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Economic Viability and Scalability of Tube Net Seaweed Farming for *Kappaphycus alvarezii* in Coastal Communities of India

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ABSTRACT

This study explores the economic viability and adoption of the tube net method for seaweed farming, particularly for Kappaphycus alvarezii cultivation, along the southeastern coast of Tamil Nadu, India. The research examines the financial feasibility, operational costs, and socio-economic characteristics of coastal farmers engaged in seaweed cultivation using this method. Primary data was collected from 120 farmers in Mandapam taluk, focusing on investment, operational expenses, yields, and labor requirements. The results show that the method offers a promising alternative to traditional bamboo raft farming, with substantial profitability potential. The system yields an estimated 39,000 kg of fresh seaweed per year, generating a gross sales income of ₹3,90,000 annually, with net earnings of ₹1,56,755 per year for a 25-raft unit. The benefit-cost ratio of 1.67 indicates a high return on investment, and the system's low break-even price of ₹59.81 per kilogram demonstrates its financial resilience. The modular design allows for scalability, making it accessible to small-scale farmers with minimal financial barriers. The study concludes that despite its advantages, the tube net method faces some challenges like limited awareness, high initial costs, and regional ecological constraints affect adoption. The method remains sustainable, profitable, and community-friendly, aligning with government livelihood schemes and blue economy goals.

Keywords: *Tube Net, Seaweed, Seaweed Farming, Kappaphycus alvarezii, Economic Viability, Profitability, Scalability, Coastal Communities.*

1. Introduction

Seaweeds, often referred to as marine macroalgae, are gaining prominence worldwide as sustainable bioresources due to their extensive applications in food, pharmaceutical, cosmetic, agricultural, and biotechnological industries [1]. In India, despite having vast coastal resources, the contribution to global seaweed production remains less than 1%, highlighting a significant underutilization of this natural capital. Recent initiatives under government programs like the Pradhan Mantri Matsya Sampada Yojana (PMMSY) and the Scheduled Caste Sub-Plan (SCSP) are increasingly promoting seaweed mariculture as a means of livelihood diversification and climate-resilient coastal development [2].

Among the various farming techniques developed in India, the tube net method has emerged as a technically viable and economically feasible innovation, particularly suited for high wave action coastal regions where traditional methods like bamboo rafts and monolines face limitations [3]. This method, which involves the use of raft based net tubes seeded with commercially valuable red seaweed species such as *Kappaphycus alvarezii* and *Gracilaria edulis*, offers several advantages, including improved seed retention, enhanced biomass yields, reduced labor requirements, and adaptability to rough sea conditions [4].

The adoption of the tube net farming system is not just a technological upgrade but a strategic intervention addressing multiple bottlenecks in India's seaweed value chain. It enables better spatial efficiency, seeding convenience, and two-stage harvesting, allowing for effective tissue segregation, separating high-value basal biomass for hydrocolloid extraction from apical tips used for reseeding. Studies have demonstrated that this method achieves an average daily growth rate of 3.40 ± 0.57% and yields up to 11.93 kg fresh weight per raft in a 45-day cycle, making it highly suitable for smallholder adoption in commercial-scale operations [4].

The tube net farming approach has demonstrated strong economic potential, with annual net returns ranging from ₹1.48 to ₹13.28 lakhs per hectare in regions like the Gulf of Mannar and northeastern Tamil Nadu. These returns are notably higher than those from traditional methods, owing to reduced seed loss, higher crop density, and lower labor costs. However, the widespread adoption of this method in India is hindered by challenges such as limited awareness, high initial capital costs, and ecological constraints. Research institutions like ICAR-CMFRI and CSIR-CSMCRI are addressing these barriers through training and capacity-building programs, helping farmers adopt and sustain tube net farming.

This study aims to conduct a comprehensive economic analysis of the tube net method of seaweed farming and assess the level of its adoption among coastal farmers in India. By doing so, it seeks to inform policy and investment decisions for scaling up seaweed mariculture as a viable, eco-friendly, and commercially sustainable sector in the Indian blue economy.

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2. Methodology

The present study was undertaken in Mandapam taluk of Ramanathapuram district, located along the southeastern coast of Tamil Nadu, India (Fig. 1) [5]. The region is known for its favorable marine conditions and active participation of coastal communities in seaweed cultivation due to shallow of the shallow sea [6]. The study specifically focused on the economics of cultivating *Kappaphycus alvarezii* using the raft-based tube net cultivation, a widely adopted low-cost technology among small-scale marine farmers [7].

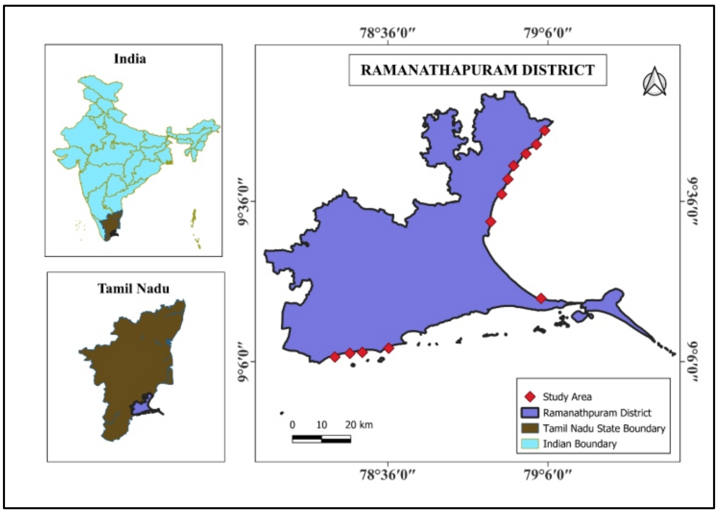

Figure 1. Location Map of the Study Area

Primary data were collected from a sample of 120 seaweed cultivators through structured interviews. The questionnaire captured detailed information on investment costs, operational expenses, yield levels, market prices, and labor inputs across six production cycles over one year. All selected farmers had practical experience in seaweed farming and were actively engaged in the cultivation of *Kappaphycus alvarezii* using the raft-based tube net system [3].

To ensure consistency and reliability, the data collection instrument was pre-tested with a subset of farmers and revised in consultation with subject-matter experts. The cost estimates were based on actual expenditures incurred by the farmers and reflect realistic field-level conditions in the study area [8].

The economic analysis was carried out using standard farm management and agricultural economics tools. The cost of cultivation was broken into initial investment costs, fixed costs, and operational costs [9]. Initial Investment Costs included the purchase of bamboo poles, iron anchors, nets, ropes, and seed materials. Fixed Costs were computed based on the depreciation of capital items (using the straight-line method based on the useful life of assets) and interest on investment at 7% per annum. Operational Costs covered recurring expenses such as labor charges for braider twining, transportation, raft maintenance, and miscellaneous inputs [10].

2.1 Fixed Cost (FC)

Fixed costs included depreciation on capital items (based on their estimated economic life) and interest on investment, calculated at 7% annually.

2.2 Operational Cost (OC)

Operational costs included recurring expenses such as transportation, raft-based tube nets maintenance, labor for braider twining and miscellaneous charges.

2.3 Total Cost of Production (TC)

Total cost of production is the sum of all expenses incurred during the production process, including both fixed and operational costs.

$$\text{Total Cost} = \text{Fixed Cost (A)} + \text{Operational Cost (B)}$$

2.4 Gross Returns (GR)

Gross returns refer to the total income generated from the sale of dried seaweed

$$\text{Gross Returns} = \text{Dried Seaweed Yield (kg)} \times \text{Market Price per kg}$$

2.5 Net Returns (NR)

Net returns are calculated by subtracting the total cost of production from gross returns.

$$\text{Net Returns} = \text{Gross Returns} - \text{Total Cost of Production}$$

2.6 Benefit-Cost (B:C) Ratio

The B:C ratio measures the economic efficiency of the farming system by comparing the returns to the costs.

This ratio indicates the profitability of the seaweed cultivation:

$$\text{B: C Ratio} = \frac{\text{Gross Returns}}{\text{Total Cost of Production}}$$

2.7 Break-even Price

Break-even price is the minimum price at which the dried seaweed must be sold to cover the total production cost.

$$\text{Break} - \text{even Price (₹/kg)} = \frac{\text{Total Cost of Production}}{\text{Total Quantity of Dried Seaweed}}$$

3. Results

The socio-economic profile of the sample respondents reveals diverse demographic characteristics influencing seaweed farming practices. As shown in Table 1, the majority of respondents belong to the middle age group (36–50 years), comprising 38% of the total sample. This is followed by the old age group (above 50 years) at 32% and the young age group (up to 35 years) at 30%, indicating a balanced participation across age ranges with a slight dominance of economically active middle-aged individuals.

Education levels indicate that 42% of respondents are illiterate, while 32% have attained only primary education. Those with secondary education account for 23%, 17% have completed pre-university courses (PUC), and a small fraction (6%) hold a degree. This suggests that seaweed farming is largely practiced by individuals with limited formal education, highlighting the importance of hands-on learning and extension support.

Family size data shows that 52% of respondents belong to small families (≤ 4 members), 38% to medium-sized families (5-7 members), and 10% to large families (> 7 members), indicating access to a moderate family labor force that impacts farming operations. Regarding experience, 40% of farmers have 15–25 years of experience, forming a strong base of moderately experienced cultivators. Additionally, 34% have less than 15 years of experience, suggesting a significant influx of new entrants, likely driven by recent government initiatives. Smaller groups (16%) have 26–35 years of experience, and only 10% have over 36 years of experience in seaweed farming.

Table 1: Socio-economic characteristics of sample respondents

Sl. No.	Particulars	Number (n=120)	Per cent
I	Age group		
1	Young age (Up to 35 years)	32	30
2	Middle age (36-50 years)	63	38
3	Old age (Above 50 years)	35	32
II	Education level		
1	Illiterate	42	42
2	Primary	32	32
3	Secondary	23	23
4	PUC	17	17
5	Degree	6	6
III	Family size		
1	Small (≤ 4 members)	62	52
2	Medium (5-7 members)	46	38
3	Large (> 7 members)	12	10
VI	Experience in farming (years)		
1	<15 years	41	34
2	15-25 years	48	40
3	26-35 years	19	16
4	≥ 36 years	12	10

Figure 2. Seaweed Cultivation Using Floating Raft-Based Tube Net Technique: (A) Kappaphycus alvarezii being filled into the tube net; (B) Raft seeded with Kappaphycus alvarezii

3.1 Seaweed farming

Kappaphycus alvarezii cultivation along the Tamil Nadu coast has increasingly adopted the floating tube net raft method, offering an efficient and scalable alternative to traditional bamboo raft culture (Fig. 2). The method involves constructing a rectangular frame made of bamboo raft, typically measuring around 4 meters by 4 meters, designed to float on the water surface with the help of buoyant floats attached at the corners and edges for stability. Seaweed fragments are seeded on polypropylene ropes stretched horizontally across the frame at regular intervals, with each tube holding weighing approximately 300–600 grams, facilitating adequate growth space and nutrient exposure.

The total seeding requirement per raft ranges from 20 to 30 kilograms, depending on raft size and density. To secure the rafts in place against currents and tidal forces, the structure is anchored using cement blocks or concrete weights, connected by mooring chains or ropes. Mooring buoys and iron anchors may be used for enhanced anchorage and ease of retrieval.

Typically, clusters of 10 to 25 rafts are deployed in nearshore waters at depths ranging from 1 to 2 meters, depending on tidal range and sea conditions. This modular method allows farmers to scale production based on available resources and market demand.

3.2 Economics of seaweed farming

The initial capital outlay for setting up a single tube net unit for seaweed cultivation is estimated at ₹3,190. This investment includes all essential structural and operational components required to establish the raft system in marine conditions. The distribution of costs across the components provides insights into the affordability and sustainability of this cultivation method.

Among all the listed items, cement blocks represent the highest share of investment, accounting for ₹1,200 or 37.62% of the total cost. These blocks are crucial as they act as anchors, providing stability to the entire raft system under oceanic forces. Their economic life of 10 years reflects their durability and long-term utility, justifying their relatively high cost.

The raft structure, costing ₹600 (18.81% of the total investment) with a 10-year life expectancy, serves as a long-term asset, reducing replacement costs. Buoyancy elements, including buoys and mooring buoys, cost ₹840 (13.79% and 12.54%, respectively) but have a shorter lifespan of 2 to 5 years, requiring more frequent replacement. The tube net, essential for seaweed attachment, costs ₹230 (7.21%) but has a short lifespan of 5 years, leading to recurring expenses. Mooring chains and installation, costing ₹320 (3.76% and 6.27%), ensure the system's secure positioning in the water.

Table 2. Initial investment in a single Raft-Based Tube Net cultivation

Particulars/Description	Unit	Quantity Required	Cost per Unit (₹)	Total Cost (₹)	Share (%)	Economic Life (Years)
Raft	No	1	600	600.00	18.81	10
Tube Net	No	10	23	230.00	7.21	5
Cement Block	No	2	600	1200.00	37.62	10
Mooring Chain	Meter	2.4	50	120.00	3.76	4
Buoy	No	4	110	440.00	13.79	2
Mooring Buoy	No	4	100	400.00	12.54	5
Mooring Installation	-	-	-	200.00	6.27	1
Total Initial Investment Cost				**3,190.00**	100.00	

The relatively low total investment requirement demonstrates that seaweed cultivation using tube net systems can be initiated with minimal financial barriers, making it a viable option for livelihood diversification in coastal areas. The setup is modular and scalable, meaning that once the viability of a single unit is proven, it can be easily expanded to multiple units based on the availability of labor, space, and market demand.

The tube net model for seaweed farming presents a cost-effective, durable, and scalable solution, with the initial investment distribution reflecting strategic prioritization (Fig. 3). Cement blocks account for 37.62% of the total cost, followed by the raft at 18.81%, highlighting their importance in maintaining structural integrity. Buoy-related components, including buoys (13.79%) and mooring buoys (12.54%), make up over a quarter of the investment, while the tube net accounts for 7.21%. Mooring installation and chains, though smaller investments at 6.27% and 3.76%, are essential for anchoring and stability. This allocation ensures both structural strength and operational stability.

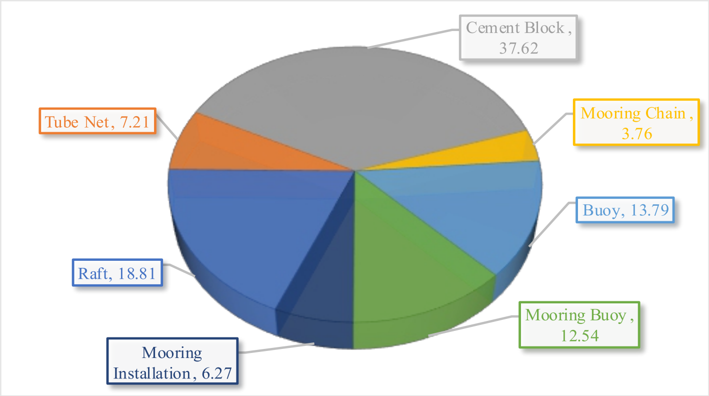

Figure 3. Share of the component in the initial investment

Fixed cost refers to the non-recurring but essential expenses associated with the ownership and use of durable assets in seaweed cultivation. As detailed in Table 3, the fixed cost for a single raft-based tube net amounts to ₹754.97. This cost is not incurred annually but is calculated based on the expected useful life of the investment assets, offering a clearer picture of capital efficiency per unit of production.

The fixed cost for a single raft consists of two main components: depreciation and interest on investment. Depreciation accounts for ₹531.67 (70.42%) and reflects the gradual reduction in value of long-term assets such as the raft, net, buoys, cement blocks, and mooring chain, with depreciation rates based on the economic life of each component (2–10 years). Interest on investment, at ₹223.30 (29.58%), represents the potential return if the initial investment of ₹3,190 per raft were placed in a 7% annual return financial instrument. The total fixed cost of ₹754.97 is modest, especially considering the multi-year lifespan of most equipment.

Table 3. Fixed cost

Description	Amount (₹)	Share (%)
Depreciation	531.67	70.42
Interest on Investment (7%)	223.30	29.58
Total Fixed Cost (A)	**754.97**	**100**

Operating costs refer to the recurring expenses required for the day-to-day functioning of a single raft-based tube net raft used in seaweed cultivation. As presented in Table 4, the total operating cost for a single raft unit is estimated at ₹800. These costs are incurred every cultivation cycle or year and are essential to ensure the system remains productive, efficient, and well-maintained.

The operating cost is primarily driven by labor, which accounts for ₹500 (62.50%) for tasks such as seeding the raft and deploying it into the sea. Seed material costs ₹200 (25%), based on 25 kg of fresh seaweed seed at ₹8 per kg. The remaining ₹100 (12.50%) covers raft maintenance and miscellaneous expenses, including repairs, cleaning, and net tightening to ensure the system's functionality throughout the cultivation period.

The operating cost structure reflects a low-input and cost-effective system, making raft-based tube net seaweed cultivation highly accessible to small and marginal coastal farmers. With a total cost of ₹800 per raft, the recurring financial burden remains light, while the income potential remains significantly higher.

Table 4. Annual operating cost

Operating Cost	Amount (₹)	Share (%)
Seed Material (25kg in a raft @ ₹8 per kg of seed material)	200	25.00
Labour charges for seeding and deployment (nos.)	500	62.50
Raft maintenance and Miscellaneous expenses	100	12.50
Total Operating Cost (B)	**800**	100
Total Cost of Production A+B	**1,554.97**	

The financial feasibility of raft-based tube net seaweed cultivation is evaluated through an analysis of its annual costs and returns. As shown in Table 5, when scaled to 25 rafts, the system yields impressive profitability metrics that strongly support its adoption as a viable income-generating activity in coastal regions.

The system yields an estimated 39,000 kg of fresh seaweed per year, calculated based on 260 kg per raft over six cultivation cycles annually (Fig. 4). After accounting for post-harvest losses, water content, and processing, the net usable dried seaweed yield is projected at 3,900 kg. This dried seaweed is the primary marketable output, with an average market price of ₹100 per kg, resulting in a gross sales income of ₹3,90,000 per year.

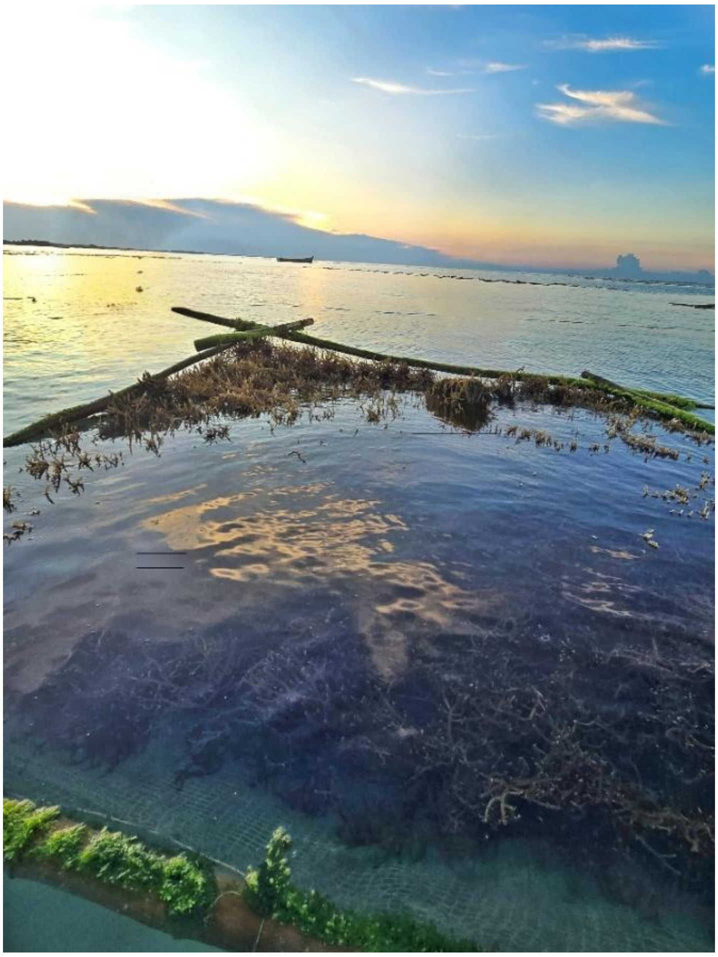

Figure 4. Seaweed raft ready for harvest

On the cost side, the total cost of production for maintaining and operating 25 rafts, including fixed and operating costs, is estimated at ₹2,33,245. This values accounts for material depreciation, labor, seed input, maintenance, and interest on capital for all 25 rafts.

Subtracting this from the gross revenue, the net earnings amount to ₹1,56,755 per year, translating into a profitability margin of 40%. The Benefit-Cost (B: C) ratio stands at 1.67, indicating that for every ₹1 invested, the system returns ₹1.67. This value surpasses the typical profitability threshold for small-scale aquaculture systems and confirms the high return on investment (ROI) associated with this model. The break-even price, or the minimum price per kilogram of dried seaweed required to cover the total cost, is calculated at ₹59.81, which is significantly lower than the prevailing market price.

Table 5: Annual Cost and Returns of Raft-Based Tube Net Seaweed Cultivation

Item Description	Quantity / Basis	Unit Price / Value (₹)	Total Amount (₹)
Estimated annual fresh seaweed yield	260 kg × 25 rafts × 6 cycles =39,000kg	—	—
Expected dried seaweed yield (10%)	10% of 39,000kg = 3,900 kg	—	—
Market price of dried seaweed	per kg	100	—
Gross sales income	3,900 kg × ₹100	—	3,90,000.00
Total cost of production for 25 rafts	1,554.97 × 25 rafts × 6 cycles	—	2,33,245.00
Net earnings from total production	Gross income – Total cost	—	1,56,755.00
Profitability ratio	(Net Income ÷ Revenue)	—	40%
Minimum sale price to cover cost (Break-even)	(Total Cost ÷ Total Quantity Sold)	—	59.81
B:C Ratio	Total Revenue ÷ Total Cost		1.67

The economic indicators from Table 5 demonstrate that raft-based tube net cultivation is not only technically feasible but also highly profitable, particularly when operated in small clusters of 25 rafts or more. The modular structure allows cultivators to start with a few units and scale up gradually based on labor availability, site suitability, and market demand. The income potential is steady and repeatable across multiple cycles in a year, making it well-suited for coastal communities seeking sustainable and low-risk livelihood options.

4. Discussion

The socio-economic distribution of seaweed farmers reveals a predominance of middle-aged individuals (36-50 years), suggesting that the workforce is stable and productive, contributing to the industry's growth [10]. Despite relatively low educational levels, with 42% of farmers being illiterate, seaweed farming remains accessible, highlighting the importance of hands-on experience and the role of extension services and training programs in enhancing productivity [2]. The data on family size suggests that larger families provide more efficient labor for the manual nature of seaweed farming, though smaller families could benefit from mechanization or government support [9].

The mix of experienced farmers and new entrants, with 40% having 15-25 years of experience and 34% being relatively new, underscores the sector's dynamic growth and the critical role of experienced farmers in transferring knowledge and integrating innovations, such as the raft-based tube net method [11]. This balanced distribution ensures long-term sustainability and growth.

The adoption of the raft-based tube net raft method for *Kappaphycus alvarezii* cultivation has been advantageous, offering durability, reduced maintenance costs, and better water circulation compared to traditional bamboo rafts [12][13]. This method's modular structure allows scalability based on labor availability, space, and market demand. The use of cement blocks and anchorage systems ensures stability, contributing to the method's success and its role in expanding seaweed farming along the Tamil Nadu coast [14]. The method's combination of low maintenance, efficient production, and adaptability positions it as a profitable and sustainable solution for coastal farmers.

The capital investment for setting up a single unit is substantial but affordable, especially considering the long-term benefits. Cement blocks, the highest cost component, ensure durability with an economic life of 10 years, justifying their cost. The raft structure, though less costly, also has a 10-year life expectancy, minimizing replacement costs [3]. The cost of buoyancy and mooring components is lower, reflecting their practical functionality and flexibility in maintenance.

The raft-based tube net system for seaweed farming, despite its relatively low initial investment, requires regular replacement of components like the tube net, which has a economic life of just five years. This recurring expense is balanced by the overall efficiency of the method, which increases productivity and reduces labor costs [13]. The modular and scalable nature of the system allows small-scale farmers to start with a few units and expand gradually as resources and market demand increase, making it highly attractive for coastal communities seeking sustainable livelihood options [4]. The investment structure prioritizes long-lasting components such as cement blocks and the raft, ensuring the stability and durability of the system even in harsh marine conditions [15]. These components receive the highest share of investment, reflecting their crucial role in the system's overall functionality [16].

The buoyancy elements and mooring chains, although representing a smaller share of the cost, are essential for maintaining the system's flotation and stability. This strategic allocation of resources ensures both operational reliability and financial manageability, making the method affordable and scalable [17]. The relatively low fixed cost of ₹754.97 for each raft is a significant advantage, especially for new and small-scale farmers in coastal areas with limited capital. The breakdown of fixed costs shows that depreciation, primarily of long-term assets like the raft and cement blocks, makes up the largest portion [19]. While components with shorter lifespans, like the buoys and mooring chain, incur more frequent replacement costs, the overall financial pressure is mitigated by the long-lasting nature of key components.

This efficient cost structure, combined with the long-term sustainability of the system, makes it an ideal solution for expanding seaweed farming in coastal regions, contributing to both economic growth and environmental sustainability [18].

The tube net-based seaweed farming system demonstrates both financial and technical viability, particularly for small-scale farmers in coastal areas. The low operating cost structure, including a significant portion for labor (62.50%), highlights the labor-intensive nature of the process, while also presenting opportunities for local employment generation in regions with limited alternative livelihoods [13]. The affordable cost of seed material, accounting for 25% of the operating costs, and the manageable maintenance costs further contribute to the financial sustainability of the system.

The system's scalability, with an ability to expand as labor and resources permit, makes it adaptable to varying market demands and resource availabilities, ensuring long-term financial stability [19].
Financially, the system is highly profitable, generating an estimated ₹1,56,755 annually, with a 40% profitability margin. The system's low break-even price of ₹59.81 per kilogram, compared to the market price of ₹100 per kilogram, offers a strong financial cushion, making it resilient to market fluctuations [20]. The Benefit-Cost (B: C) ratio of 1.67 demonstrates a high return on investment (ROI), confirming its suitability for small-scale farmers. The system's affordability, simplicity, and low-risk nature make it an excellent fit for community-based livelihood programs, women's self-help groups, and coastal aquaculture cooperatives. The model holds potential for integration into government-supported schemes and broader blue economy initiatives, providing socio-economic benefits and fostering the growth of women-led microenterprises and coastal cooperatives [21]. The prospect of value-added seaweed products, such as cosmetics and biofertilizers, broadens its market scope, contributing to both economic and environmental sustainability.

5. Conclusion
The study concludes that the raft-based tube net method for cultivating *Kappaphycus alvarezii* presents a technically feasible, economically viable, and socially inclusive livelihood option for coastal communities in Tamil Nadu. With low initial investment, manageable operating costs, and high profitability demonstrated by a 40% profit margin and a favorable B: C ratio of 1.67, the system supports sustainable seaweed farming at scale. The modular design allows farmers to expand operations based on resource availability and market demand, while the labor-intensive nature of the activity offers employment opportunities, especially for women and smallholder farmers. The method's durability, cost-efficiency, and alignment with blue economy goals make it ideal for policy inclusion under government-supported coastal development programs. However, to scale this method nationally, challenges like awareness, startup cost, and ecological adaptability must be addressed through targeted policy support. The raft-based tube net model ensures long-term sustainability and offers significant potential for improving income, enhancing food security, and supporting environmental resilience in coastal regions.

6. Future Scope
The study suggests future research in scaling the model to other coastal regions, integrating value-added processing, and exploring climate resilience through mixed-species cultivation.

7. Conflict of Interest
The authors declare no conflict of interest.

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