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Exploring Promising Species and Innovative Techniques for Sustainable Island Mariculture: A Comprehensive Review

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Abstract

The aquaculture sector has emerged as the fastest-growing food-producing industry globally, meeting the escalating demand for aquatic food sources. In India, this phenomenon is mirrored, with the aquaculture sector experiencing remarkable growth, positioning the country as the second leading producer of cultured fish. Notably, during the 2021-22 period, India exhibited an impressive average annual growth rate of 8.0%, underscoring the sector's robust expansion. With an extensive coastline spanning 8129 km across nine coastal states and three union territories, including the scenic Andaman Islands, India possesses a diverse landscape for aquaculture development. The Andaman Islands, renowned for their natural beauty, boast a rich marine ecosystem with potentially undiscovered fish species, contributing significantly to India's total coastline, approximately a quarter thereof. Mariculture technologies tailored for island ecosystems encompass a spectrum, ranging from onshore aquaculture with facilities like tanks, ponds, and aquaponics systems that afford precise control over conditions, to inshore aquaculture providing a more natural environment for farmed species, and offshore aquaculture featuring enclosed sections in open water, exposing species to varied natural conditions such as currents and nutrient cycles. The present review delves into the specific realm of mariculture in island ecosystems, shedding light on global trends, issues within these unique environments, and considerations imperative for the successful and sustainable development of mariculture. The paper extends beyond India, encapsulating the broader context of island mariculture worldwide, offering insights into the challenges and opportunities inherent in these ecosystems. Ultimately, the review strives to contribute to the discourse on fostering sustainable practices, balancing environmental conservation with economic viability, and addressing social considerations to ensure the long-term resilience of island mariculture.

Key words: *Aquaculture, mariculture technologies, islands, species, sustainability*

Introduction

Mariculture is a component of aquaculture that involves the cultivation, management, and harvesting of marine organisms in their natural habitats (like estuarine, brackish, coastal, and offshore waters) or within controlled enclosures such as cages, pens, tanks, or channels. This form of aquaculture specifically focuses on marine species, including fish, shellfish, seaweed, and other aquatic organisms. In contrast, commercial fishing involves the harvesting of wild fish from natural marine or freshwater environments. This distinction is essential to understand the methods and approaches involved in both practices, one being controlled cultivation and the other involving the capture of wild aquatic species. Mariculture is crucial for meeting the growing global demand for seafood while reducing the pressure on wild fisheries. It allows for controlled and sustainable production of marine organisms, offering economic benefits to coastal communities and contributing to food security.

Aquaculture is the fastest-growing food-producing sector on a global scale, displaying immense potential to address the ever-increasing demand for aquatic food. In 2020, the sector made a substantial contribution, yielding 214 million tonnes of fish, aquatic animals, and algae for human consumption, with 178 million tonnes comprised of aquatic animals and 36 million tonnes of algae (FAO, 2022). Asia, in particular, has been a key player in this growth, boasting a significant surge in aquaculture activities. It's vital, however, to emphasize sustainable practices and responsible resource management to ensure the long-term viability of this essential industry. Declining in fish catch from wild in recent past, has led to rapid growth of fish farming in different farming systems across the world to meet the fish requirement. Consequently, the world food fish aquaculture production has increased considerably at an average growth rate of 6.7% in the year 2022.

The aquaculture sector in India is mirroring the global trend of remarkable growth. The substantial increase in aquaculture production has positioned India as a leading producer of cultured fish, showcasing an impressive average annual growth rate of 8.0% during the 2021-22 period. This growth is significant and underlines the importance of aquaculture in meeting the rising demand for aquatic food. Aquaculture is practiced in both freshwater and coastal areas throughout India, with freshwater aquaculture contributing significantly to the overall aquaculture production in the country, as highlighted by the Food and Agriculture Organization (FAO) in 2020 . Notably, the coastal aquaculture and mariculture sector have seen substantial development, marked by the introduction of new species suitable for culture. However, there remains considerable untapped potential in coastal aquaculture and mariculture that requires focused attention to effectively utilize the available area and address the increasing demand for marine fish food in India and around the world. Striking a balance between sustainable practices, technological advancements, and responsible resource management is essential to harness this potential while ensuring the long-term sustainability of the aquaculture industry in India.

India possesses abundant resources for mariculture, including an extensive coastline spanning 8129 km, a vast Exclusive Economic Zone (EEZ) of 2.2 million km^2, substantial continental shelf area, expansive brackishwater and inland saline areas, as well as 20 million ha designated for sea farming (Modayil *et al*., 2008). Despite this rich potential, mariculture production in the country remains in its nascent stages compared to global standards.

The estimated marine fish landings along the coast of the mainland of India during 2022 was 3.49 million tonnes, showing an increase of 14.53% compared to the landings in 2021 (CMFRI, 2023). However, India's mariculture production lags significantly behind its potential, estimated at 4 to 8 million tonnes annually. Presently, mariculture production stands at less than 0.01 million tonnes, accounting for approximately 2.0% of the total aquaculture production (Gopalakrishnan *et al*., 2019). This emphasizes a substantial opportunity for growth and development within the mariculture sector in India. Efforts to leverage these resources effectively and develop sustainable mariculture practices can significantly contribute to meeting the increasing demand for aquatic food and enhancing India's position in the global aquaculture landscape.

At present, coastal aquaculture contribute major share in production, which is mainly from shrimp culture. In India only 13% of total available potential area is under coastal aquaculture operation. In 2019, the production of both vannamei and monodon shrimp was less than 600,000 tonnes. Production rose to 650,000 tonnes in 2020 and by 2021, the volume escalated to 930,000 tonnes and expected a production decline to 902,525 tonnes in 2023 (SAP, 2023). The major species groups farmed in the Asia-Pacific region are: finfishes, crustaceans, molluscs, echinoderms and aquatic plants. Marine finfish aquaculture in the Asia-Pacific region is exceptionally diverse. The commonly cultivable brackish and marine water fish species/group in Asia and Pacific region includes milk fish, sea bass, jacks, sea bream, flat fishes, groupers, cobia, mullets, snappers, pompanos and other marine fishes such as eels, croakers & drums. Japanese amberjack (*Seriola quinqueradiata*) makes up 17% of regional marine finfish production. Most of the species are available in Indian seas, and they can be domesticated and cultured in India.

Understanding the importance of the mariculture potential in Indian seas, ICAR research institutions, such as Central Marine Fisheries Research Institute and Central Institute of Brackishwater Aquaculture had initiated different mariculture programmes and has developed seed production and farming technologies of different species including Cobia (*Rachycentron canadum*), Orange-spotted grouper (*Epinephelus coioides*), Silver pompano (*Trachinotus blochii*), Indian pompano (*T. mookalee*), Pink- ear sea bream (*Lethrinus lentjan*), banded grunter

(*Pomadasys furcatus*), John's snapper (*Lutjanus johnii*), Vermiculated spine foot (*Siganus vermiculatus*) and picnic seabream (*Acanthopagrus berda*) (Shinoj *et al.,* 2023, Gopalakrishnan *et al.,* 2019; Anuraj *et al*., 2021; Suresh Babu *et al*., 2022). Aiasn seabass, (*Lates calcarifer*), and mangrove red snapper (*L. argentimaculatus*) (CIBA) (Arasu *et al*., 2009). Apart from the above, a recent publication from ICAR-CMFRI has prioritized 76 finfish and shellfish species that could be targeted for future expansion of mariculture production in the country (Ranjan *et al*., 2017). Using these potential cultivable species, mariculture production from Indian seas can be considerably improved by adopting hatchery based and capture based culture methods both mainland and island in Indian coastal areas.

Island Ecosystems

Island ecosystem is very unique in terms of its biodiversity, physical environment and threat by various natural and anthropogenic factors. However the diversity is not uniformly distributed among the tropical islands, which are conditioned by the natural forces and the influence of human activity significantly altered it. Tropical islands are known to have uniquely naturally variable ecosystems, including tropical rainforests, open woodlands and grass savannahs, freshwater lakes and streams, salt marshes and mudflats, mangrove and coastal littoral forests, seagrass, fringing and offshore coral reefs, and deep sea trenches and abyssal plains (SPREP, 2012). Due to favourable climatic and edaphic conditions, the tropical region ecosystems have high species turnover and an unusual richness of endemic terrestrial and freshwater species. Isolation of islands promotes high endemism and specialised flora and fauna (MacArthur and Wilson, 1967). Because the isolation of islands over a period of time exerts unique evolutionary forces that result in the development of a distinct genetic reservoir and the emergence of highly specialised species with entirely new characteristics and the occurrence of unusual adaptations. In the same context patterns of species diversity on islands have also yielded significant insights into evolutionary and ecological processes such as immigration, speciation and extinction (Witt and Maliakal-Witt, 2007).

India has an 8129 km long coastline which extends across nine coastal states and three union territories, namely the Damn & Diu, Andaman and Nicobar and Lakshadweep islands. According to the bio-geographic classification of India (Rodgers et al 2002), the coasts fall under zones 8A (west coast), 8 B (east coast), 8 C (Lakshadweep), 10A (island-Andamans) and 10B (island-Nicobars). The Lakshadweep and Andaman & Nicobar Islands form the major groups of islands in the country, comprising 36 and 572 islands, respectively. The Lakshadweep Islands lie 220 to 440 km off the coast of Kerala in the Arabian Sea, with an area of 32 km (http://lakshadweep.nic.in/). The Andaman & Nicobar archipelagos are situated between latitudes 6° and 14° N and longitudes 92° and 94° E, in the Bay of Bengal (http://www.andamans.gov.in/). These islands have received much attention in the recent past due to their rich coastal and marine ecosystems, which harbour many critical species and provide a source of livelihood to over 4,00,000 people (Census of India, 2011). Several studies in the past have focused on the biodiversity of both the island groups, the Lakshadweep Islands (Murty 2002; Apte 2009; James 2011; Venkataraman, *et al*., 2012; Reddy *et al.,* 2013) and the Andaman & Nicobar Islands (Sankaran 1998; Ravindran *et al*., 1999; Davidar *et al*., 2002; Padalia *et al*., 2004; Ramachandran *et al*., 2005; Andrews et al 2006; Aul *et al*., 2014).

There are 21 islands and 3 groups of islands of peninsular India, their biodiversity and related threats. In addition to these two main islands, Lakshadweep and Andaman & Nicobar groups of islands all these small islands are having greater scope in developing fisheries and, mariculture in peninsular India. Many islands dot the east coast of India from West Bengal to Tamil Nadu, of which some are, Halliday Island, Lothian Island, Dhanchi Island, Sagar isaland, in West Bengal; Wheeler Island in Odisha; Hope Island, Sriharikota Island in Andhra Pradesh: Pamban Island, Gulf of Mannar group of islands in Tamil Nadu. Similarly, the western coastal plain is a 50-100 km wide strip of land sandwiched between the Western Ghats and the Arabian Sea. It extends from Gujarat, in the north, through Maharashtra, Goa and Karnataka to Kerala. Which includes, Gulf of Kutch group of islands, Diu (union territory of Daman &

Diu) in Gujrat; Elephanta island, Murud-Janjira Islands, Padamdurg islands, Khanderi islands, underi islands, islands at Vengurla rocks in Maharastra; Chorao islands, Divar islands, Jacinto islands, cumbarjua islands in Goa: Netrani islands, St. Mary's islands in Karnataka; Kochin group of islands in Kerala. Islands that are close to mainland India are critical in many ways to human beings. These islands are breeding grounds for several fishes, protect the sea shore from natural calamities such as cyclones and Tsunamis and provide livelihoods to thousands of coastal communities (Pande et al., 2014). The rich island potential as the breeding ground for many marine fishes can be used judiciously with the advent of some of the mariculture technologies.

The Andaman Islands, known for their unparalleled natural beauty, boast a rich marine ecosystem with an abundance of fish species, some of which may still be undiscovered. The islands are blessed with a vast coastline spanning 1,962 km, accounting for about a quarter of India's total coastline. Furthermore, the exclusive economic zone (EEZ) of the Andaman Islands extends across approximately 0.6 million km², encompassing about 30% of the Indian subcontinent's EEZ. Given these expansive marine resources and the favourable environmental conditions, the Andaman Islands are highly conducive to mariculture. Mariculture, which involves the cultivation of marine organisms in controlled environments, can thrive in the Andaman's pristine coastal waters. The region's diverse marine habitats, including coral reefs, seagrass beds, and coastal areas, provide an ideal setting for cultivating various species of fish, shellfish, and other marine organisms. Efforts to harness the mariculture potential in the Andaman Islands should focus on research, technological advancements, and sustainable practices. Collaboration between research institutions, government agencies, local communities, and the private sector is essential for realizing the full potential of mariculture in this unique and ecologically valuable region. It is also reported that after the post-tsunami earthquake, an area of about 1,300 ha was permanently inundated, of which 830 ha is suitable for brackish water aquaculture apart from the abundant freshwater sources where freshwater aquaculture is also possible.

Mariculture in Island ecosystems

Utilizing mariculture in the Island ecosystems offer several benefits, including:

Diversification of Aquaculture: Mariculture diversifies the aquaculture sector by incorporating a wide range of marine species, reducing reliance on traditional forms of aquaculture.

Sustainable Seafood Production: Cultivating marine species through mariculture contributes to sustainable seafood production, meeting the increasing demand for high-quality marine products.

Economic Growth and Employment Opportunities: Mariculture can drive economic growth by creating employment opportunities in coastal communities and supporting related industries.

Food Security: By enhancing seafood production, mariculture contributes to food security by providing a steady supply of nutritious marine products.

Conservation and Sustainable Use: Mariculture allows for the conservation and sustainable use of marine resources, reducing pressure on wild populations and promoting responsible aquaculture practices.

Tourism and Eco-Tourism: The success of mariculture can attract eco-tourists interested in sustainable practices, benefiting the local tourism industry.

Suitable Mariculture Species for Island ecosystems

Shrimp and Prawns (Penaeid Shrimp)

Black tiger shrimp (*Penaeus monodon*), Pacific white shrimp (*Litopenaeus vannamei*), Indian white shrimp (*Penaeus indicus*)

Finfishes

Asian Seabass (*Lates calcarifer*), Grouper (*Epinephelus* spp.), Pompano (*Trachinotus mookalee* and *Trachinotus blochii*), Milkfish (*Chanos chanos*), Cobia (*Rachycentron canadum*)

Bivalve Molluscs

Green mussel (*Perna viridis*), Indian *backwater oyster (Crassostrea madrasensis), Pearl oyster (Pinctada fucata, Pinctada* margaritifera)

Seaweeds

Kappaphycus alvarezii, *Gracilaria* spp.

Mariculture Technologies for Island ecosystems

Mariculture, encompasses various cultivation methods. Well-planned and managed mariculture can also contribute positively to coastal environmental integrity. However, future development of mariculture will occur, in many areas, with increasing pressure on coastal resources caused by rising populations, and increasing competition for resources. Thus, considerable attention will be necessary to improve the environmental management of aquaculture through environmentally sound technology and better management, supported by effective policy and planning strategies and legislation.

Mariculture can be done on land in artificial facilities like tanks, ponds, or aquaponics systems (onshore aquaculture), offering precise control over conditions. In well-sheltered shallow waters near the shore (inshore aquaculture), species experience a more naturalistic environment. Offshore aquaculture involves enclosed sections in open water, where species are kept in cages or racks, exposed to diverse natural conditions such as currents and nutrient cycles. Each approach has unique advantages and challenges, influencing the choice based on species, environmental factors, sustainability, and technology. Responsible mariculture practices are essential for industry sustainability and environmental preservation.

Farming technologies

The geographical advantage of being surrounded by the sea, coupled with abundant brackishwater and freshwater areas, positions islands as highly conducive for various types of aquaculture. Inland aquaculture, which employs diverse culture techniques and facilities worldwide, finds a favourable environment on islands due to their proximity to water bodies. The following farming technologies are feasible and successful in island settings:

Land-based Systems: Land-based systems such as pond culture systems, raceways, and different types of intensive and semi-intensive tank cultures, including modern Recirculating Aquaculture Systems (RAS), can be effectively operated on islands. These systems offer controlled conditions for aquatic organisms, ensuring optimal growth and production.

Open Water-based Culture Systems: Open water-based culture systems, including pens and cages, are suitable for islands. These systems allow aquatic animals to grow in their natural environments within enclosed structures. By selecting appropriate sites and species, open water-based systems can yield successful aquaculture production.

Traditional, extensive, semi-intensive, and intensive are the existing farming practices. Mussel farming is an example of an extensive method of mariculture used around the globe, whereby the farmer provides a rope or a stake for the juveniles to attach to and undertakes some culling so that the density does not get too high, but otherwise leaves the mussels to grow without further interference. Some of the noted and well-developed mariculture technologies across the world (Imelda-Joseph and Asha-Augustine, 2020) are given below:

Ponds: Suitable for semi-intensive or intensive culture in ponds for shrimp, prawns, and fish. The advantages include controlled environment, efficient space utilization, water quality management, and ease of monitoring.

Raising finfish and other aquatic species in constructed earthen ponds is a widespread and highly effective culture method globally. Coastal aquaculture, typically practiced in constructed ponds either onshore or in intertidal zones, is a cornerstone of livelihoods, employment, and economic development in many developing countries, particularly across Asia. This farming technology is well-suited for adoption in the inland waters of islands, offering flexibility in terms of operational practices, input intensity, technological sophistication, and integration with other farm activities. The selection of species for cultivation depends on factors such as availability, salinity, water quality parameters, and biological characteristics. Shrimps and various marine fish are commonly cultivated in these ponds. The production of young shrimp and fish often begins in hatcheries, although in some cases, young animals may be collected from natural sources. Ponds can be filled with suitable water either by pumping or through tidal flow, where farmers regulate water levels by opening and closing floodgates based on tides. The time required for the cultivated species to reach market size varies depending on the species and stocking size, ranging from a few months to a year. A significant advantage of this system is the ability to monitor and manipulate culture conditions from zero to 100%, allowing for a range of culture intensities based on cost-effectiveness. The culture methods can vary from extensive water exchange systems, depending on tidal influx, to zero water exchange systems where conditions are meticulously controlled. Additionally, farmers have the flexibility to choose between polyculture with minimal screening or monoculture of selected species based on their preferences and objectives. This adaptability and versatility make pond-based coastal aquaculture a crucial tool in sustainable aquaculture practices.

Although coastal ponds for aquaculture, whether modern or traditional, can be found in regions across the globe, they are more concentrated in South, Southeast, and East Asia, as well as Latin America. These areas primarily focus on raising crustaceans, finfish, molluscs, and, to a lesser extent, seaweeds through aquaculture. Many countries, especially in Asia, have developed expertise and support institutions dedicated to marine and coastal aquaculture.

Some of the most popular species cultured in marine ponds include sea bass, grouper, red sea bream, yellowtail, rabbitfish, and marine shrimps. In Asia, which accounts for a significant portion of global aquaculture production, fish ponds predominantly use freshwater or brackish water, with marine ponds being less common. This highlights the prevalence and preference for brackish or freshwater systems in the region for aquaculture practices.

Raceways

Controlled flow of water through raceways or tanks for fish culture, particularly suitable for fast-growing species. The advantages are: better water quality control, efficient feeding, and reduced disease risks.

A raceway, also known as a flow-through system, is a commonly used artificial channel in aquaculture for culturing aquatic organisms. It represents one of the earliest methods employed in inland aquaculture. Typically, a raceway consists of rectangular basins or canals constructed from materials like concrete and is designed with an inlet and outlet system. In its simplest form, a raceway is essentially a flume designed for water transportation. Raceways used for fish culture are relatively shallow tanks that depend on a high water flow in proportion to their volume to maintain the aquatic life within. In successful aquaculture, it's vital for the inflowing water to align with the temperature tolerance of the species being cultured. Ideally, the temperature should closely match the optimum temperature required for the target species.

In addition to temperature control, the incoming water into the raceway serves as a source of oxygen, which is crucial for the health and survival of the cultured aquatic organisms. Proper oxygen levels are maintained through adequate water flow and management practices within the raceway system. This makes raceways a popular choice for aquaculture, providing controlled environments that support the growth and development of aquatic species.

Indoor Facilities

Fish can be effectively cultured for domestic and commercial purposes using various types and sizes of tanks, allowing for flexibility in production based on specific requirements and input levels. The highest level of technological advancement in fish farming is often seen in indoor facilities, where fish are grown in specialized tanks such as circular raceways. These tanks receive pumped seawater, which may be directly sourced from the ocean. The water can be cycled through the tanks, discarded, recirculated, or processed through advanced water treatment systems. These facilities are capable of rearing marine species to market size, but they are frequently utilized as hatcheries and for holding broodstock (adults used for reproduction). Aquaponics systems represent another innovative approach, integrating fish culture with vegetable cultivation. This system is designed for minimal water usage while optimizing resource efficiency. The waste generated by fish serves as a nutrient source for growing plants, and the plants, in turn, help filter and purify the water, creating a sustainable and symbiotic ecosystem. Additionally, the floc system, employing suitable consortia of organisms, presents an integrated approach that can be utilized for fish production. This system involves the strategic arrangement of multiple organisms, potentially including fish, to maximize production and resource utilization.

These diverse approaches showcase the adaptability and versatility of fish farming methods, providing options for efficient and sustainable production across various scales and needs, ranging from small-scale domestic use to large-scale commercial ventures. Integration, advanced technologies, and sustainable practices are key to optimizing the potential of these systems for successful fish culture and aquaculture.

Recirculating Aquaculture Systems (RAS)

Closed-loop systems that recycle and treat water for fish and shrimp culture. The advantages are: minimizes water usage, controls water quality parameters, reduces environmental impact, and allows for land-based culture.

RAS are indoor, tank-based systems in which fish are grown at high density under controlled environmental conditions. Generally, farmers adopt a more intensive approach (higher densities and more rigorous management) than other aquaculture production systems. Recirculating aquaculture systems are indoor, tank-based systems in which fish are grown at high density under controlled environmental conditions with different levels of filtration systems (Espinal and Matulic, 2019). Recirculation is growing rapidly in many areas of the fish farming sector, and systems are deployed in production units that vary from huge plants generating many tonnes of fish per year for consumption to small sophisticated systems used for restocking or saving endangered species. It has always been recommended to use recirculation systems to produce expensive fish because a high selling price leaves room for higher production costs. A good example is the eel farming business where a high selling price allows relatively high production costs. The suitability of rearing specific fish species in recirculation depends on many different factors, such as profitability, environmental concerns, and biological suitability. It should be mentioned that for small fish the use of recirculation is always recommended, because small fish grow faster and are therefore particularly suited to a controlled environment until they have reached the size for growing. Some of the saltwater fish species cultured in worldwide in RAS based culture system are Atlantic salmon, smolt (*Salmo salar*), Grouper (*Epinephelus spp)*; Rainbow trout (*Oncorhynchus mykiss*), Seabass/ Seabream (*Dicentrarchus labrax / Sparus aurata*), Yellowtail amberjack (*Seriola lalandi*), Cobia (*Rachycentron canadum),* Indian pompano *(Trachinotus mookalee)*

Farming in Cages

Sea cage farming (salmon, breams, snapper, seabass, grouper): High-density, low volume system with maximum production in unit area than in any other culture systems. The sea cage farming has been expanding in recent years on a global basis and it is viewed by many stakeholders in the industry as the aquaculture system of the millennium. Cage culture has made possible the large-scale production of commercial finfish in many parts of the world and can be considered as the most efficient and economical way of rising fish. The rapid growth of the industry across the globe is attributed to (i) availability of suitable sites for cage culture (ii) well established breeding techniques that yield a sufficient quantity of various marine and freshwater fish juveniles (iii) availability of supporting industries such and feed, net manufactures, fish processors etc. (iv) strong research and development initiatives from institutions, governments and universities and (v) the private sector ensuring refinement and improvement of techniques/ culture systems, thereby further developing the industry. Industrial marine fish farming is a relatively young phenomenon but has grown to be a major industry in many regions of the world, producing some 6.6 million tons of fish per year. The standard production units, sea-cage fish farms, are variations on a common theme, floating, surface-based structures holding large nets which contain thousands to hundreds of thousands of fish. The major species produces using the mariculture technology is the Atlantic salmon, *Salmo salar* (2.44 million metric tonnes), and 0.767 million metric tonnes of other marine fin fishes including different species of breams, snapper, seabass, grouper, pompanos, etc. (FAO,2022).

Farming in pens

Inexpensive pen structures are constructed in shallow natural bodies of water such as creeks, swamps, lagoons, lakes, and bays, with water depths ranging from 1 to 3 meters. The bottom of the pen culture sites should ideally consist of firm clay or mud, allowing for the installation of supporting poles and posts for the pen structure. Traditionally, pens were constructed using materials like wooden planks and split bamboo. However, in modern times, synthetic materials such as nylon, polypropylene, and polythene are commonly used for pen construction. The pen structure typically consists of vertical net barriers, with a portion buried in the mud or ground using a footrope and small weights. These weights are secured to a chain link between concrete sinkers, ensuring stability. Floats are provided at the upper level to keep the structure afloat. In this system, fingerlings stocked in the pens primarily feed on natural food available in the lagoon or lake, and artificial feed is usually not provided. Milkfish (*Chanos chanos*) is the principal fish species cultured in Southeast Asian countries using these pen structures. The design and setup of these pens allow for efficient milkfish farming, making use of the natural aquatic environment and maximizing the growth and development of the fish within the pens.

Bottom culture or suspended culture for bivalve molluscs (mussels, oysters)

Marine bivalves, such as mussels, oysters, clams, and cockles, represent a sustainable source of food production due to their position low in the trophic chain as herbivores, with a trophic position of 2. In contrast, the average trophic position of the total marine capture fishery is higher at 3.1 (Duarte et al., 2009). This emphasizes the ecological efficiency and sustainability of bivalve aquaculture. With challenges related to decreasing seed resources and environmental concerns associated with seed fisheries, there has been a shift towards producing seed resources for marine bivalve aquaculture within land-based hatcheries. Over the years, aquaculture production of marine bivalves has seen a substantial increase, rising from 1.18 million tonnes per year in the period 1970–1974 to 13.47 million tonnes per year in the period 2010–2015.

One of the popular methods for cultivating marine bivalves is raft culture, where seeded ropes are suspended from a raft positioned in a suitable site and depth within the inshore area. These ropes are spaced around 0.5 to 1m apart, ensuring the end of the rope is approximately 2m above the water bottom. Marine bivalve aquaculture significantly contributes to the overall aquaculture production of aquatic animals, accounting for a substantial portion. In particular, the cultivation of marine bivalves contributes approximately 17.7 million tonnes of molluscs (valued at USD 29.8 billion), with countries like New Zealand, France, Spain, the Republic of Korea, Italy, and Japan being major contributors, surpassing the world average in terms of production percentage.

Rope culture or longline culture for seaweed cultivation: Seaweed mariculture has its origins dating back to the Tokugawa (or Edo) Era in Japan (AD 1600–1868). In the contemporary era, a substantial 92% of the global seaweed supply is sourced from cultivated species. The success of seaweed cultivation is influenced by the selection of species, understanding their biology, life history, tissue specialization, and considering the socioeconomic conditions of the region where cultivation occurs. Cultivation technologies can range from low-tech, which employs simple and highly efficient culture techniques often requiring intensive manual labour at low costs, to highly advanced and mechanized systems. The latter may involve on-land cultivation for seeding certain phases of the life history before transferring the seaweed to open-sea aquaculture sites.

Global seaweed cultivation, witnessed a growth of half a million tonnes in 2020, reflecting a 1.4% increase from 2019, reaching a total of 34.6 million tonnes. In seaweed farming, a diverse array of 13 culture methods have been employed globally, catering to different seaweed species and varying sea climatic conditions. Selection of a particular method depends on its suitability to the prevailing sea conditions. Common methods for shallow waters include off-bottom monoline, broadcast, floating bamboo, net systems, and tubular nets. On the other hand, deeper waters typically utilize methods such as multiple raft long line, spider web, hanging basket, and free swing methods. The selection of an appropriate method is crucial for optimizing the productivity and sustainability of seaweed cultivation operations.

Integrated Multi-trophic Aquaculture (IMTA)

Combining different species with complementary ecological niches to optimize resource use and reduce environmental impact. For example, integrating fish, shrimp, and seaweed culture in the same area. The advantages include enhanced sustainability, nutrient recycling, and increased production efficiency.

IMTA represents a significant shift in aquaculture practices, providing a more sustainable and environmentally friendly approach. The conventional intensive monoculture systems have posed challenges related to sustainability, environmental degradation, and disease problems. IMTA offers a solution by integrating commercially important species from different trophic levels to create balanced systems that promote environmental stability, economic stability, and social acceptability.

In IMTA, the cultivation of fed aquaculture species (e.g., fin fish, shrimp) is combined with organic extractive aquaculture species (e.g., shellfish, herbivorous fish) and inorganic extractive aquaculture species (e.g., seaweed). This integrated approach aims to mitigate the environmental impact caused by excess nutrients and organic matter generated by intensive aquaculture activities, especially in marine waters. By incorporating species from various trophic levels into the same system, IMTA helps in maintaining a more harmonious and balanced ecosystem.

IMTA is aligned with the principles of the ecosystem approach to aquaculture (EAA) advocated by the Food and Agriculture Organization (FAO). It not only addresses environmental concerns but also diversifies products and reduces risks, contributing to economic stability. Furthermore, IMTA can enhance the production capacity of a specific site, making it a holistic and efficient method of aquaculture.

Integrated Mangrove-Shrimp Farming

Cultivating shrimp in ponds with integrated mangrove areas for ecological balance and waste assimilation. Advantages are, natural filtration, improved water quality, and additional income from mangrove products.

Status of mariculture in island ecosystem

Mariculture, or marine aquaculture, takes place in the sea for the entire cycle or only during the grow-out phase. In the first case, the production cycle takes place entirely in the seas for those species dependent on wild seeds from the sea, especially bivalve culture. Otherwise, mariculture refers only to the grow-out phase of the production cycle when a species is produced from a land-based hatchery and sometimes even in freshwater (FAO, 2022). Mariculure has been extensively practised in different ecosystems, where the protected coastal ecosystem considered to be the one the most suited for the mariculture practices due to its inherent advantageous. The islands are having protected sea, mostly grouped and are also moderately indented. As a result there are numerous bays, lagoons, creeks and inlets with varying depths and different substrata which are optimal for several types of mariculture operations. Ideal situations exist for raft culture and cage culture in the bays; shallow lagoons are suited for pen culture; the water bodies in the creeks and inlets with the adjoining land area can be used for the development of costal fish farms and land based farming methods and hatchery establishment due to its contamination free water quality

Presently, there is a continuous increase in demand for seafood across the globe, and it is estimated that aquaculture will dominate global fish supplies by 2030, with less than half the fish consumed coming from capture fisheries. Thus, emphasis has been given to island ecosystem by the different nations on the aquaculture development plan for island regions is to provide a sound basis for developing a new aquaculture industry in the islands. While at the same time conserving the unique environment of the islands for present and future generations, and minimizing conflict between aquaculture and existing and future users of the islands. Also considering the growing population, static levels of wild capture fisheries, an increasing recognition of seafood as part of a healthy diet and growing affluence among the populations of some key export markets. The island ecosystem provides an ample opportunity mainly towards the production of premium species. According to the United Nations Sustainable Development Goals (SDGs), aquaculture activity can permeate several of these objectives, namely SDG2 (zero hunger), SDG12 (responsible consumption and production), and S14 (life below water). Target 14.7 specifically states that by 2030 it is necessary to increase the economic benefits for small island developing states and countries of lower relative development from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture, and tourism (The Global Goals 2022).

Understanding importance of the aquaculture development in increasing fish food requirement, different countries have made and rode map or action plan for the developing island eco system for augmenting fish production using different mariculture technologies. Among which, cage culture is considered to be the most popular culture operation in different island in different regions. Some of the major islands in Atlantic and pacific oceans are well developed with mariculture activities, and contribute major share in mariculture production in FAO production data base.

Atlantic islands

Marine aquaculture activity in Madeira started in 1996 with a pilot project of floating cages for sea bream production. In recent years, efforts have been made to expand the activity, where in 2016, the Regional Government defined 5 coastal areas with the greatest potential for the development of marine aquaculture, so-called ZIAs (Zones of Interest for Aquaculture), all of which are located on the south coast of Madeira Island in Atlantic islands (Machado et al., 2023). The Faroe Islands is a self-governing archipelago, part of the Kingdom of Denmark. It comprises 18 rocky, volcanic islands between Iceland and Norway in the North Atlantic Ocean, connected by road tunnels, ferries, causeways and bridge. The Faroe Islands rely heavily on fisheries and aquaculture activities. Fish and fish products make up almost 95% of the total export income and 20% of the total Faroese gross national product. Alongside wild capture fisheries, aquaculture has become an important Faroese industry, both economically and socially. Atlantic salmon dominates production, with some small production of seaweed. Economically, aquaculture is an important industry in the Faroe Islands. Over the past decade, it has grown to represent 40–45% of total goods exported (8% of the gross national product). With 5% of the total labour force employed within aquaculture, the industry has a much stronger influence on society and the economy when compared to other International Council for the Exploration of the Sea (ICES) ecoregions. In the year 2020, the Faroe Islands alone has produced around 89, 000 tonnes of marine finfishes alone majorly contributed by Atlantic salmon and Atlantic cod (*Gadus morhua*). Most salmon are raised in very large floating fish farms located in the narrow straits between islands. These are quite vulnerable to storms, but well managed with a high degree of mechanization. Salmon farming rapidly became an important export activity for the Faroe Islands, channelling most of its products through Denmark to the European markets (FEAP, 2002).

The Canary Islands are an autonomous community of Spain and an outermost region of the European Union. They form an archipelago located off the northwest coast of mainland Africa. The Canarian jurisdictional waters have three national maritime borders, with Portugal, Morocco and Western Sahara. The aquaculture development in the island ecosystem has been supported by the European Maritime and Fisheries Fund (EMFF). Due the favourable climatic conditions in the island, sea bass and sea bream have long been produced, soles and shrimps are cultivated slightly less quantities. Floating sea cages and Race way system are the two major production systems contribute for fish production. In a 2022 report on the blue economy of the Canary Islands authored by the Technological Centre for Marine Sciences (CETECIMA), data from the Ministry of Agriculture, Livestock and

Fisheries of the Government of the Canary Islands show that of the eight islands in the archipelago four have fish farming production and/or marketing activities. Production capacity on the four islands has remained stable since2014 at about 11,000 tonnes. Both sea bass and sea bream are cultivated in the islands, but only from the grow-out systems. Juveniles typically weighing 5-15 g are obtained either from the Spanish mainland or imported from other countries and introduced into cages in the sea where they grow to market size (FAO, 2020)

Pacific Islands

Aquaculture operation is currently of little commercial significance to the Pacific Islands. Shrimp (*Penaeus* spp.) farming has been a focus of commercial development in several islands with varying degrees of success; tilapia (*Oreochromis niloticus*) aquaculture has entered the subsistence economy in some areas, and seaweed (*Kappaphycus spp.*) is a well-developed industry. Profitable aquaculture of penaeid shrimps and black lip pearl oysters has now been established in some areas of the Pacific islands by commercial interests. Stand-alone enterprises producing penaeid shrimps for export markets are firmly established in New Caledonia, Fiji and Solomon Islands. These enterprises are applying technology developed originally in Japan, Taiwan and France, and now common place throughout the tropics. A large, sustainable, industry for culturing pearls using the black lip pearl oyster (*Pinctada margaritifera*) has been established in the Tuamotu Archipelago, French Polynesia, and on a couple of atolls in the Cook Islands (Fassler, 1995). In French Polynesia, the value of cultured pearls exceeds US$150 million per annum. In Cook Islands, the industry is currently worth US$5 million and is the second largest source of revenue for the country after tourism. Black pearl farming in French Polynesia and Cook Islands, and shrimp aquaculture in New Caledonia represented more than 98% of the total value of aquaculture production. Solomon island is the one the major player in production of culture seaweed, occupied 12th position in seaweed producing countries with 5.5 thousand tonnes of seaweed during 2018-19 (Gillett and Tauati, 2018). In the Pacific Islands, there are few traditional collection fisheries for juvenile fish to support grow-out operations. The exception is collection of milkfish (*Chanos chanos*) for pond grow-out in several Pacific Island countries, including Kirabati and Nauru

The NOAA Fisheries Pacific Islands Regional Office works with the aquaculture industry and research partners to develop, evaluate, and transfer appropriate technologies to the pacific islands. NOAA Fisheries has prepared a Programmatic Environmental Impact Statement (PEIS), in coordination with the Western Pacific Regional Fishery Management Council, to analyse the potential environmental effects of a potential Pacific Islands aquaculture management program and alternatives. Such a program would support an environmentally sound and economically sustainable aquaculture industry in Federal waters of the Pacific Islands. In 2016, the NOAA Fisheries Pacific Islands Regional Office completed its environmental review and issued a Special Coral Reef Ecosystem Fishing Permit (SCREFP) to Kampachi Farms, LLC., to allow the culture and harvest of palmaco jack (*Seriola rivoliana*), or kampachi, using a net pen system with production capacity of approximately 60 tonnes.

Islands in Indonesia

Grow out is carried out in many areas of Indonesia, and grouper farming in particular is growing fast, especially in the Lampung area of southern Sumatra. Cage culture can be found throughout Indonesia, including the islands Sumatra, Bangka, Bengkulu, Lampung, Kepulauan Seribu, Banten, Java, Lombok, Kalimantan and Sulawesi. However, much of this culture is based on wild fish seed. Recent developments in Lampung have been largely driven by the availability of hatchery-reared grouper seed (Halwart, et al., 2007).

Addressing the issues in Island based ecosystems

The islands in spite of their wide diversity, are all confronted to a greater or lesser extent with similar problems including, isolation and remoteness, limited natural and human resources, difficulties in terms of competitiveness and economic development, and fragile environments. Work in island regions involves consideration of potentials and constraints in various aspects of development. Island ecosystem required a special agro-ecological approach in the pursuit of sustainable development (Brooks, 2002). Agriculture, fisheries and forestry have provided for centuries the main source of livelihood for the population of the islands. Their sustainable management remains crucial for the future. Mariculture development activities in the island ecosystem islands should involve consideration of potentials and constraints in the various aspects of development, including:

Economic issues: narrow resource base, isolation from major markets, vulnerability to volatile international markets, erosion of preferential trade arrangements, high external debt, high level of foreign aid and remittances, difficulties in conforming to sanitary regulations, importance of tourism and dominance of public sector.

Ecological issues: rich marine and terrestrial biodiversity, vulnerability to natural hazards, harsh competition for scarce natural resources, particularly fresh water, degradation of coastal habitats, loss of traditional agricultural systems and over-exploitation of forest and coastal resources.

Social issues: high population growth and mobility, limited variety of dietary intakes and nutritional problems, institutional "brain drain", scarcity of skilled manpower and weak institutional capacities.

Mariculture initiatives in Indian Islands

The Andaman and Nicobar Islands, with their vast coastline and extensive Exclusive Economic Zone, present a prime opportunity for mariculture and aquaculture development in India. Despite abundant marine fisheries potential and high demand for fish products, current harvest levels remain considerably below the capacity. Challenges such as limited seed availability, transportation constraints, adverse climatic conditions, and a lack of awareness about alternative livelihoods like cage culture impede the sector's growth. However, recent research initiatives and policy recommendations emphasize the potential of cage farming for various marine finfishes. Government support, including the establishment of a marine fish hatchery and grow-out farm, aims to overcome challenges and further unlock the region's mariculture potential, crucial for sustainable economic development and meeting the growing demand for seafood (Kiruba-Sankar *et al.,* 2019).

Considerations for Successful Mariculture

Environmental Impact Assessment (EIA): Conduct thorough assessments to ensure that mariculture activities do not harm the surrounding ecosystem.

Water Quality Management: Regular monitoring and management of water parameters like temperature, salinity, dissolved oxygen, and nutrient levels are crucial.

Biosecurity Measures: Implement measures to prevent and control **disease outbreaks, including quarantine procedures and disease-free seed stock.**

Sustainable Feed Management: Optimize feed formulation and feeding practices to minimize waste and reduce reliance on wild fish for feed ingredients.

Community Engagement and Training: Involve local communities, provide training, and promote sustainable mariculture practices to ensure long-term benefits and acceptance of mariculture initiatives.

India, like many other countries, faces the necessity to increase seafood production to meet the rising demand. Projections indicate a need to produce about 18 million tonnes of fish by 2030, compared to the approximately 13 million tonnes produced at present. This implies that aquaculture production needs to escalate from about 5 million tonnes to about 12 million tonnes to bridge this gap. While enhancing fish production from the inland sector has limitations in terms of scope, the bulk of the additional demand is expected to be met through the development and expansion of mariculture.

Sustainable mariculture practices in Indian island ecosystems can contribute to food security, economic development, and environmental conservation, provided they are implemented with careful planning and adherence to best practices.

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