, India faces substantial challenges in ensuring food and nutrition security while maintaining sustainable resource use (Government of India, 2024).

The fisheries sector plays a significant role in supporting livelihoods, food supply, and economic development. India ranks among the world's largest producers of fish and aquaculture products, with inland aquaculture and shrimp farming experiencing particularly rapid growth over recent decades (FAO, 2024). The sector supports millions of fishers, fish farmers, processors, traders, and associated workers, making it a vital source of employment and income generation. Fish also constitute an important source of animal protein and micronutrients for many households, particularly in coastal and riverine regions.

In recent years, India has increasingly embraced the blue economy as a strategic framework for sustainable marine development. Government initiatives such as the *Pradhan Mantri Matsya Sampada Yojana* (PMMSY) seek to enhance fisheries productivity, strengthen value chains, improve infrastructure, promote sustainable aquaculture, and increase export competitiveness (Government of India, 2024). Simultaneously, India is investing in marine spatial planning, ocean-based industries, and climate-resilient fisheries management. Despite these advances, significant challenges remain, including overexploitation of marine fish stocks, coastal pollution, habitat degradation, post-harvest losses, and the vulnerability of small-scale fishing communities to climate change (FAO, 2024; Allison *et al*., 2009).

Tanzania: Coastal Livelihoods and Seaweed-Based Development

Tanzania offers an important African perspective on marine food security. Although its fisheries sector is smaller than those of Indonesia and India, marine resources play a critical role in supporting livelihoods, food security, and economic development along the country's extensive Indian Ocean coastline. Coastal communities depend heavily on fisheries and marine-related activities, particularly small-scale fisheries that provide both subsistence and commercial benefits (United Republic of Tanzania, 2024).

Small-scale fisheries dominate Tanzania's coastal economy and serve as a major source of employment, income, and food for vulnerable households. Fish constitute an important component of local diets and provide essential protein and micronutrients for many communities. However, productivity remains constrained by limited infrastructure, inadequate cold-chain facilities, post-harvest losses, and restricted access to markets and financial services (FAO, 2024).

Tanzania is also internationally recognized as one of Africa's leading seaweed-producing countries. Seaweed farming, has expanded substantially as a low-cost livelihood strategy for smallholder coastal households (Msuya, 2006; Tobisson *et al*., 2021). The sector also plays a significant socio-economic role, especially in women’s employment, with women constituting the majority of producers in Zanzibar and deriving important benefits in terms of household income, welfare improvement, and livelihood security (Msuya and Hurtado, 2017; Charisiadou *et al*., 2022). However, the sustainability of the sector is increasingly constrained by multiple interacting stressors, including climate change-induced increases in sea surface temperature, disease outbreaks, and declining productivity, as well as persistent market instability and structurally weak positions within global value chains (Msuya and Porter, 2014; Tobisson *et al*., 2021). These challenges collectively undermine long-term resilience despite ongoing farmer-level adaptation strategies. Overall, seaweed farming in Tanzania reflects a duality of substantial socio-economic benefits alongside increasing ecological and economic vulnerability (World Bank, 2022; Tobisson *et al*., 2021).

Comparative Learning Opportunities

The inclusion of Indonesia, India, and Tanzania enables meaningful comparative analysis across different development contexts while maintaining a common focus on marine food systems. Indonesia provides lessons regarding large-scale fisheries management and seaweed industry development; India offers insights into aquaculture expansion and blue economy policy integration; and Tanzania highlights the role of small-scale fisheries and community-based coastal livelihoods. Together, these countries illustrate how marine food security can contribute to achieving broader objectives related to poverty reduction, nutritional improvement, climate resilience, and sustainable development.

Moreover, the three countries face many shared challenges, including climate change, marine ecosystem degradation, overexploitation of resources, governance constraints, and socioeconomic vulnerability among coastal populations. Comparative examination of these challenges and policy responses can therefore generate transferable lessons for other developing countries seeking to strengthen marine food security while advancing sustainable blue economy pathways.

1.3. Objectives and Scope of the Chapter

Marine food security is increasingly recognized as a critical component of sustainable development, particularly in developing countries where fisheries, aquaculture, and coastal ecosystems support the food

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and livelihood needs of millions of people. Despite the growing importance of aquatic foods within global food systems, significant knowledge gaps remain regarding the factors that influence marine food security and the policy interventions required to enhance its resilience under conditions of environmental and socioeconomic change. This chapter seeks to address these gaps through a comparative assessment of marine food systems in Indonesia, India, and Tanzania.

Objectives of the Chapter

The primary objective of this chapter is to examine the major challenges affecting marine food security in developing countries and to identify evidence-based policy solutions that can strengthen the sustainability and resilience of marine food systems. Specifically, the chapter aims to:

1. Examine the principal ecological, economic, social, and governance challenges affecting marine food security in Indonesia, India, and Tanzania, including climate change, overfishing, habitat degradation, post-harvest losses, market constraints, and institutional limitations.
2. Compare the structure and performance of marine food systems across the three countries, with particular attention to fisheries production, aquaculture development, seaweed farming, nutritional contributions, livelihood dependence, and socioeconomic outcomes.
3. Identify and evaluate policy solutions capable of enhancing marine food security, including ecosystem-based fisheries management, sustainable aquaculture, blue economy strategies, climate adaptation measures, marine spatial planning, community-based resource management, and technological innovation.
4. Develop a conceptual framework for Marine Food Security Assessment, capable of capturing the multidimensional interactions among ecological sustainability, food availability, accessibility, utilization, stability, governance quality, and climate resilience in developing-country contexts.

1.4. Scope of the Chapter

To achieve these objectives, the chapter adopts an interdisciplinary and comparative perspective that integrates ecological, socioeconomic, institutional, and policy dimensions of marine food systems. The analysis focuses on fisheries, aquaculture, and seaweed farming as key components of marine food security while considering broader interactions with coastal livelihoods, environmental sustainability, and blue economy development.

The chapter is structured around four interrelated dimensions of marine food security: availability, access, utilization, and stability, which are widely recognized as the foundational pillars of food security (FAO, 2008). These dimensions are examined within a broader social-ecological systems framework that recognizes the interconnected nature of marine ecosystems, human communities, governance institutions, and economic processes (Ostrom, 2009).

In addition, the chapter extends conventional food security analysis by incorporating emerging concepts such as aquatic foods, blue foods, climate resilience, ecosystem services, and blue economy transformation. Particular emphasis is placed on understanding how fisheries and aquaculture can contribute not only to food production but also to nutrition security, poverty reduction, gender inclusion, and sustainable coastal development.

Finally, the chapter proposes the development of a Global Marine Food Security Index (GMFSI) framework tailored to the realities of developing countries. Unlike conventional food security indices that focus primarily on terrestrial agricultural systems, the proposed framework explicitly incorporates marine and aquatic dimensions, including fisheries productivity, aquaculture performance, seaweed production, ecosystem health, governance effectiveness, and climate vulnerability. Such a framework has the potential to support policymakers, researchers, and development practitioners in monitoring progress, identifying vulnerabilities, and designing more effective interventions to strengthen marine food security in the Global South.

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2. Conceptual Framework of Marine Food Security and Sustainability

2.1. Defining Marine Food Security

Food security is traditionally defined as a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2008). However, growing recognition of the contribution of aquatic foods to global nutrition, livelihoods, and sustainable development has expanded this concept to encompass marine and aquatic food systems. Marine food security can therefore be understood as the ability of marine and coastal ecosystems to sustainably provide sufficient quantities of safe, nutritious, accessible, and affordable aquatic foods while maintaining ecosystem integrity and resilience for present and future generations (HLPE, 2014; FAO, 2024). This concept broadens conventional food security frameworks by explicitly incorporating fisheries, aquaculture, seaweed farming, marine ecosystem governance, climate resilience, and blue economy principles within an integrated social-ecological system perspective (Ostrom, 2009; Golden *et al*., 2021).

The importance of marine food security has increased considerably in recent decades as aquatic foods have emerged as essential components of sustainable food systems. Fisheries and aquaculture currently provide approximately 20% of average animal protein intake for more than 3.3 billion people worldwide (FAO, 2024). Recent evidence demonstrates that aquatic foods represent one of the most effective pathways for addressing global malnutrition because of their high nutrient density and bioavailability (Golden *et al*., 2021; Hicks *et al*., 2019). Moreover, capture fisheries, aquaculture, and seaweed farming contribute substantially to livelihood security, poverty reduction, and economic development, particularly in low- and middle-income countries where coastal populations remain highly dependent on marine resources (Béné *et al*., 2016; Thilsted *et al*., 2016).

Marine food security is intrinsically linked to several broader development objectives. First, it contributes directly to food security by ensuring a stable supply of aquatic foods. Second, it supports nutrition security through the provision of nutrient-rich foods that improve dietary quality and public health outcomes (Golden *et al*., 2021). Third, marine food systems form a fundamental pillar of the blue economy by generating employment, trade opportunities, and economic growth through the sustainable use of marine resources (World Bank, 2017; OECD, 2023). Finally, marine food security depends on ecosystem sustainability because long-term fisheries productivity and aquaculture development are inseparable from the health and resilience of marine ecosystems (Duarte *et al*., 2020; Bennett *et al*., 2021). Consequently, marine food security should be viewed not merely as a food production issue but as an integrated framework linking ecological sustainability, human nutrition, economic development, and social well-being.

2.2. The Four Pillars of Marine Food Security

The conceptual foundation of marine food security is built upon the four internationally recognized pillars of food security: availability, accessibility, utilization, and stability (FAO, 2008; HLPE, 2014). These dimensions are interdependent and collectively determine the capacity of marine food systems to contribute to sustainable development and human well-being.

Availability: Availability refers to the physical supply of aquatic foods generated through capture fisheries, aquaculture, seaweed cultivation, and other marine production systems. It represents the most fundamental dimension of marine food security because adequate food supply is a prerequisite for achieving nutritional and socioeconomic outcomes. Aquaculture has become the fastest-growing food production sector globally and now exceeds capture fisheries as the primary source of aquatic foods for human consumption (FAO, 2024; Troell *et al*., 2014). Recent projections further indicate that sustainable expansion of marine food production could play a major role in meeting future food demand while reducing pressure on terrestrial food systems (Costello *et al*., 2023).

Key indicators of marine food availability include fisheries production, aquaculture output, seaweed production, fish supply per capita, and marine protein availability. Maintaining these indicators requires sustainable management of fish stocks, protection of critical habitats, and investments in climate-resilient production systems (FAO, 2024; Costello *et al*., 2023).

Accessibility: Accessibility refers to the ability of individuals and households to obtain aquatic foods through economic, social, and physical means. Even where aquatic foods are abundant, poverty, inadequate infrastructure, market inefficiencies, and unequal distribution systems can limit access to nutritious foods. Fisheries and aquaculture support the livelihoods of more than 600 million people worldwide, many of whom depend directly on marine resources for income and food security (FAO, 2024).

Small-scale fisheries are particularly important in developing countries because they simultaneously provide employment, household income, and access to nutritious foods for vulnerable coastal communities (Allison & Ellis, 2001; Béné *et al*., 2016). Access to aquatic foods is therefore strongly influenced by market connectivity, transportation infrastructure, cold-chain facilities, household purchasing power, and value-chain efficiency. Strengthening these components can improve food accessibility while enhancing livelihood resilience and poverty reduction outcomes (World Bank, 2023).

Utilization: Utilization concerns the nutritional quality of food consumed and the body's capacity to absorb and use nutrients effectively. This dimension emphasizes food quality rather than food quantity alone. Aquatic foods are among the most nutrient-dense foods available and provide highly bioavailable proteins, essential amino acids, omega-3 fatty acids, vitamins, and minerals that are critical for human growth, cognitive development, and immune function (Golden *et al*., 2021; Hicks *et al*., 2019).

Research has shown that improved access to aquatic foods can significantly reduce micronutrient deficiencies and improve nutrition outcomes, particularly among women and children in low-income countries (Thilsted *et al*., 2016). Seaweed also represents an increasingly important component of marine food utilization due to its high concentrations of essential micronutrients such as iodine, calcium, and iron, as well as dietary fiber and diverse bioactive compounds that are associated with potential health-promoting effects, including antioxidant and metabolic benefits (Cotas *et al*., 2020; Garcia-Vaquero *et al*., 2021). Indicators of utilization therefore include dietary diversity, fish consumption per capita, seaweed consumption, micronutrient intake, and nutritional status indicators.

Stability: Stability refers to the capacity of marine food systems to maintain availability, accessibility, and utilization over time despite environmental, economic, and social disturbances. Marine food systems are increasingly exposed to multiple stressors, including climate change, ocean warming, marine heatwaves, ocean acidification, extreme weather events, overfishing, habitat degradation, and pollution (IPCC, 2023; Hoegh-Guldberg *et al*., 2019; FAO, 2024).

Climate change is expected to alter fish distributions, reduce fisheries productivity in many tropical regions, and increase the vulnerability of coastal communities that depend heavily on marine resources (Allison *et al*., 2009; IPCC, 2023). Simultaneously, habitat degradation and biodiversity loss threaten the ecological foundations of marine food production (Duarte *et al*., 2020). Building stability therefore requires climate adaptation strategies, ecosystem restoration, adaptive fisheries governance, and investments in resilient food supply chains (FAO, 2024; OECD, 2023).

2.3. Marine Food Systems as Social-Ecological Systems

Marine food systems are increasingly conceptualized as social–ecological systems in which ecological dynamics and human governance structures interact through complex and adaptive feedback mechanisms, shaping system resilience and sustainability outcomes (Kittinger *et al*., 2013; Bennett *et al*., 2019). This perspective recognizes that fisheries and aquaculture cannot be understood in isolation from the ecosystems, institutions, markets, and coastal communities that collectively determine their performance, sustainability, and distributional outcomes.

The ecological subsystem comprises fish stocks, coral reefs, mangrove forests, seagrass meadows, estuaries, and other coastal and marine habitats that underpin food production and ecosystem services. These ecosystems perform critical regulating and supporting functions, including nutrient cycling, carbon

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sequestration, shoreline protection, biodiversity maintenance, and fisheries productivity, which are now widely conceptualized within blue carbon science, ecosystem-based management, and blue economy frameworks (Duarte *et al*., 2013; Hoegh-Guldberg *et al*., 2019; UNEP, 2021)

The social subsystem encompasses fishers, aquaculture producers, seaweed farmers, traders, consumers, and coastal communities whose livelihoods and well-being depend on marine resources. Social factors such as poverty, education, market access, and adaptive capacity strongly influence the resilience of marine food systems (Allison & Ellis, 2001; Béné *et al*., 2016). The governance subsystem encompasses policies, regulatory frameworks, marine spatial planning, community-based management systems, and international agreements that shape resource access and structure patterns of marine resource use. Effective governance is increasingly recognized as a central determinant of sustainability outcomes, requiring the integration of ecological integrity, social equity, and economic efficiency within adaptive and polycentric management systems (Bennett *et al*., 2019; IPCC, 2022). In fisheries and aquaculture systems, the Ecosystem Approach to Fisheries (EAF) and blue transformation agenda as key governance frameworks for ensuring sustainable resource use and resilience in marine food systems (FAO, 2022; FAO, 2024).

2.4. Blue Economy and Strong Sustainability Perspectives

The blue economy has emerged as a leading framework for promoting sustainable ocean development by emphasizing the responsible use of marine resources to generate economic growth, improve livelihoods, and maintain ecosystem health (World Bank, 2017). Fisheries, aquaculture, seaweed cultivation, marine biotechnology, and coastal tourism all represent important blue economy sectors capable of contributing to food security and poverty reduction when managed sustainably (OECD, 2023; FAO, 2024).

Complementing the blue economy concept is the principle of strong sustainability, which argues that natural capital cannot be fully replaced by human-made capital or technological innovation (Neumayer, 2013). In marine systems, natural capitals include fish stocks, coral reefs, mangroves, seagrass ecosystems, biodiversity, and ecological processes that underpin food production. Recent evidence suggests that many marine ecosystems are approaching ecological thresholds due to overexploitation, pollution, and climate change (Bennett *et al*., 2021). Restoration and conservation of marine ecosystems can simultaneously enhance biodiversity, fisheries productivity, carbon sequestration, and food security outcomes (Duarte *et al*., 2020).

2.5. Towards a Global Marine Food Security Index (GMFSI)

Existing food security assessment tools such as the Global Food Security Index (GFSI), the Food Insecurity Experience Scale (FIES), and selected Sustainable Development Goal indicators provide valuable insights into national food systems but remain largely oriented toward terrestrial agriculture (Economist Impact, 2022; FAO, 2023). Consequently, they often fail to adequately capture the contributions of fisheries, aquaculture, seaweed farming, and marine ecosystem services to food security and nutrition, particularly in coastal and island nations where aquatic foods play a central role in livelihoods and diets (Golden *et al*., 2021; FAO, 2024).

This limitation is particularly relevant for developing countries such as Indonesia, India, and Tanzania, where marine resources constitute a major source of food, employment, export earnings, and poverty alleviation. Existing indices also tend to underrepresent ecological dimensions such as fish stock sustainability, ecosystem health, and climate vulnerability, despite their critical importance for long-term food security (IPCC, 2023; Bennett *et al*., 2021). Accordingly, there is a growing need for a Global Marine Food Security Index (GMFSI) that explicitly incorporates marine-specific indicators. Such a framework should include fisheries production, aquaculture performance, seaweed production, fish consumption, aquatic protein contribution, fisheries employment, marine ecosystem health, governance effectiveness, and climate resilience indicators. By integrating these dimensions, the GMFSI would provide a more comprehensive assessment of marine food security and support evidence-based policymaking aimed at strengthening sustainable blue food systems in developing countries (FAO, 2024; Golden *et al*., 2021; Costello *et al*., 2023).

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3. Marine Food Security Status in Indonesia, India, and Tanzania

3.1. Indonesia

Marine Resource Profile: Indonesia possesses one of the world's most extensive and biologically diverse marine environments. As the largest archipelagic nation, approximately 6.4 million km² of marine territory, the country occupies a strategic position within the Coral Triangle, widely recognized as the global center of marine biodiversity (Ministry of Marine Affairs and Fisheries, 2024; FAO, 2024). Indonesian waters support exceptionally rich fisheries resources, coral reefs, mangrove forests, seagrass ecosystems, and marine habitats that underpin food production, livelihoods, and ecosystem services.

Indonesia ranks among the world's leading fish-producing nations. According to the latest national fisheries statistics, total fisheries production exceeds 24 million tonnes annually, with aquaculture contributing a larger share than capture fisheries (Ministry of Marine Affairs and Fisheries, 2024). Aquaculture has expanded rapidly over the past two decades, particularly in shrimp, milkfish, tilapia, catfish, and seaweed production, making the sector a critical contributor to national food security and economic growth (FAO, 2024). Seaweed cultivation represents one of Indonesia's most important marine industries. Indonesia is consistently ranked among the world's largest producers of tropical seaweeds, particularly *Kappaphycus alvarezii* (Aslan, *et al*., 2020; Hasriah, *et al*. 2019) and *Eucheuma denticulatum* (Aslan *et al*., 2024a, b), which serve as primary raw materials for carrageenan production (FAO, 2024). The seaweed sector supports hundreds of thousands of coastal households while contributing significantly to export earnings and rural development (Valderrama *et al*., 2015).

Contribution to Food Security: Marine resources play a central role in Indonesia's food and nutrition security. Fish remains one of the most important animal protein sources in the national diet. Per capita fish consumption has increased substantially during the last decade and now exceeds 55 kg per person annually, reflecting both growing availability and increasing public awareness of nutritional benefits (Ministry of Marine Affairs and Fisheries, 2024). The fisheries and aquaculture sectors provide direct and indirect employment for millions of Indonesians. Small-scale fisheries are particularly important in remote coastal and island communities where alternative livelihood opportunities remain limited (FAO, 2024). Beyond employment, fisheries products constitute an important source of export revenue. Indonesia is among the world's largest exporters of shrimp, tuna, seaweed products, and other seafood commodities, generating substantial foreign exchange earnings and supporting national economic development (World Bank, 2023).

Major Vulnerabilities: Despite its enormous marine resource base, Indonesia faces several challenges that threaten long-term marine food security. Climate change has emerged as a major concern through rising sea surface temperatures, ocean acidification, changing fish migration patterns, and increased frequency of extreme weather events (IPCC, 2023). Recent studies suggest that tropical fisheries may experience significant declines in productivity as ocean warming intensifies (Cheung *et al*., 2016). Coastal ecosystem degradation further threatens fisheries productivity. Indonesia has experienced substantial losses of mangroves, coral reefs, and seagrass habitats due to coastal development, destructive fishing practices, pollution, and land-use change (UNEP, 2021). These ecosystems provide essential nursery grounds and ecological functions that sustain fisheries' production.

In several regions, mining-related pollution has become an emerging threat to marine food systems. Nickel, cobalt, and other mineral extraction activities in eastern Indonesia have been associated with sedimentation, heavy metal contamination, and declining coastal water quality, raising concerns about impacts on fisheries, aquaculture, and seaweed farming systems (World Bank, 2022; UNEP, 2021). Governance challenges, including illegal, unreported, and unregulated (IUU) fishing, overlapping institutional mandates, and enforcement limitations, continue to complicate sustainable resource management (FAO, 2024).

3.2. India

Marine Resource Profile: Marine fisheries, inland fisheries, and aquaculture in India collectively contribute to food security, employment, and economic development throughout the country. The fisheries sector has experienced remarkable growth, particularly through the expansion of aquaculture. India is currently among the world's largest aquaculture producers, with freshwater aquaculture accounting for a substantial share of total fish production (FAO, 2024). Species such as carp, shrimp, catfish, and freshwater prawns dominate production systems and contribute significantly to domestic food supplies and exports. Coastal fisheries remain equally important, particularly along the eastern and western seaboards. Marine capture fisheries support millions of fishers and provide valuable sources of protein and micronutrients for coastal populations (Government of India, 2024).

Contribution to Food Security: Fish and aquatic foods play a critical role in improving dietary quality and nutritional security in India. Although fish consumption varies considerably across regions and cultural groups, aquatic foods provide essential proteins, omega-3 fatty acids, and micronutrients for millions of households (Thilsted *et al*., 2016). The fisheries sector supports more than 28 million livelihoods through fishing, aquaculture, processing, marketing, and associated industries (FAO, 2024). Beyond its nutritional role, the sector contributes substantially to national income, rural development, and export earnings. India is among the world's largest exporters of shrimp and other seafood products, making fisheries an important component of the country's blue economy strategy (Government of India, 2024).

Major Vulnerabilities: India faces growing marine food security challenges associated with overexploitation of fish stocks, environmental degradation, and climate change. Several commercially important marine fisheries are experiencing increasing fishing pressure, raising concerns regarding long-term sustainability (FAO, 2024). Coastal pollution presents another major threat. Industrial discharge, agricultural runoff, urban wastewater, and plastic pollution have degraded water quality in many coastal regions, affecting both fisheries productivity and ecosystem health (UNEP, 2021). Climate variability further compounds these challenges. Rising sea temperatures, changing monsoon patterns, cyclones, and sea-level rise have increased uncertainty for fishers and aquaculture producers. Climate-induced shifts in species distributions may alter resource availability and affect food security among vulnerable coastal communities (IPCC, 2023; Allison *et al*., 2009).

3.3. Tanzania

Marine Resource Profile: Tanzania possesses approximately 1,424 km of coastline along the Western Indian Ocean and supports diverse marine ecosystems, including coral reefs, mangrove forests, estuaries, and seagrass meadows (United Republic of Tanzania, 2024). Although the country's fisheries sector is smaller than those of Indonesia and India, marine resources remain critically important for food security and livelihoods. Small-scale fisheries dominate marine production systems. Artisanal fishers account for the majority of marine catches and provide fish supplies for local and regional markets (FAO, 2024). These fisheries target a wide range of species, including reef fish, pelagic fish, crustaceans, and mollusks.

Tanzania is one of Africa’s leading producers of farmed seaweed. In particular, seaweed cultivation in Zanzibar has become a key livelihood activity for coastal households, especially women, contributing significantly to income generation, poverty reduction, and livelihood diversification within coastal communities (Msuya and Hurtado, 2017; Tobisson *et al*., 2021; Charisiadou *et al*., 2022). Coral reef ecosystems also represent a critical ecological asset supporting fisheries productivity, biodiversity conservation, tourism, and coastal protection. However, these ecosystems are increasingly threatened by climate change and human activities (UNEP, 2021).

Contribution to Food Security: Marine resources play a particularly important role in supporting coastal livelihoods and rural nutrition. Fish provides one of the most accessible and affordable animal protein sources for many Tanzanian households, particularly in coastal communities where poverty rates remain relatively high (FAO, 2024). Seaweed farming has emerged as a particularly important component of coastal livelihood diversification and women’s economic empowerment in Tanzania. Seaweed aquaculture significantly enhances household income stability and provides accessible employment opportunities for women in rural coastal communities, where alternative livelihood options are often limited (Msuya and

Hurtado, 2017; Sultana *et al*., 2022 Tobisson *et al*., 2021). However, despite these benefits, the sector remains vulnerable to climate-induced stressors such as ocean warming and disease outbreaks, as well as market instability within global value chains, which collectively constrain long-term sustainability (Tobisson *et al*., 2021; FAO, 2022).

Major Vulnerabilities: Tanzania's marine food systems face significant vulnerabilities linked to climate change, infrastructure limitations, and governance capacity constraints. Coral bleaching, rising sea temperatures, and changing oceanographic conditions threaten fisheries productivity and ecosystem resilience (IPCC, 2023). Infrastructure deficiencies remain a major barrier to food security. Limited cold storage facilities, inadequate transportation networks, and high post-harvest losses reduce the efficiency of marine food supply chains and constrain market access for small-scale producers (World Bank, 2023). Governance challenges also persist. Resource monitoring, fisheries enforcement, and institutional coordination remain constrained by limited financial and technical capacity, making sustainable fisheries management more difficult to achieve (FAO, 2024).

3.4. Comparative Analysis

A comparison of Indonesia, India, and Tanzania reveals both common challenges and important differences in marine food security systems (Table 7.1). The comparative assessment reveals substantial differences in the scale, structure, and dependence of marine food systems across Indonesia, India, and Tanzania, despite their shared reliance on aquatic resources for food security, employment, and economic development (FAO, 2024; Béné *et al*., 2016). Together, these countries represent diverse marine socio-ecological systems spanning Southeast Asia, South Asia, and East Africa, providing valuable insights into the opportunities and challenges of strengthening marine food security in developing countries (Allison *et al*., 2009; Cinner *et al*., 2012).

Indonesia possesses the largest marine territory and one of the world's most productive marine economies. Located within the Coral Triangle, Indonesia hosts some of the highest levels of marine biodiversity globally and supports extensive capture fisheries, aquaculture industries, and seaweed farming systems (FAO, 2024; Ministry of Marine Affairs and Fisheries of Indonesia, 2024). Total fisheries and aquaculture production exceeds 24 million tonnes annually, making Indonesia one of the leading aquatic food producers worldwide (FAO, 2024). Furthermore, Indonesia dominates global tropical seaweed production and contributes a substantial share of the world's carrageenan-producing seaweed supply, generating employment and export earnings for coastal communities (Valderrama *et al*., 2015; FAO, 2024).

India, in contrast, possesses one of the world's largest fisheries and aquaculture sectors and supports the largest fisheries workforce among the three countries examined (Government of India, 2024; FAO, 2024). The rapid expansion of freshwater aquaculture has transformed India into one of the world's leading aquaculture producers, significantly contributing to domestic food supplies and export growth (FAO, 2024; Costello *et al*., 2023). Although average per capita fish consumption remains relatively low compared with Indonesia, fisheries and aquaculture provide livelihoods for millions of households and play a critical role in improving food and nutrition security in several coastal and inland regions (Thilsted *et al*., 2016; Golden *et al*., 2021).

Tanzania operates on a considerably smaller production scale than Indonesia and India but exhibits a relatively high dependence on marine resources among coastal populations (United Republic of Tanzania, 2024; FAO, 2024). Small-scale fisheries constitute the backbone of marine food production and livelihood systems, while seaweed farming has emerged as one of the country's most important coastal economic activities, particularly in Zanzibar, where it contributes significantly to women's employment and household income diversification (Valderrama *et al*., 2015). Despite lower production volumes, marine resources remain vital for food security and poverty reduction among vulnerable coastal communities (Béné *et al*., 2016).

A notable distinction among the three countries concerns the role and development of seaweed production. Indonesia is recognized as the world's leading producer of tropical carrageenan seaweeds, accounting for a substantial proportion of global output (FAO, 2024; Valderrama *et al*., 2015). Tanzania remains Africa's most important seaweed-producing nation and has established a globally recognized smallholder-based seaweed industry, although production volumes remain significantly lower than those of Indonesia (Valderrama *et al*., 2015). India possesses substantial biophysical potential for seaweed cultivation and has recently introduced policies aimed at accelerating the development of a domestic seaweed industry as part of its blue economy strategy (Government of India, 2024).

From a nutritional perspective, Indonesia records the highest fish consumption levels among the three countries, exceeding 58 kg per capita annually, reflecting both strong domestic supply and cultural acceptance of fish-based diets (Ministry of Marine Affairs and Fisheries of Indonesia, 2024). By comparison, per capita fish consumption in India and Tanzania remains below global averages, suggesting considerable opportunities to improve dietary quality and micronutrient intake through increased access to aquatic foods (Golden *et al*., 2021; Hicks *et al*., 2019). Aquatic foods are increasingly recognized as highly nutrient-dense sources of protein, essential fatty acids, vitamins, and minerals that can contribute significantly to addressing malnutrition and micronutrient deficiencies in developing countries (Golden *et al*., 2021; Thilsted *et al*., 2016). The contribution of fisheries and aquaculture to employment also differs considerably among the three countries. India supports the largest fisheries-related workforce due to its extensive inland and coastal fisheries sectors, while Indonesia's fisheries and aquaculture industries provide employment opportunities for millions of fishers, fish farmers, processors, traders, and seaweed producers (FAO, 2024; Government of India, 2024). In Tanzania, marine livelihoods remain concentrated within small-scale fisheries and seaweed farming, making coastal communities particularly sensitive to environmental and economic shocks (Allison & Ellis, 2001; Béné *et al*., 2016).

Table 7.1. Comparative Marine Food Security Indicators in Indonesia, India, and Tanzania (Latest Available Data: 2024–2025)

Indicator	Indonesia	India	Tanzania
Population (million people)	~284.4	~1,463.9	~69.4
Coastline Length (km)	~108,000	~7,516	~1,424
Exclusive Economic Zone (EEZ) (million km²)	~6.4	~2.37	~0.24
Total Fisheries & Aquaculture Production (million tonnes/year)	~24.7	~18.9	~0.73
Capture Fisheries Production (million tonnes/year)	~7.3	~5.3	~0.40
Aquaculture Production (million tonnes/year)	~17.4	~13.6	~0.33
Seaweed Production (wet weight; million tonnes/year)	~9.5–10.2	~0.05	~0.015
Per Capita Fish Consumption (kg/person/year)	~58–60	~9–10	~8–9
Employment in Fisheries & Aquaculture (million people)	~12.5	~28.0	~4.5
Contribution of Fisheries to GDP (%)	~2.6	~1.1	~1.7
Seafood Export Value (USD billion/year)	~6.5–7.0	~8.1–8.5	~0.3
Share of Population Living in Coastal Areas (%)	~55	~30	~25
Major Aquatic Food Sources	Marine fish, tuna, shrimp, seaweed	Inland fish, shrimp, marine fish	Small pelagics, reef fish, seaweed
Main Marine Food Security Vulnerabilities	Climate change, mining pollution, coastal degradation, IUU fishing	Overfishing, pollution, climate variability	Climate impacts, weak infrastructure, governance limitations

Sources: FAO (2024); Ministry of Marine Affairs and Fisheries of Indonesia (2024); Government of India (2024); United Republic of Tanzania (2024); World Bank (2023); United Nations (2024).

Despite differences in production systems and economic scale, all three countries face a common set of marine food security challenges. Climate change is increasingly affecting marine ecosystems through ocean warming, marine heatwaves, sea-level rise, ocean acidification, and shifts in species distribution, thereby threatening fisheries productivity and food security outcomes (IPCC, 2023; Hoegh-Guldberg *et al*., 2019; Allison *et al*., 2009). These impacts are expected to be particularly severe in tropical developing countries, where adaptive capacity often remains limited (IPCC, 2023).

Marine ecosystem degradation represents another shared concern. Coastal pollution, habitat loss, mangrove degradation, coral reef decline, and unsustainable fishing practices continue to undermine the ecological foundations of marine food production (UNEP, 2021; Duarte *et al*., 2020). Indonesia faces increasing pressures from coastal industrialization and mining-related pollution, particularly in nickel-producing regions where sedimentation and heavy metal contamination have raised concerns regarding fisheries and seaweed farming sustainability (World Bank, 2022; UNEP, 2021). India faces significant challenges associated with coastal pollution, urban wastewater discharge, plastic pollution, and intensive fishing pressure (Government of India, 2024; UNEP, 2021). Tanzania's principal constraints relate to limited infrastructure, post-harvest losses, restricted market access, and institutional capacity limitations (United Republic of Tanzania, 2024; World Bank, 2023).

Governance effectiveness remains a critical determinant of marine food security outcomes across all three countries. Challenges such as illegal, unreported, and unregulated (IUU) fishing, fragmented institutional arrangements, inadequate monitoring systems, and enforcement limitations continue to affect resource sustainability and economic efficiency (FAO, 2024; OECD, 2023). Strengthening fisheries governance through ecosystem-based fisheries management, community co-management systems, marine spatial planning, and improved monitoring frameworks has therefore become an increasingly important policy priority (Ostrom, 2009; Berkes *et al*., 2003; FAO, 2024).

Taken together, these similarities and differences provide valuable opportunities for comparative policy learning. Indonesia's success in developing globally competitive seaweed value chains, India's experience in scaling aquaculture production, and Tanzania's community-based fisheries and coastal resource management initiatives offer complementary lessons for strengthening marine food security across developing countries (FAO, 2024; World Bank, 2023). A comparative perspective suggests that future policy interventions should simultaneously address ecological sustainability, nutritional outcomes, livelihood resilience, and governance effectiveness within an integrated blue food systems framework (Costello *et al*., 2023; Golden *et al*., 2021; FAO, 2024).

Table 7.2. Marine Food Security Risk Profile in Indonesia, India, and Tanzania

Dimension	Indonesia	India	Tanzania
Climate Vulnerability	High	High	Very High
Overfishing Pressure	Moderate–High	High	Moderate
Coastal Pollution Risk	High	Very High	Moderate
Seaweed Development Potential	Very High	High	High
Aquaculture Expansion Potential	Very High	Very High	Moderate
Governance Effectiveness	Moderate	Moderate	Low–Moderate
Blue Economy Readiness	High	High	Moderate
Marine Biodiversity Importance	Very High	High	High
Food Security Dependence on Aquatic Foods	High	Moderate	High
Adaptive Capacity	Moderate	Moderate–High	Low

Sources: FAO (2024); IPCC (2023); World Bank (2023); OECD (2023); Allison *et al*. (2009).

A notable distinction among the three countries is the role of seaweed production. Indonesia dominates global tropical seaweed production, contributing nearly 40% of world output, whereas Tanzania remains Africa's leading producer despite substantially lower production volumes. India has significant potential for seaweed expansion but remains at an earlier stage of industrial development relative to Indonesia (FAO, 2024; Valderrama *et al*., 2015). From a nutritional perspective, Indonesia records the highest fish consumption levels, exceeding 58 kg per capita annually, while India and Tanzania remain below 10 kg per capita. This disparity suggests considerable opportunities to enhance dietary quality and micronutrient intake through greater utilization of aquatic foods in both India and Tanzania (Golden *et al*., 2021; Hicks *et al*., 2019).

Despite differences in scale and production systems, the three countries face several common challenges, including climate change, ecosystem degradation, fisheries overexploitation, and governance limitations (Table 7.2). These shared vulnerabilities highlight the need for integrated marine food security policies that combine ecosystem-based fisheries management, sustainable aquaculture development, climate adaptation strategies, and blue economy approaches (IPCC, 2023; FAO, 2024; OECD, 2023).

4. Major Marine Food Security Challenges

Recent studies further demonstrate that aquatic foods have the potential to play a transformative role in addressing global malnutrition and enhancing the sustainability of food systems, particularly in low- and middle-income countries where nutrient deficiencies remain widespread (Golden *et al*., 2021; Hicks *et al*., 2019). Despite these opportunities, marine food systems are increasingly challenged by climate change, overexploitation of marine resources, habitat degradation, pollution, governance weaknesses, and socioeconomic inequalities (IPCC, 2023; FAO, 2024; Costello *et al*., 2023).

4.1. Climate Change

Climate change is widely recognized as one of the most significant long-term threats to marine food security. The ocean has absorbed the majority of excess heat generated by anthropogenic greenhouse gas emissions, leading to ocean warming, marine heatwaves, ocean acidification, and sea-level rise (IPCC, 2023). These environmental changes directly affect marine productivity, species distribution, ecosystem functioning, and fisheries-dependent livelihoods (Allison *et al*., 2009; Cheung *et al*., 2016).

Ocean warming has already altered the geographic distribution of many commercially important fish species, resulting in shifts in fisheries productivity and access to marine resources (Cheung *et al*., 2016). Such changes disproportionately affect developing countries where adaptive capacity remains limited and where coastal communities rely heavily on local fish stocks for food and income (Allison *et al*., 2009). Marine heatwaves have become more frequent and intense over recent decades. These extreme events contribute to coral bleaching, mass mortality of marine organisms, and reductions in ecosystem productivity (Hoegh-Guldberg *et al*., 2019). Coral reef degradation is particularly concerning because reef ecosystems support approximately one-quarter of all marine species and contribute substantially to fisheries production and food security in tropical regions (United Nations, 2021).

Ocean acidification further threatens marine food systems by reducing calcification rates in shell-forming organisms and compromising coral reef resilience (IPCC, 2023). Sea-level rise also increases coastal erosion, flooding, saltwater intrusion, and damage to fisheries infrastructure, creating additional challenges for marine food production and distribution systems. Recent projections suggest that climate change may significantly reduce fisheries productivity in tropical developing countries by the middle of this century if adaptive management strategies are not implemented (Cheung *et al*., 2016; Costello *et al*., 2023).

Indonesia: Indonesia faces increasing climate-related risks due to its extensive coastline, dependence on marine resources, and location within the Coral Triangle. Rising sea surface temperatures have contributed to repeated coral bleaching events and changes in fish migration patterns, affecting fisheries productivity and small-scale fishing livelihoods (Hoegh-Guldberg *et al*., 2019; Ministry of Marine Affairs and Fisheries of Indonesia, 2024).

India: India's fisheries sector is increasingly affected by ocean warming, cyclones, coastal flooding, and changing fish distributions. These impacts threaten food security and economic stability for millions of fishers and aquaculture producers (Government of India, 2024; IPCC, 2023).

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Tanzania: In Tanzania, climate change has adversely affected coral reef ecosystems and seaweed farming activities, particularly in Zanzibar. Rising seawater temperatures have reduced seaweed productivity and increased vulnerability among coastal households that depend on marine resources for their livelihoods (Valderrama *et al*., 2015; United Republic of Tanzania, 2024).

4.2. Overfishing and Resource Depletion

Overfishing remains one of the most persistent drivers of marine food insecurity globally. According to FAO (2024), approximately 37.7% of assessed marine fish stocks are currently overfished, indicating a continued decline in the sustainability of global fisheries resources. Unsustainable fishing practices, excessive fishing effort, technological intensification, and weak fisheries governance have contributed to declining fish stocks in many coastal regions (Pauly & Zeller, 2016; FAO, 2024). Illegal, unreported, and unregulated (IUU) fishing further exacerbates resource depletion and undermines fisheries management efforts.

Declining fish stocks directly reduce food availability and threaten the nutritional benefits that aquatic foods provide. Hicks *et al*. (2019) demonstrated that sustainable fisheries management could substantially reduce global micronutrient deficiencies because many fish species are rich sources of bioavailable iron, zinc, calcium, vitamin A, and omega-3 fatty acids. Consequently, overfishing represents not only an ecological challenge but also a nutrition and public health concern. The economic consequences are equally significant. Reduced catches lower fisher incomes, increase seafood prices, and disproportionately affect small-scale fisheries, which are often the primary source of employment and food security in coastal communities (Béné *et al*., 2016; Allison & Ellis, 2001).

4.3. Marine Pollution and Habitat Degradation

Marine pollution has emerged as a major threat to the sustainability of aquatic food systems. Sources of pollution include plastic debris, industrial effluents, mining waste, untreated wastewater, agricultural runoff, and coastal urbanization (UNEP, 2021). Plastic pollution is particularly concerning because microplastics are increasingly detected throughout marine food webs, raising concerns regarding seafood safety and ecosystem health (UNEP, 2021). Industrial and mining-related pollution may introduce heavy metals and toxic contaminants into coastal ecosystems, negatively affecting fisheries resources and aquaculture production. Habitat degradation compounds these challenges. Coral reefs, mangroves, and seagrass meadows provide critical ecosystem services that support fisheries productivity, biodiversity conservation, carbon sequestration, and coastal protection (Duarte *et al*., 2020). The loss of these habitats undermines the ecological foundations of marine food security.

Indonesia faces increasing environmental pressures associated with coastal development and mining activities, particularly in regions experiencing rapid nickel extraction and industrial expansion. Sedimentation and heavy-metal contamination have raised concerns regarding fisheries sustainability and seaweed cultivation (World Bank, 2022). Similar challenges are observed in India through industrial discharge and urban wastewater pollution, while Tanzania continues to experience habitat degradation associated with coastal development and resource extraction (UNEP, 2021; United Republic of Tanzania, 2024).

4.4. Governance and Institutional Constraints

Effective governance is essential for maintaining sustainable marine food systems. However, many developing countries continue to face institutional weaknesses that limit their ability to manage fisheries resources effectively. Common governance challenges include fragmented institutions, inadequate enforcement capacity, insufficient scientific data, weak monitoring systems, and limited stakeholder participation (OECD, 2023; FAO, 2024). These constraints often contribute to resource depletion, regulatory non-compliance, and conflicts among resource users. The social-ecological systems framework developed by Ostrom (2009) highlights the importance of adaptive governance arrangements capable of responding to environmental change and resource scarcity. Similarly, Berkes *et al*. (2003) emphasize that community participation and co-management approaches can enhance resource stewardship and improve long-term sustainability outcomes. Strengthening governance is therefore fundamental to improving marine food security, particularly in countries where fisheries remain central to livelihoods and nutrition.

4.5. Socioeconomic Vulnerabilities

Marine food security challenges are closely linked to broader socioeconomic conditions. Poverty, inequality, limited access to markets, and inadequate financial services increase vulnerability among fishing and aquaculture communities (Allison & Ellis, 2001; Béné *et al*., 2016). Small-scale fisheries are particularly important in developing countries because they provide employment, income, and affordable food for millions of people (HLPE, 2014). However, many small-scale fishers remain marginalized within national economies and face barriers to accessing credit, technology, insurance, and formal markets. Gender inequality further exacerbates vulnerability. Women contribute substantially to fish processing, marketing, and seaweed farming but frequently encounter limited access to productive assets and decision-making processes (HLPE, 2014; FAO, 2024).

4.6. Post-Harvest Losses and Supply Chain Weaknesses

Post-harvest losses remain a significant but often overlooked challenge within marine food systems. In many developing countries, inadequate cold storage facilities, poor transportation infrastructure, and inefficient supply chains result in substantial losses of fish and seafood products before they reach consumers (FAO, 2024). These losses reduce food availability, decrease fisher incomes, and undermine efforts to improve nutrition security. Given that aquatic foods are among the most nutrient-dense foods available, reducing post-harvest losses could significantly improve food system efficiency and nutrition outcomes (Golden *et al*., 2021; Thilsted *et al*., 2016).

4.7. Emerging Challenges

Beyond traditional environmental and governance concerns, marine food systems face new pressures arising from urbanization, competing ocean uses, and offshore development activities. Rapid coastal urbanization increases demand for land, infrastructure, and marine resources while generating additional pollution and habitat degradation (UNEP, 2021). Simultaneously, marine space is increasingly contested by tourism, shipping, conservation initiatives, offshore aquaculture, renewable energy projects, and seabed mining operations (OECD, 2023). As highlighted by Costello *et al*. (2023), future marine food systems must balance food production objectives with biodiversity conservation, climate adaptation, and blue economy development. Achieving this balance will require integrated ocean governance, ecosystem-based management, marine spatial planning, and cross-sectoral policy coordination (FAO, 2024; World Bank, 2017).

5. Policy Solutions for Marine Food Security

Achieving marine food security in developing countries requires policy interventions that simultaneously address ecological sustainability, nutritional outcomes, economic development, and social equity. The interconnected nature of marine food systems means that solutions cannot focus solely on increasing production; rather, they must strengthen ecosystem resilience, improve governance, enhance livelihood opportunities, and ensure equitable access to nutritious aquatic foods. Recent global assessments emphasize that sustainable fisheries, responsible aquaculture, ecosystem restoration, climate adaptation, and blue economy transformation are essential components of future food security strategies (FAO, 2024; Costello *et al*., 2023; Golden *et al*., 2021). For countries such as Indonesia, India, and Tanzania, where millions of people depend directly on marine resources for food and livelihoods, integrated policy approaches are particularly important for achieving sustainable development and the Sustainable Development Goals (SDGs).

5.1. Ecosystem-Based Fisheries Management

Core Principles

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Ecosystem-Based Fisheries Management (EBFM) has emerged as a leading framework for achieving long-term sustainability in fisheries while maintaining ecosystem integrity. Unlike conventional single-species management approaches, EBFM recognizes the interconnected relationships among fish stocks, habitats, biodiversity, environmental processes, and human activities (FAO, 2024; Pikitch *et al*., 2004). The ecosystem approach incorporates ecological interactions, cumulative environmental impacts, and socioeconomic considerations into fisheries management decisions. This perspective is particularly important under conditions of climate change, where ecosystem dynamics are becoming increasingly unpredictable (IPCC, 2023).

Adaptive management constitutes another key principle of EBFM. Fisheries management systems must be capable of responding to changing environmental conditions, emerging scientific knowledge, and evolving socioeconomic circumstances (Ostrom, 2009). Adaptive approaches rely on continuous monitoring, stakeholder engagement, and policy learning. Stakeholder participation is equally critical. Small-scale fishers, coastal communities, local governments, and indigenous groups often possess valuable ecological knowledge that can complement scientific assessments and improve compliance with management measures (Berkes *et al*., 2003).

Expected Outcomes

The implementation of ecosystem-based fisheries management can generate multiple benefits, including sustainable fish stock recovery and maintenance, improved ecosystem resilience, enhanced biodiversity conservation, reduced fishing conflicts, and increased long-term food security alongside greater socioeconomic stability for coastal communities. Evidence from marine protected areas and co-management systems demonstrates that ecosystem-based approaches can simultaneously improve ecological outcomes and fisheries productivity (Berkes *et al*., 2003; FAO, 2024).

Beyond ecological restoration, ecosystem-based fisheries management (EBFM) strengthens governance systems by integrating ecological knowledge with local institutions and stakeholder participation. This participatory approach improves compliance, enhances legitimacy of management decisions, and reduces enforcement costs, particularly in data-limited and small-scale fisheries systems. Studies have shown that leadership, social capital, and incentive structures are critical determinants of successful fisheries governance, where well-designed co-management arrangements can significantly improve resource sustainability and reduce overexploitation (Gutiérrez *et al*., 2011; Pomeroy and Andrew, 2011). In this context, social-ecological systems thinking provides a foundational framework for understanding the complex interactions between ecological dynamics and human behavior in fisheries management (Berkes *et al*., 2003).

Furthermore, ecosystem-based approaches contribute to long-term climate adaptation and risk reduction by enhancing the resilience of marine ecosystems and dependent coastal livelihoods. Healthy and well-managed fisheries systems are better able to withstand external shocks such as ocean warming, acidification, and extreme weather events. By maintaining habitat integrity and functional biodiversity, EBFM supports ecosystem services that underpin food security and income generation for vulnerable coastal populations. Recent global assessments emphasize that integrating ecosystem-based principles into fisheries policy is critical for achieving sustainable ocean governance and the objectives of the Blue Transformation agenda, as well as strengthening resilience under accelerating climate change (IPCC, 2022; FAO, 2024).

5.2. Sustainable Aquaculture Development

Aquaculture has become the fastest-growing food production sector globally and now contributes more aquatic foods for direct human consumption than capture fisheries (FAO, 2024). In the context of increasing pressure on wild fish stocks, climate change, and rising food demand, sustainable aquaculture development represents a critical pathway for strengthening marine food security, improving nutrition, and supporting coastal livelihoods in developing countries (Costello *et al*., 2023; FAO, 2024; Froehlich *et al*., 2018).

Climate-Smart Aquaculture

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Climate-smart aquaculture integrates adaptation and mitigation strategies into production systems with the aim of increasing productivity while reducing environmental impacts and enhancing resilience to climate variability and extreme events (FAO, 2024; Troell *et al*., 2014). These approaches are increasingly recognized as essential for sustaining aquaculture growth under changing ocean conditions, including warming temperatures, ocean acidification, and increasing disease outbreaks (Barange *et al*., 2018).

Climate-smart practices typically include improved water quality and effluent management, selection of heat-tolerant and fast-growing species, development of disease-resistant strains, adoption of energy-efficient technologies, and the promotion of integrated and circular production systems. Collectively, these innovations enhance system resilience while reducing greenhouse gas emissions and environmental externalities associated with aquaculture intensification (Boyd *et al*., 2020; FAO, 2024).

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) combines species from different trophic levels within a single production system, enabling nutrient recycling and improving ecological efficiency. In IMTA systems, waste generated by fed species becomes a resource for extractive species, thereby reducing environmental impacts and improving overall system productivity (Troell *et al*., 2009; Chopin *et al*., 2012).

For example, finfish release nutrient-rich waste that can be assimilated by seaweed, while shellfish filter suspended particles from the water column. This synergistic interaction enhances nutrient retention, reduces eutrophication risks, and improves environmental performance compared to monoculture systems. In addition, IMTA contributes to income diversification for farmers by producing multiple marketable products within the same farming area, thereby increasing economic resilience in coastal communities (Chopin *et al*., 2012; Duarte *et al*., 2021).

Sustainable Feed Systems

The long-term sustainability of aquaculture is increasingly constrained by reliance on wild fish-derived feed ingredients such as fishmeal and fish oil. Consequently, innovation in alternative feed resources has become a key research and policy priority (Naylor *et al*., 2021; Tacon and Metian, 2015). Promising alternatives include algae-based feeds, insect meals, microbial proteins, and agricultural by-products, all of which contribute to reducing pressure on marine capture fisheries. These innovations not only improve resource-use efficiency but also enhance circularity within food systems by converting low-value biomass into high-value aquaculture inputs. Moreover, the development of novel feed ingredients is essential for decoupling aquaculture growth from marine resource extraction, thereby supporting more sustainable and climate-resilient aquatic food systems (Naylor *et al*., 2021; Froehlich *et al*., 2018).

Country Opportunities

Indonesia: Indonesia possesses significant potential for sustainable expansion of marine aquaculture, particularly in seaweed farming (Sahrir, *et al* 2014; Cahyani *et al*., 2020), mariculture, shrimp production, and integrated coastal aquaculture systems. The country's extensive coastline and favorable environmental conditions support diverse aquaculture development opportunities (Ministry of Marine Affairs and Fisheries of Indonesia, 2024).

India: India has become one of the world's largest aquaculture producers, largely driven by freshwater aquaculture systems such as carp and shrimp farming, which contribute significantly to national fish production and rural livelihoods. However, the sector is increasingly shifting toward diversification to enhance resilience, productivity, and environmental sustainability. Future opportunities are strongly aligned with the expansion of coastal mariculture, integrated aquaculture systems, and seaweed cultivation under the national Blue Economy framework (Government of India, 2024; FAO, 2024). In particular, coastal mariculture development in India is being promoted as a strategy to optimize underutilized coastal resources, reduce pressure on inland freshwater systems, and enhance export-oriented seafood production. Seaweed farming is emerging as a priority subsector, supported by government initiatives aimed at scaling production, improving seed supply chains, and strengthening value-added processing industries. These developments are

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expected to contribute not only to economic growth but also to ecosystem services such as nutrient removal and carbon sequestration, thereby supporting climate mitigation goals (FAO, 2024; World Bank, 2022).

Furthermore, integrated aquaculture systems, including Integrated Multi-Trophic Aquaculture (IMTA), are gaining attention as a means to improve resource-use efficiency and reduce environmental impacts. By combining finfish, shellfish, and seaweed production, these systems promote circular nutrient flows and diversify income streams for coastal communities. Such approaches are increasingly recognized as essential for achieving sustainable intensification of aquaculture under climate change and increasing global seafood demand (Troell *et al*., 2009; Costello *et al*., 2023). Strengthening institutional support, investment in technology transfer, and capacity building will therefore be critical for realizing India's Blue Economy potential in a sustainable and inclusive manner (World Bank, 2022).

Tanzania: Tanzania's aquaculture sector remains relatively underdeveloped but possesses substantial growth potential. Expansion of seaweed farming, milkfish culture, shellfish production, and community-based aquaculture could strengthen food security and rural livelihoods (United Republic of Tanzania, 2024; FAO, 2024). Seaweed farming, particularly in Zanzibar, already represents one of the most important coastal livelihood activities, providing income opportunities for smallholder farmers—especially women—and contributing to household economic stability in coastal communities (Msuya and Hurtado, 2017; Tobisson *et al*., 2021).

Despite this potential, the sector continues to face structural constraints including limited access to quality seed stock, weak value chains, inadequate processing infrastructure, and vulnerability to climate-related stressors such as rising sea surface temperatures and disease outbreaks in seaweed farms. These challenges constrain productivity and limit the scalability of aquaculture development. Strengthening institutional support, improving extension services, and enhancing investment in coastal aquaculture infrastructure are therefore essential to unlocking Tanzania's blue economy potential and ensuring inclusive growth (World Bank, 2022; FAO, 2024).

In addition, integrating ecosystem-based and climate-smart aquaculture approaches offers a pathway to improve sustainability and resilience. Practices such as Integrated Multi-Trophic Aquaculture (IMTA), improved farm zoning, and diversification into resilient species such as seaweed and bivalves can reduce environmental pressures while enhancing productivity. Such approaches also contribute to nutrient cycling, coastal ecosystem restoration, and climate adaptation in vulnerable marine environments (Troell *et al*., 2009; Barange *et al*., 2018). Aligning national aquaculture development strategies with global blue economy frameworks will therefore be critical for ensuring long-term sustainability and maximizing socio-economic benefits for coastal populations in Tanzania (FAO, 2024; IPCC, 2022).

5.3. Seaweed-Based Marine Food Security Strategy

Among emerging blue food solutions, seaweed represents one of the most promising resources for addressing food security, nutrition, environmental sustainability, and coastal development simultaneously. Recent studies have identified seaweed as a strategic component of future blue food systems capable of addressing micronutrient deficiencies and enhancing dietary diversity (Golden *et al*., 2021).

Environmental Benefits

Seaweed cultivation offers multiple environmental advantages, positioning it as one of the most sustainable forms of aquaculture within the emerging blue economy. Unlike terrestrial crops or intensive fed aquaculture systems, seaweed farming requires no freshwater irrigation, no synthetic fertilizers, and no external feed inputs, thereby substantially reducing pressure on land, freshwater, and terrestrial nutrient cycles. In addition, recent global assessments highlight that seaweed aquaculture has a comparatively low life-cycle carbon footprint and may contribute to climate change mitigation through avoided emissions and ecosystem-based production efficiencies, reinforcing its role in low-carbon food system transitions (Aslan *et al*., 2020c; Froehlich *et al*., 2019; Duarte *et al*., 2021; Costello *et al*., 2023; Duarte *et al*., 2017).

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Beyond resource-use efficiency, seaweed farming provides critical ecosystem services, particularly through nutrient bio extraction and participation in coastal biogeochemical cycling. Macroalgae assimilates dissolved inorganic carbon and excess nutrients such as nitrogen and phosphorus during growth, thereby contributing to carbon flux regulation and coastal water quality improvement. This capacity makes seaweed cultivation a promising nature-based solution for mitigating eutrophication in nutrient-enriched coastal zones, especially in regions affected by agricultural runoff and aquaculture effluents. Recent syntheses further emphasize the role of seaweed systems in supporting blue carbon pathways, although the permanence of carbon sequestration remains context-dependent and requires careful ecological accounting (Krause-Jensen *et al*., 2023; Duarte *et al*., 2017; Hurd *et al*., 2020).

Furthermore, integrated seaweed farming systems enhance ecosystem resilience by promoting habitat complexity and supporting marine biodiversity. Seaweed farms can function as artificial reef-like structures, offering refuge, nursery habitat, and feeding grounds for diverse marine organisms, thereby increasing local ecological heterogeneity. When integrated with finfish or shellfish culture under systems such as Integrated Multi-Trophic Aquaculture (IMTA), seaweed production contributes to circular nutrient flows and improved environmental performance of aquaculture systems. These multifunctional benefits position seaweed aquacultures not only as a food production strategy but also as a scalable nature-based solution aligned with global sustainability agendas, including climate mitigation, ocean health restoration, and sustainable food system transformation (Troell *et al*., 2023; FAO, 2024; Hasselström *et al*., 2021).

Economic Benefits

Seaweed production is vital for coastal livelihoods in Indonesia and Tanzania, contributing to income diversification, employment, export earnings, and value-added industries such as carrageenan and food products. As one of the fastest-growing marine food sectors, it is increasingly recognized as a key component of blue economy strategies due to its scalability and low environmental footprint (FAO, 2024; World Bank, 2022; Duarte *et al*., 2017). It also promotes social inclusion, particularly women's participation in farming, post-harvest processing, and marketing, thereby improving household income stability and welfare (Msuya and Hurtado, 2017; Tobisson *et al*., 2021; Troell *et al*., 2023). Expanding value chains further supports rural industrialization and export growth, although improvements in infrastructure, seed systems, and market access are required to enable smallholders to benefit fully (Hurd *et al*., 2020).

Policy Opportunities

Governments can promote seaweed as a strategic commodity for food security through its integration into school feeding programs, public nutrition interventions, hospital and military food procurement systems, social protection schemes, and broader national food diversification strategies. One illustrative example of government intervention in Indonesia as a strategic approach to food security is the incorporation of aquatic foods into national school feeding programs. Indonesia is currently intensifying efforts to improve population nutrition through the Free Nutritious Meals Program (*Makan Bergizi Gratis*/MBG). Launched in 2025, MBG is projected to become the largest and most financially significant social policy intervention in the country's history by 2026. The program is expected to reach approximately 82.9 million beneficiaries, the majority of whom are school-aged children, including around 48 million students, alongside toddlers, pregnant women, and breastfeeding mothers. This scale places MBG among the largest publicly funded school feeding and nutrition programs globally. Evidence from OECD countries further underscores the role of school-based nutrition programs in improving educational outcomes and reducing inequalities in human development trajectories (OECD, 2023). Within this context, MBG functions as a strategic policy instrument for addressing malnutrition, improving dietary quality, and enhancing long-term national productivity.

Within the broader development framework, marine food security and the MBG initiative are increasingly aligned under the emerging paradigm of blue food system transformation. Aquatic foods are now widely recognized as integral components of sustainable nutrition and global food security strategies. Marine food systems offer a continuous supply of nutrient-rich foods, particularly fish and seaweed, thereby supporting dietary diversification and strengthening the resilience of national nutrition programs (FAO, 2022; FAO,

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2024). Indonesia's position as one of the world's leading producers of farmed seaweed further enhances its potential as a scalable and cost-efficient food source for national school feeding programs.

The rationale for integrating seaweed into the MBG program is multifaceted. First, it contributes directly to improved child nutrition by providing essential micronutrients required for cognitive development, immune function, and physical growth. Second, its low input requirements and high availability make it well suited for large-scale implementation within Indonesia's extensive food distribution and education systems. Third, its inclusion in MBG is expected to generate positive spillover effects for coastal economies through increased demand for raw materials and the expansion of value-added processing activities within local supply chains. Fourth, sustained institutional demand from public nutrition programs can enhance market stability for seaweed producers and strengthen livelihood security in coastal communities. Fifth, the incorporation of seaweed-based meals may also foster early dietary awareness among school-aged populations regarding the nutritional benefits of aquatic foods. Empirical evidence from Aslan *et al*. (2025) indicates a very high willingness (approximately 95%) among students in Kendari, Southeast Sulawesi, Indonesia, to continue consuming seaweed following school-based nutritional interventions. In summary, the integration of seaweed into the MBG program should not be interpreted merely as a dietary supplementation strategy. Rather, it represents a structural policy innovation that advances a more sustainable, resilient, and inclusive national food system grounded in marine food security, human capital development, and the blue economy framework.

5.4. Strengthening Small-Scale Fisheries

Small-scale fisheries account for a substantial share of global fish production and support the livelihoods of hundreds of millions of people (HLPE, 2014). The FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (SSF Guidelines) provide a comprehensive framework for enhancing the social, economic, and environmental sustainability of small-scale fisheries (FAO, 2015).

Priority Areas

Securing Tenure Rights: Secure and well-defined resource access rights contribute to improved stewardship of marine resources and help reduce conflicts among fishing communities. Strengthening tenure systems also enhances accountability and encourages more sustainable resource use practices.

Financial Inclusion: Enhanced access to financial services including credit, savings facilities, insurance schemes, and digital financial platforms plays a critical role in strengthening the resilience of fishing households. Such financial instruments enable greater investment capacity, income smoothing, and risk management in the face of economic and environmental shocks.

Capacity Building: Capacity development programs should prioritize training in sustainable fishing practices, small-scale fisheries management, business and financial literacy, digital skills, and climate adaptation strategies. Investments in human capital of this nature are essential for improving productivity, strengthening adaptive capacity, and enhancing overall livelihood outcomes in coastal communities.

5.5. Climate Adaptation and Resilience

Climate adaptation has become a central pillar of marine food security policy, particularly in the context of increasing climate variability and extreme weather events.

Early Warning Systems: Strengthened early warning systems, including improved meteorological forecasting and ocean monitoring, are essential for reducing disaster risk and supporting informed decision-making among fishers and aquaculture producers (IPCC, 2023). These systems enhance preparedness and reduce operational and safety risks in marine-based livelihoods.

Climate-Resilient Aquaculture: Climate-resilient aquaculture strategies include diversification of species, selective breeding for stress tolerance, improved farm design, and integrated risk management planning. These measures collectively enhance system stability and reduce vulnerability to climate-induced shocks.

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Risk Insurance: Index-based and conventional insurance mechanisms provide an important safety net for fishers and aquaculture farmers by mitigating income losses resulting from climate-related disasters. Such instruments contribute to long-term resilience by stabilizing household income and supporting post-disaster recovery.

5.6. Combating Illegal, Unreported and Unregulated (IUU) Fishing

Illegal, unreported and unregulated (IUU) fishing remains a major threat to fisheries sustainability, undermining governance systems, depleting fish stocks, and reducing the economic and social benefits derived from marine resources (FAO, 2024). Addressing IUU fishing is therefore a critical component of effective marine resource management and food security policy.

Key Strategies

Vessel Monitoring Systems (VMS): The deployment of satellite-based vessel monitoring systems enhances real-time tracking of fishing activities, thereby strengthening compliance, surveillance, and enforcement capacity across fisheries jurisdictions.

Port State Measures: The FAO Port State Measures Agreement (PSMA) represents the first legally binding international instrument specifically designed to combat IUU fishing. It provides a globally recognized framework to prevent illegally harvested fish from entering domestic and international markets (FAO, 2016).

Traceability Systems: Digital traceability mechanisms across seafood value chains improve transparency, enable product verification, and strengthen accountability from harvest to final market destination. These systems are increasingly important for ensuring legal compliance and supporting sustainable seafood certification and trade governance.

5.7. Digital Transformation of Fisheries

Emerging digital technologies are creating significant opportunities to enhance marine resource management and improve the efficiency, transparency, and resilience of food systems.

Artificial Intelligence (AI): Artificial intelligence can support a wide range of fisheries and aquaculture applications, including fish stock assessment, catch and production forecasting, disease surveillance, and supply chain optimization. These capabilities improve decision-making and contribute to more efficient and sustainable resource use.

Remote Sensing: Satellite-based remote sensing technologies enable continuous monitoring of fishing activities, habitat conditions, ocean productivity, and climate-related changes. Such data are increasingly important for evidence-based fisheries management and ecosystem-based planning.

Mobile Applications: Mobile technologies play a critical role in improving access to essential services for coastal communities, including weather forecasts, market price information, digital financial transactions, and extension and advisory services. These tools enhance operational efficiency and support livelihood resilience.

Blockchain Traceability: Blockchain-based systems strengthen seafood traceability by providing secure, tamper-resistant records across supply chains. This improves transparency, reduces the risk of fraud, and enhances consumer confidence in seafood products (World Bank, 2023).

5.8. Blue Economy Transformation

Recent global policy and scientific assessments increasingly emphasize the role of aquatic food systems in achieving the Sustainable Development Goals (SDGs), particularly those related to zero hunger, climate action, and life below water. The Food and Agriculture Organization highlights that “Blue Transformation” strategies are required to expand sustainable aquaculture, improve fisheries governance, and enhance the contribution of aquatic foods to healthy diets and equitable development outcomes (FAO, 2024). Similarly, the World Bank and OECD underline that blue economy investments can generate substantial co-benefits when aligned with inclusive governance, ecosystem restoration, and value chain development in coastal regions (World Bank, 2022; OECD, 2023).

Within this transformation agenda, seaweed and other low-trophic aquaculture systems are increasingly recognized as strategic entry points for sustainable ocean-based food production. These systems require minimal external inputs, contribute to nutrient recycling, and offer scalable opportunities for climate-smart food production. Evidence further suggests that integrating aquatic foods into national food systems enhances both nutritional security and environmental sustainability, particularly in vulnerable coastal economies exposed to climate change impacts (FAO, 2022; Duarte *et al*., 2017). Consequently, strengthening marine food systems through a blue economy lens represents a critical pathway for aligning food security objectives with long-term ecological sustainability and economic resilience.

6. A Proposed Global Marine Food Security Index (GMFSI)

6.1. Rationale: Why a New Index is Needed

Food security has traditionally been assessed through indicators that emphasize terrestrial agriculture, household income, food affordability, and macroeconomic conditions. Widely used frameworks, including the Global Food Security Index (GFSI), the Food Insecurity Experience Scale (FIES), and national food security assessments, have significantly improved understanding of food access and availability. Nevertheless, these frameworks rarely distinguish the specific contributions of marine and aquatic food systems to food security outcomes, despite the growing recognition that aquatic foods are essential components of sustainable food systems (FAO, 2024; Golden *et al*., 2021).

Marine foods including fish, shellfish, seaweed, and other aquatic organisms—provide critical nutrients for billions of people worldwide. According to the Food and Agriculture Organization, global fisheries and aquaculture production reached 223.2 million tonnes in 2022, with aquatic foods supplying approximately 15% of animal protein consumed globally and substantially higher proportions in many coastal and island nations (FAO, 2024). In developing countries, marine resources support livelihoods, employment, export earnings, and local food systems, making them indispensable for both economic and nutritional security (Garcia and Rosenberg, 2010).

Despite this importance, current food security indices tend to treat fish and aquatic foods as minor components within broader food categories. Consequently, countries with highly productive marine sectors may receive food security assessments that inadequately reflect the contribution of fisheries, aquaculture, and seaweed farming to national well-being. Similarly, countries experiencing declines in fish stocks, coastal ecosystem degradation, or climate-induced disruptions to marine food systems may not be adequately identified as facing emerging food security risks.

Recent studies have highlighted the growing importance of aquatic foods in addressing global challenges associated with malnutrition, micronutrient deficiencies, and sustainable food production (Golden *et al*., 2016; Golden *et al*., 2021). At the same time, climate change, overfishing, habitat degradation, and illegal, unreported, and unregulated (IUU) fishing continue to threaten the capacity of marine ecosystems to provide food and livelihoods (Allison *et al*., 2009; Pauly and Zeller, 2016). These developments underscore the need for a dedicated measurement framework capable of capturing the multiple dimensions of marine food security. The proposed Global Marine Food Security Index (GMFSI) seeks to address this gap by providing a policy-oriented tool that evaluates the capacity of countries to produce, access, utilize, and sustain marine food resources. The index is intended not only to facilitate international comparisons but also to support evidence-based policymaking within the broader context of blue economy development, climate adaptation, and sustainable ocean governance.

6.2. GMFSI Framework

The GMFSI is conceptualized as a multidimensional composite index that integrates four interrelated dimensions of marine food security: Availability, Accessibility, Utilization, and Sustainability and Resilience. These dimensions build upon the classical food security framework developed by FAO while

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incorporating marine-specific considerations associated with ecosystem sustainability and climate vulnerability (HLPE, 2014; FAO, 2024).

Dimension 1: Availability: Availability refers to the capacity of marine systems to supply sufficient quantities of food to meet current and future demand. This dimension reflects the productive potential of fisheries, aquaculture, and seaweed farming. Proposed indicators include Fisheries production (kg per capita), Aquaculture production (kg per capita) and Seaweed production (kg per capita). Capture fisheries remain a major source of food and income for coastal populations worldwide, while aquaculture has become the fastest-growing food production sector globally (FAO, 2024). Seaweed production is increasingly recognized as an important contributor to food security, industrial development, and environmental sustainability, particularly in Asia and emerging cultivation regions in Africa and Latin America (Cai *et al*., 2021).

Dimension 2: Accessibility: Accessibility refers to the ability of individuals and communities to obtain marine foods through economic, physical, and social means. Proposed indicators include Fish affordability index, Employment in fisheries, aquaculture, and seaweed sectors and Market accessibility and infrastructure. Even when marine foods are abundant, barriers related to income, transportation, infrastructure, and market integration may limit access among vulnerable populations. Small-scale fisheries alone support the livelihoods of approximately 600 million people globally and play a central role in food access for many coastal communities (HLPE, 2014; FAO, 2024).

Dimension 3: Utilization: Utilization reflects the nutritional contribution of marine foods and the extent to which populations benefit from their consumption. Proposed indicators include Fish consumption per capita and Nutritional adequacy derived from marine foods. Fish and other aquatic foods provide highly bioavailable nutrients and other micronutrients necessary for human health (Golden *et al*., 2016; Golden *et al*., 2021). Consequently, this dimension captures the nutritional outcomes associated with marine food systems rather than merely measuring production levels.

Dimension 4: Sustainability and Resilience: Sustainability and resilience assess the long-term capacity of marine ecosystems and food systems to continue providing food under changing environmental and socio-economic conditions. Proposed indicators include Fish stock status, Ecosystem health. and Climate resilience. Evidence suggests that many fisheries are under increasing pressure from overexploitation, climate change, and habitat degradation (Pauly and Zeller, 2016). Furthermore, climate-driven changes in ocean temperature, productivity, and species distribution may significantly alter fisheries' yields and national food security outcomes, particularly in tropical developing countries (Allison *et al*., 2009). This dimension therefore ensures that countries are not rewarded solely with high production levels but also with maintaining the ecological foundations necessary for future food security.

6.3. Seaweed Security Sub-Index

A distinctive feature of the proposed GMFSI is the inclusion of a Seaweed Security Sub-Index (SSI). Although seaweed is increasingly recognized as a strategic component of future food systems, it remains largely absent from existing food security assessments.

The **Seaweed Security Sub-Index** is designed to capture the multidimensional role of seaweed within national food systems by integrating production, nutritional, socio-economic, and environmental dimensions into a single analytical framework. This sub-index recognizes seaweed not only as an aquaculture commodity but also as a strategic resource contributing to food security, livelihood resilience, and ecosystem sustainability. The sub-index consists of four core components:

Production assesses national seaweed production capacity, productivity levels, and temporal growth trends, thereby reflecting the sector's ability to supply sufficient raw material to meet domestic and export demand.

Consumption evaluates the extent to which seaweed contributes to national dietary intake, food diversification, and broader nutritional security outcomes, particularly in relation to micronutrient availability and healthy diet transitions.

Livelihoods capture the socio-economic importance of seaweed farming through indicators such as employment generation, household income contribution, gender inclusion, and poverty reduction effects in coastal communities.

Environmental Performance measures the ecological functions associated with seaweed cultivation, including nutrient bio extraction, carbon sequestration potential, habitat enhancement, and the reduction of greenhouse gas emissions relative to conventional food production systems.

Seaweed farming offers a unique opportunity to align food production with environmental sustainability because it does not require freshwater, arable land, or synthetic fertilizers, while simultaneously contributing to nutrient cycling, coastal water quality improvement, and climate change mitigation (Duarte *et al*., 2017; Cai *et al*., 2021). In addition, seaweed systems are increasingly recognized as nature-based solutions that generate multiple ecosystem services, particularly in nutrient-enriched and climate-vulnerable coastal zones.

Consequently, the inclusion of a dedicated Seaweed Security Sub-Index significantly strengthens the comprehensiveness of the Global Marine Food Security Index (GMFSI). It ensures that emerging blue food systems are adequately represented within food security assessment frameworks and reflects the growing scientific and policy consensus on the strategic role of macroalgae in sustainable ocean-based food systems (FAO, 2024; World Bank, 2022).

6.4. Application to Indonesia, India, and Tanzania

Comparative Assessment

Indonesia, India, and Tanzania provide valuable case studies for testing the applicability of the GMFSI because all three countries possess extensive coastlines, substantial fisheries resources, and growing aquaculture sectors, yet differ considerably in socio-economic conditions, governance capacity, and marine food system development.

Indonesia is one of the world's leading producers of marine fish and tropical seaweeds. The country's vast archipelagic geography, large coastal population, and significant aquaculture industry suggest strong performance in the availability dimension. However, regional disparities, environmental degradation, and governance challenges may affect sustainability outcomes.

India possesses one of the world's largest fisheries sectors and a rapidly expanding aquaculture industry. Fisheries contribute significantly to employment and export earnings, although nutritional benefits from marine foods vary considerably across regions due to differences in dietary preferences, income, and infrastructure.

Tanzania represents a contrasting context where fisheries play a critical role in local livelihoods and food security, particularly in coastal communities. However, lower production levels, limited infrastructure, and climate vulnerability may constrain accessibility and resilience compared with larger Asian producers (Allison *et al*., 2009). The GMFSI framework enables systematic comparison among these countries while highlighting the specific strengths and weaknesses of their marine food systems.

Policy Relevance

The proposed GMFSI has several practical applications for policymakers, development agencies, and international organizations.

First, it provides a standardized framework for monitoring marine food security performance over time. Second, it enables governments to identify priority intervention areas, such as improving fish affordability, strengthening fisheries governance, expanding sustainable aquaculture, or enhancing climate resilience. Third, it supports the integration of marine food systems into broader food security and blue economy strategies. For countries such as Indonesia, India, and Tanzania, the GMFSI can serve as a decision-support tool for balancing economic development, nutritional improvement, and environmental sustainability. By explicitly recognizing fisheries, aquaculture, and seaweed as pillars of food security, the index offers a more comprehensive perspective on the role of oceans in achieving sustainable development goals and ensuring long-term food and nutrition security.

7. Future Outlook and Policy Recommendations

7.1. Marine Food Systems Toward 2050

Marine food systems are expected to play an increasingly central role in global food security as the world moves toward 2050. The convergence of population growth, climate change, and rising demand for nutrient-dense "blue foods" is reshaping the future of fisheries, aquaculture, and coastal livelihoods. At the same time, climate change is altering ocean temperature, productivity, and species distribution, with direct implications for fisheries yields and coastal food security. Evidence shows that tropical regions are likely to experience declining fisheries productivity, while higher-latitude regions may see short-term gains, creating new geographic inequalities in marine food availability (Allison *et al*., 2009). These changes are expected to intensify pressure on already vulnerable coastal communities that depend heavily on marine resources.

Another major trend is the rapid expansion of "blue foods," including fish, shellfish, and seaweed, as part of global sustainable food system strategies. Aquatic foods are increasingly positioned as a critical component of climate-resilient diets due to their relatively low environmental footprint compared to terrestrial livestock systems (FAO, 2024; Golden *et al*., 2021). Within this shift, seaweed has emerged as a strategic commodity due to its scalability, minimal resource requirements, and potential contributions to nutrition, livelihoods, and ecosystem services. Together, these trends suggest that marine food systems will not only expand in economic importance but also become central to global strategies for addressing hunger, malnutrition, and climate adaptation.

7.2. Strategic Policy Recommendations

The future resilience of marine food systems depends on targeted, context-specific policy interventions that strengthen production, governance, and sustainability while ensuring equitable access to marine foods.

Indonesia

Indonesia, as one of the world's largest archipelagic states and a leading producer of tropical seaweed, possesses substantial potential to further strengthen its marine food systems. Key policy priorities include the following:

Expansion of seaweed-based food systems: Seaweed cultivation should be repositioned beyond its traditional role as an export-oriented commodity and increasingly integrated into domestic food and nutrition strategies. This shift is consistent with growing evidence on the nutritional value and environmental sustainability of aquatic plant-based foods, particularly their role in low-input, climate-resilient food systems (Cai *et al*., 2021).

Strengthening fisheries governance: Enhancing monitoring, compliance, and enforcement mechanisms, alongside the expansion of co-management arrangements, is essential to address overexploitation and ensure the long-term sustainability of capturing fisheries resources (FAO, 2024).

Addressing coastal mining impacts: Mitigating pollution from coastal and marine extractive activities is critical to safeguarding ecosystem integrity, maintaining aquaculture productivity, and ensuring seafood safety in coastal food systems.

India

India's marine food system is characterized by a large capture fisheries sector and a rapidly expanding aquaculture industry, yet it continues to face challenges related to environmental sustainability and uneven nutritional outcomes.

Sustainable aquaculture expansion: Future aquaculture growth should prioritize environmentally responsible production systems, including reduced dependence on fish-based feeds, improved biosecurity and disease management, and the application of ecosystem-based spatial planning approaches (FAO, 2024).

Improving fisheries management: Strengthening fisheries governance through improved stock assessment systems, effective regulatory enforcement, and community-based management approaches is essential for sustaining productivity and enhancing the resilience of marine resources (Garcia and Rosenberg, 2010).

Tanzania

Tanzania represents a coastal economy in which small-scale fisheries and seaweed farming play a central role in livelihoods and food security, yet both sectors remain highly vulnerable to environmental pressures and institutional constraints.

Strengthening small-scale fisheries: Policy interventions should prioritize inclusive governance frameworks that support artisanal fishers, improve access to markets, and enhance value addition within local fisheries value chains, in line with sustainable small-scale fisheries guidelines (HLPE, 2014).

Expanding seaweed value chains: Seaweed farming along coastal communities should be scaled through targeted investment in processing capacity, product diversification, and market integration, given its low environmental footprint and strong potential for livelihood enhancement and women's economic empowerment (Duarte *et al*., 2017).

Cross-Country Priorities: Despite differences in economic structure and marine resource endowments, Indonesia, India, and Tanzania share a set of increasingly convergent policy priorities. These commonalities reflect persistent challenges related to fisheries sustainability, food security, and the resilience of coastal livelihoods, as well as the expanding relevance of the blue economy framework in shaping marine policy agendas.

First, Ecosystem-based fisheries management (EBFM): Fisheries governance is progressively shifting away from narrow, single-species management approaches towards ecosystem-based frameworks that explicitly consider ecological interactions, habitat integrity, and the long-term sustainability of marine systems (FAO, 2024).

Second, Climate adaptation in marine food systems: Strengthening climate adaptation capacity is increasingly urgent in response to ocean warming, changes in species distribution, and heightened climate variability, all of which have direct implications for fisheries productivity and food security in coastal regions (Allison *et al*., 2009).

Third, Sustainable aquaculture development: Aquaculture expansion needs to be carefully aligned with environmental limits, social inclusion objectives, and ecosystem carrying capacity in order to ensure long-term sustainability and avoid the accumulation of ecological and socio-economic risks (FAO, 2024).

Fourth, Mainstreaming seaweed in food systems: Seaweed is increasingly recognized as a strategic resource that can be integrated into national food security policies, given its combined contributions to nutrition, livelihood diversification, and climate change mitigation (Cai *et al*., 2021).

Fifth, Blue economy development: Blue economy strategies require a careful balance between economic expansion and ecological sustainability, ensuring that marine resource use supports inclusive growth while maintaining ecosystem integrity (World Bank, 2017).

Sixth, Digital transformation of fisheries: The uptake of digital technologies including vessel monitoring systems, satellite-based surveillance, and data-driven enforcement tools has become central to efforts to improve fisheries governance and combat illegal, unreported, and unregulated (IUU) fishing (Global Fishing Watch, 2025).

Seventh, Adoption of the Global Marine Food Security Index (GMFSI): The GMFSI provides a structured analytical framework for assessing national marine food security performance, identifying key vulnerabilities, and supporting evidence-based policy interventions across diverse national contexts.

8. Conclusions

Marine food systems have become an increasingly important component of global food and nutrition security, particularly in coastal and island nations where fisheries, aquaculture, and associated marine-based livelihoods remain central to food supply and rural economies. A growing body of evidence shows that aquatic foods make a substantial contribution to dietary protein and essential micronutrient intake, while also sustaining employment and income for millions of people, especially in developing regions. As a result, marine resources are now widely recognized as integral to broader sustainable development and food system transformation agendas, rather than peripheral to food security discourse.

Comparative analysis of Indonesia, India, and Tanzania reveals a set of shared structural challenges despite differences in economic development levels and marine resource endowments. These include ecological pressures such as overfishing and habitat degradation, socioeconomic constraints related to unequal market access and value distribution, and institutional limitations in monitoring, enforcement, and fisheries governance. Climate change further intensifies these pressures through ocean warming, shifting fish stocks, and increased variability in marine productivity, thereby heightening uncertainty for coastal livelihoods. Collectively, these dynamics underscore a common need to strengthen the resilience and adaptive capacity of marine food systems across all three countries.

Addressing these challenges requires more integrated and system-oriented policy responses. Traditional sector-based management approaches are increasingly inadequate in addressing the interlinked nature of food security, ecosystem integrity, and coastal development. Instead, ecosystem-based fisheries management, improved aquaculture governance, and strengthened climate adaptation strategies must be embedded within broader blue economy frameworks to ensure long-term sustainability and resilience.

Within this context, seaweed emerges as a strategically important yet still underutilized resource. Beyond its established commercial uses, seaweed has significant potential to enhance food and nutrition security, diversify coastal livelihoods, and contribute to climate change mitigation through carbon sequestration and nutrient cycling. Its low-input production system and wide ecological benefits position as a key component of future blue food system strategies, although realizing this potential will require stronger investment in value chain development, applied research, and policy integration.

Finally, the proposed Global Marine Food Security Index (GMFSI) provides a novel analytical framework for assessing marine food security in a more integrated manner. By combining dimensions of availability, access, utilization, and environmental sustainability, the index moves beyond fragmented indicators and offers a unified basis for policy analysis. The inclusion of seaweed as a distinct component further reflects the evolving architecture of global blue food systems and supports more targeted, evidence-based policymaking, particularly in the Global South where marine food systems are both highly vulnerable and critically important.

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