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Culture potential of *Gracilaria salicornia* in the brackishwater ecosystem: A multifaceted approach towards sustainable development goals

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Abstract

Seaweed farming is a sustainable practice that contributes to several of the United Nations' sustainable development goals (SDGs). Cultivation of *Gracilaria salicornia*, a species of red algae known for its high economic value and ecological benefits. *G. salicornia* is widely used in various industries, including food, pharmaceuticals and cosmetics, due to its rich content of agar, a gelatinous substance with numerous applications. This study investigated the potential of *G. salicornia* cultivation in the brackishwater environment using a raft-based system with twelve 3 m² rafts, each equipped with twelve 25 mm mesh mono line tube nets. The initial stocking density was set at 1.2 kg of *G. salicornia* per tube net. The seaweed growth assessment and water samples were assessed at once in 15-day intervals. Results showed a robust initial growth phase, with an average biomass of 5.07 kg per tube net by the 15th DOC, 7.67 kg by the 30th DOC and further increased to 9.09 kg by the 45th DOC. Specific growth rates (SGR) followed a similar trend, with an initial rapid increase followed by a gradual decline, reaching 9.59% d⁻¹ on the 15th DOC and decreasing to 4.50% d⁻¹ by the 45th DOC. This study demonstrated the viability of *G. salicornia* cultivation in brackishwater environments using raft methods and its potential to provide alternative livelihood opportunities for coastal communities. This study provides valuable data for optimizing *G. salicornia* cultivation strategies and promoting sustainable seaweed farming practices.

Keywords Brackishwater, *Gracilaria Salicornia*, Raft method, Seaweed cultivation, Livelihood

Introduction

Seaweed farming is emerging as one of the sustainable aquaculture practices globally, offering both ecological and economic benefits [1, 2]. The global seaweed industry is experiencing remarkable growth, characterized by significant regional differences and a focus on specific

species [3, 4]. Since 1950, seaweed cultivation has seen an extraordinary thousand-fold increase in volume [5]. This trend culminated in a global seaweed production of 35.2 million tons (live weight) in 2021 [6]. The industry's market value has also witnessed substantial growth, more than tripling from \$5 billion in 2000 to \$17 billion in 2021, with projections indicating a further seven-fold increase to \$85 billion by 2026 [7].

Seaweed farming offers a multifaceted opportunity to enhance the socio-economic resilience and environmental sustainability of coastal communities. By providing an accessible livelihood option, seaweed cultivation

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generates income and empowers marginalized groups, particularly women [5, 8]. The industry's expansion diversifies income streams and fosters community development through job creation and infrastructure improvements. When practised responsibly, seaweed farming promotes healthier coastal ecosystems, fostering environmental stewardship and mitigating the adverse effects of nutrient pollution and ocean acidification [5]. At a national level, seaweed cultivation addresses food security challenges by offering a nutritious and sustainable food source. This is particularly vital in regions prone to malnutrition, where seaweed's rich nutrient profile can improve dietary quality and overall health [9]. The environmental benefits extend beyond carbon sequestration, as seaweed farming enhances water quality, reduces coastal erosion and supports biodiversity by providing habitats for marine and brackishwater organisms. Economically, seaweed farming is a burgeoning sector with significant growth potential [10]. By creating jobs across the entire value chain from cultivation and processing to marketing and distribution the industry stimulates economic activity and reduces unemployment. The growing global demand for seaweed-based products, spanning food, cosmetics and pharmaceuticals, opens lucrative export opportunities, generating foreign exchange earnings and bolstering the national economy [2, 7]. Furthermore, the development of innovative seaweed-based products and technologies drives advancements across various sectors, positioning the nation as a leader in the emerging blue economy [11].

Seaweed farming aligns seamlessly with sustainable development goals, providing a renewable resource, supporting local livelihoods, protecting and restoring the environment, and contributing to climate change mitigation [2]. While seaweed farming is predominantly carried out in marine ecosystems, brackishwater ecosystems remain largely untapped. Brackishwater environments, characterized by their fluctuating salinity levels, present unique opportunities for seaweed cultivation and are well-suited for this purpose [12]. *Gracilaria salicornia*, a red seaweed species known for its rapid growth rate, tolerance to varying salinity levels, and potential applications across multiple industries, can play a significant role in these environments. The cultivation of *G. salicornia* can contribute to food security by providing a nutritious and sustainable food source, particularly in coastal communities where traditional agriculture may be limited. Furthermore, its ability to absorb excess nutrients from the water can improve water quality and mitigate nutrient pollution [2, 13–17].

Hence this study aims to investigate the potential of *G. salicornia* cultivation in a brackishwater environment using a raft-based system to evaluate the growth

performance and assess the feasibility of scaling up this cultivation method for commercial production.

Materials and methods

Study area

A culture trial for *G. salicornia* farming using the raft method was conducted in Muttukadu lagoon, a brackish-water ecosystem south of Chennai on the Bay of Bengal coast. This lagoon is characterized by fluctuating salinity and tidal influences, creating a dynamic environment suitable for seaweed growth. The study area map with culture site location is given in Fig. 1.

Collection of seaweed samples

G. salicornia seaweeds were collected from natural habitats, thoroughly cleaned to remove epiphytes and debris and then transferred to FRP (Fibre-Reinforced Plastic) tanks, stored till the onset of the experiment in Crustacean Culture Division (CCD), Muttukadu Experimental Station (MES) of ICAR–Central Institute of Brackishwater Aquaculture, Tamil Nadu, India.

Assessment of water quality parameters and seaweed growth

Water samples were collected and analysed at fortnightly intervals. Water samples were collected in 250 ml brown bottles and stored at 4 °C for analysis. Water temperature was assessed using a handheld thermometer in the field. In the laboratory, the following parameters were examined using specific instruments: pH with a LAQUAtwin Horiba probe, dissolved oxygen (DO) with a Lutron DO- 5510, salinity with an ATAGO handheld digital salinometer, calcium (Ca^{2+}), sodium (Na^+), potassium (K^+) with Horiba probes, magnesium (Mg^{2+}) with a Horiba digital probe and turbidity with TN 100 Thermo Scientific Eutech (US). Phosphate phosphorus ($\text{PO}_4\text{-P}$) and ammonia–nitrogen ($\text{NH}_4\text{-N}$) were analysed using phosphomolybdic acid-ascorbic acid and phenol hypochlorite, respectively. Nitrite (NO_2) was examined using the sulphanilamide NED technique. The Biochemical Oxygen Demand (BOD) analysis was carried out with an initial measurement of dissolved oxygen (DO) using a DO meter. Then, BOD nutrient buffer solutions and seed microorganisms were added to the samples. The BOD bottles were sealed and incubated at a controlled temperature of 20 °C for 5 days. After the incubation period, the final DO measurement was recorded. The BOD value was calculated by determining the difference between the initial and final DO levels. Total hardness was measured using the EDTA titration method. Carbonate, bicarbonate and total alkalinity were measured using titration method. All analyses were conducted within two days at MES of ICAR-CIBA following APHA guidelines [18].

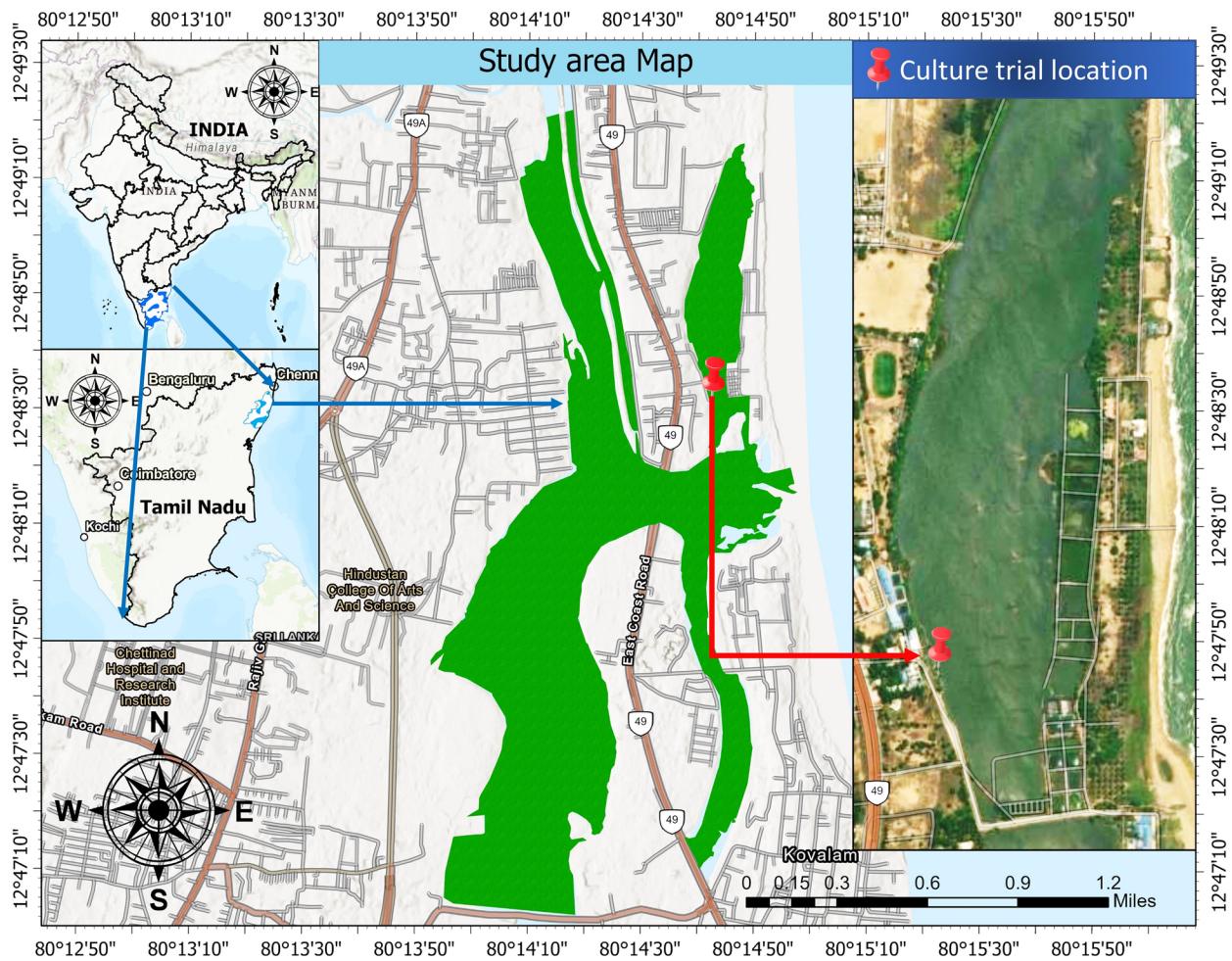


Fig. 1 Study area with culture site location

Seaweed biomass was assessed using the weighing balance. The specific growth rate (SGR) for seaweed was calculated using the formula [19].

$$\text{SGR (\% day}^{-1}\text{)} = \frac{\log(\text{final biomass}) - \log(\text{initial biomass})}{\text{Days of culture}} \times 100$$

Experimental design

A culture trial of *G. salicornia* was conducted using a raft method comprising twelve 3 m² rafts, totalling 36 m² of cultivation area as shown in Fig. 2. Each raft was outfitted with twelve 25 mm mesh monoline tube nets. An initial stocking density of 1.2 kg of *G. salicornia* per tube net was implemented. The mono-line design of the tube nets facilitates horizontal growth, while the mesh size provides adequate water exchange and sunlight.

Statistical analysis

A one-way ANOVA was conducted to analyze the effect of different Days of Culture (DOC) on various water quality parameters in SPSS V26. The water quality parameters measured included pH, salinity, dissolved oxygen (DO), biological oxygen demand (BOD), chlorophyll, carbonate, bicarbonate, total alkalinity, total hardness, ammonia, nitrite, nitrate, phosphate, calcium, magnesium, sodium, and potassium. The independent variable was the DOC with four levels vis., Initial, 15 th DOC, 30 th DOC, and 45 th DOC. Post hoc comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to identify specific group differences.

Socio-economic analysis

The economic feasibility of *G. salicornia* cultivation in brackishwater ecosystems was rigorously assessed. Based on the cost and production results from the trial, the revenue for 50 units was estimated. The number of monoline

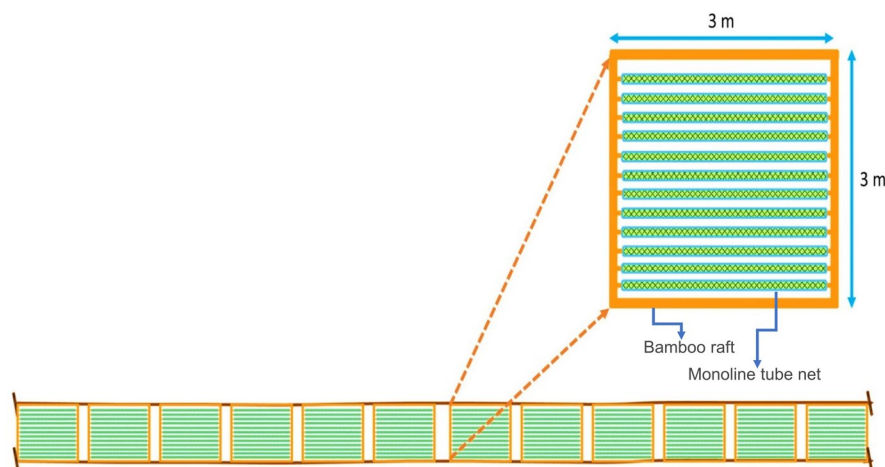


Fig. 2 Schematic diagram of the experimental setup used for *G. salicornia* culture trials using raft method

tube nets for cost economic was considered to be 18 since the maximum capacity for the raft is 18–20 monolines. The following calculations were employed to determine the economic viability of each cultivation method.

Harvestable Biomass per Unit: Total Biomass (kg fresh weight)—Seed stock for the next cycle (kg fresh weight)

Total Wet Biomass: Harvestable Biomass per unit (kg) x Number of units (number of rafts, length of monolines, etc.)

Dried Seaweed Biomass: Total Wet Biomass (kg) x (100—Moisture Content (% w/w))/100

Gross Revenue (₹): Dried Seaweed Biomass (kg) x Price per kg (₹)

Annual Gross Revenue (₹): Gross Revenue (₹) x Crop Cycles per Year

Net Revenue in Rupees (Year 1): Annual Gross Revenue (₹) — (Capital cost (₹) + Operational cost (₹))

Net Revenue in Rupees (Year 2 onwards): Annual Gross Revenue (₹)—Operational cost (₹.)

Results

Results showed a robust initial growth phase, with biomass reaching 5.07 kg per tube net at the 15 th DOC. This figure increased to approximately 7.67 kg by the 30 th DOC and further to 9.09 kg by the 45 th DOC as shown in Fig. 3, demonstrating the viability of *G. salicornia* cultivation within this framework. The observed SGR for *G. salicornia* cultivated using the raft method exhibited a growth pattern similar to that observed in the monoline tube net trials, characterized by an initial rapid increase followed by a gradual decline. On the 15 th day, the SGR was about 9.59% d⁻¹ and the SGR at the

30 th and 45 th DOC was about 6.16% d⁻¹ and 4.50% d⁻¹ respectively as shown in Fig. 4. This suggests that the overall growth trend of this seaweed species is relatively consistent across different cultivation methods.

An unforeseen environmental challenge in the form of Cyclone Michang impacted the study area during the trial (after the 45 th DOC). The cyclonic conditions, characterized by strong winds and currents, resulted in partial biomass loss from the tube nets. While this incident underscores the potential vulnerability of *G. salicornia* cultivation to environmental stressors, the overall trend indicates a significant production potential, even under such challenging conditions. The experimental setup itself demonstrated resilience to the cyclonic event. The water quality in the lagoon during the culture trial is given in Table 1. The *G. salicornia* raft farming sampling and harvest images are given in Fig. 5.

Economic assessment of *G. salicornia* cultivation in brackishwater ecosystems

The raft method necessitated a higher initial capital investment of ₹. 90,000 for 50 units, as indicated in Table 2. This was primarily attributed to the cost of bamboo rafts or tube nets, which was ₹. 1,800 per unit, inclusive of materials and labour. Despite the upfront expense, this method yielded a substantial annual harvest of 710.65 kg of dried seaweed for 50 units. With a market price of ₹. 25 per kg, the gross revenue reached ₹. 1,24,362 in the first year. This resulted in a net profit of ₹. 24,362 after deducting capital costs and miscellaneous expense charges. The second-year net revenue was about ₹. 1,14,362. The short 45-day crop cycle allows for seven harvests annually, optimizing production efficiency

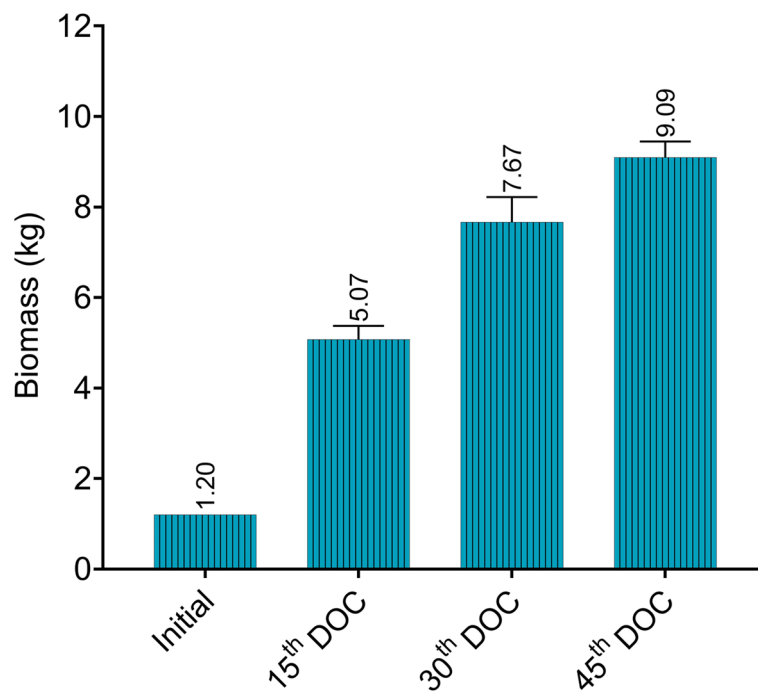


Fig. 3 Biomass of *G. salicornia* cultivated using the raft method

and maximizing returns. The capital cost and production details for raft farming are given in Tables 2 & 3.

Discussion

Commercial viability and cultivation characteristics of *G. salicornia*

This study demonstrated a pronounced enhancement in the productivity of *G. salicornia* cultivated within a brackishwater ecosystem. Over a 45-day culture period, a remarkable eightfold increase in biomass. This represented a substantial improvement over typical yields reported for *G. salicornia* cultivation in marine environments. This augmented growth rate was attributed to the unique physiochemical properties of the brackishwater system, characterized by salinity levels ranging from 20 to 31 ppt. Such conditions appeared to foster a more conducive environment for *G. salicornia* growth, potentially due to the elevated concentration and bio-availability of essential nutrients in brackishwater compared to the more dispersed nutrient profiles observed in marine ecosystems. The capacity of *G. salicornia* to flourish across this salinity spectrum underscored its euryhaline adaptation, enabling efficient utilization of the abundant nutrient resources available within this dynamic environment. The observed vigour of *G. salicornia* in brackishwater corroborated previous research emphasizing the species' resilience and suitability for cultivation. For instance, Ollando et al. [14] investigated the

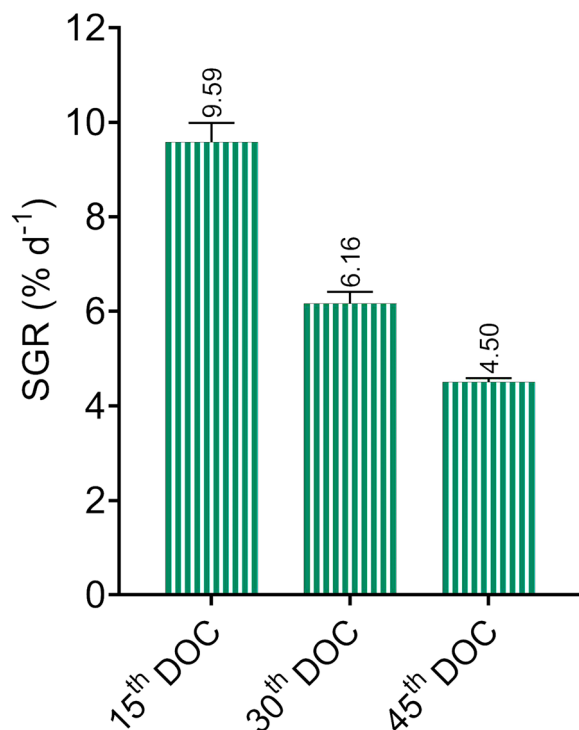


Fig. 4 SGR of *G. salicornia* cultivated using the raft method

Table 1 Physico-chemical parameters of water samples during raft culture in Muttukadu Lagoon

Water quality parameters	Initial	15 th DOC	30 th DOC	45 th DOC
pH	7.77 ± 0.09 ^a	8.15 ± 0.24 ^b	8.75 ± 0.58 ^c	8.11 ± 0.06 ^{ab}
Salinity (ppt)	31.00 ± 0.00	25.00 ± 0.00	24.00 ± 0.00	20.00 ± 0.00
DO (mg/L)	6.53 ± 0.61 ^a	6.93 ± 0.23 ^a	6.00 ± 0.23 ^a	6.67 ± 0.15 ^a
BOD (mg/L)	4.40 ± 0.00 ^c	4.13 ± 0.23 ^c	3.07 ± 0.00 ^b	2.37 ± 0.06 ^a
Chlorophyll (mg/m ³)	35.87 ± 7.66 ^a	44.50 ± 44.21 ^a	13.38 ± 0.40 ^a	43.36 ± 4.42 ^a
Carbonate (mg/L)	6.75 ± 0.00 ^a	22.59 ± 7.53 ^b	18.00 ± 9.06 ^{ab}	6.72 ± 0.73 ^a
Bicarbonate (mg/L)	155.55 ± 7.92 ^b	285.81 ± 8.84 ^c	167.29 ± 0.00 ^b	126.82 ± 4.62 ^a
Total Alkalinity (mg/L)	150.00 ± 6.50 ^a	271.92 ± 7.25 ^c	167.12 ± 7.34 ^b	137.55 ± 2.78 ^a
Total Hardness (mg/L)	6,324 ± 122 ^c	4,995 ± 141 ^a	5,554 ± 64.02 ^b	4,100.00 ± 103 ^a
Ammonia (mg/L)	0.12 ± 0.01 ^a	0.28 ± 0.12 ^a	0.09 ± 0.01 ^a	1.02 ± 0.58 ^b
Nitrite (mg/L)	0.017 ± 0.006 ^a	0.071 ± 0.010 ^a	0.032 ± 0.001 ^a	0.285 ± 0.127 ^b
Nitrate (mg/L)	0.044 ± 0.004 ^a	0.243 ± 0.026 ^b	0.015 ± 0.008 ^a	0.280 ± 0.057 ^b
Phosphate (mg/L)	0.131 ± 0.023 ^b	0.180 ± 0.012 ^c	0.049 ± 1.978 ^a	0.025 ± 0.003 ^a
Calcium (mg/L)	381 ± 12.75 ^c	361 ± 8.72 ^{bc}	343 ± 20.45 ^b	213 ± 23.09 ^a
Magnesium (mg/L)	1,305 ± 29.74 ^d	994 ± 39.76 ^b	1,141 ± 80.03 ^c	380 ± 14.03 ^a
Sodium (mg/L)	12,365 ± 567.21 ^c	8,171 ± 256.55 ^b	12,250 ± 26.02 ^c	4,988 ± 100.96 ^a
Potassium (mg/L)	518 ± 40.42 ^d	332 ± 21.50 ^b	433 ± 21.93 ^c	217 ± 6.43 ^a

Data expressed as mean ± S.E (n = 3)

**Fig. 5** *G. salicornia* raft culture trial in the Muttukadu lagoon

feasibility of cultivating *G. salicornia* for commercial agar extraction in Kibuyuni, South Coast Kenya, employing a 42-day cultivation cycle. Their findings demonstrated the capacity of *G. salicornia* to withstand fluctuating environmental parameters, including salinity and nutrient availability, suggesting its suitability for agar production. Furthermore, Ollando et al. [14] reported consistent growth and agar yields across distinct monsoonal seasons, underscoring the adaptability of *G. salicornia* to variable environmental regimes. Their study concluded that *G. salicornia* exhibits greater resilience compared to *K. alvarezii*, another commercially significant seaweed species. The present study reinforced these observations by demonstrating the high productivity of *G. salicornia* in a brackishwater ecosystem, further substantiating its potential for scalable cultivation and agar production. The enhanced productivity of *G. salicornia* documented in this study carried significant implications for the development of sustainable cultivation practices. Escalating

Table 2 Capital cost for production of 1 raft unit

Sl. No	Particulars	Cost (₹)
1	Cost of one Bamboo Raft (3 m * 3 m)	1,000
2	Other Input Costs: Expenses for anchor poles, net materials and braided ropes (framing, anchoring and raft linking)	400
3	Seaweed seed material collection (from natural stock) and seed stocking for culture labour charges	400
4	Unit cost for a single unit (₹. 1,000 + ₹. 400 + ₹. 400)	1,800
5	Total cost for installation of 50 units (₹. 1,800 * 50)	90,000

Table 3 Seaweed production potential for 50 rafts

Sl. No	Components	Details	Particulars
1	Crop cycle	45 days	45
2	Initial stocking in one unit	18 mono lines @1.2 kg per mono line	21.6 kg
3	Total production from one unit	7.58 times the initial stocking (21.6 kg * 7.58)	163.73 kg
4	Net Production per Unit (after restocking)	Total Production—Seed stock for the next cycle	142.13 kg
5	Total wet weight	(Production/unit × 50 units)	7,106.5 kg
6	Dried seaweed	10% moisture	710.65 kg
7	Price per kg (Dried)	₹. 25	₹. 25
8	Gross Revenue	Dried seaweed * ₹. 25 (710.65 * 25)	₹. 17,766
9	Crop Cycles per Year	-	7
10	Annual Gross Revenue	Gross Revenue * Crop cycles	₹. 1,24,362
11	Operational cost	Maintenance & other expenditures	₹. 10,000
12	Net Revenue (1 st year)	Annual Gross Revenue – (Capital cost + Operational cost)	₹. 24,362
13	Net Revenue (2nd year)	Annual Gross Revenue—Operational cost	₹. 1,14,362

global demand for agar, coupled with the documented decline in natural seaweed stocks, necessitated the implementation of efficient and ecologically sound cultivation strategies. In this context, Ganesan et al. [1] reviewed the diminishing natural reserves of *G. edulis*, a primary agarophyte and the consequent overexploitation of *G. salicornia* as an alternative source. They underscored the critical need for sustainable cultivation protocols to meet the growing demand for agar while mitigating anthropogenic pressure on natural populations. Ganesan et al. [1] advocated for the tube-net cultivation method as a promising approach for *G. salicornia*, wherein the seaweed is affixed to nets suspended from rafts, optimizing space utilization and facilitating controlled growth conditions. This study's findings suggested that brackishwater environments may further augment the efficacy of the tube-net method, potentially leading to elevated yields and abbreviated cultivation durations. This could contribute to the economic viability of *G. salicornia* farming while alleviating pressure on wild stocks. Finally, it is important to consider the broader context of *Gracilaria sp.* within the global agar industry. *Gracilaria sp.* constituted a cornerstone of this industry, representing over half of the world's agar supply [20–25]. This rendered it an invaluable resource for a multitude of applications spanning the food, pharmaceutical, cosmetic and biotechnology sectors.

The industries offered farmers low prices due to elevated transportation costs. When sold to nearby industries within a 50–100 km radius, dried *Gracilaria spp* fetched ₹. 40–60 rupees. A comprehensive assessment indicated that optimal utilization of the area could be achieved with the installation of 400–600 rafts per hectare. Furthermore, assessment from various studies

indicated that each hectare of seaweed cultivation could potentially support approximately 8–12 families. Furthermore, several industries provided farmers with cultivation materials and subsequently procured the harvested seaweeds. Projected revenue generation indicated significant potential for coastal fisherfolk livelihood development. It is important to acknowledge that these figures represent preliminary estimates.

Seaweed cultivation in India benefits from a supportive policy environment. Government agencies, including National Bank for Agriculture and Rural Development, Tamil Nadu Department of Fisheries and National Fisheries Development Board, play a crucial role in providing financial assistance, training programs, infrastructure development and technical expertise to seaweed farmers [5–10, 33, 37]. Furthermore, private sector engagement, exemplified by buyback agreements with companies like Aquagri Processing Private Limited, ensures market access for harvested seaweed. Despite the sector's promise, challenges persist. Limited awareness of seaweed farming's economic and environmental benefits within coastal communities necessitates targeted outreach and education initiatives [2, 13, 26–32]. Ensuring access to high quality seedlings and mitigating price fluctuations in the seaweed market also remain critical areas for intervention [33–35]. The government's proactive measures to address these challenges, including awareness campaigns, seed bank establishment and market development initiatives, are crucial for fostering sustainable growth in this promising sector [36–41].

In addition achieving optimal returns remains contingent upon various dynamic factors, including drying efficiency, market volatility, operational costs and

environmental variables. Thorough due diligence and meticulous planning are essential to mitigate potential risks and maximize profitability. With prudent management and strategic decision-making, this venture promises a substantial return on investment [5–9, 37, 38].

The successful cultivation of *G. salicornia*, particularly within brackishwater systems, presented a compelling opportunity for socioeconomic advancement in coastal communities. By providing a sustainable source of agar, *G. salicornia* farming could generate income, stimulate employment opportunities and enhance the livelihoods of coastal fisherfolk.

Conclusion

This study demonstrates the potential of *G. salicornia* cultivation in brackishwater ecosystems to generate significant revenue for coastal communities, particularly women. By diversifying livelihoods and providing alternative income sources, it can enhance economic well-being. However, the cost of seaweed production plays a crucial role in determining the economic viability and overall success of this livelihood strategy. Therefore, government initiatives that support seaweed farmers by addressing production costs, providing training and resources and facilitating market access would be crucial in promoting sustainable seaweed farming in India and maximizing its positive impact on coastal communities.

Acknowledgements

We are thankful to the Director, ICAR–CIBA for the resources and facilities provided for carrying out this work.

Authors' contributions

NRP, AR, JR, AK and BCP: Design, Conceptualization, Planning of the work, Supervision, Formal Analysis and Writing—Review & Editing. NRR: Writing—Original Draft, Data collection, Formal analysis, interpretation, manuscript preparation, Writing—Review & Editing. AKS: Data collection and Formal analysis.

Funding

We are grateful to the NFDB for funding this work.

Data availability

All data used is available within the manuscript.

Declarations

Ethics approval and consent to participate

No studies on animals or humans have been conducted, so ethical approval is not required.

Consent for publication

All authors agree to give their consent for publication.

Competing interests

The authors declare no competing interests.

Received: 6 January 2025 Accepted: 20 April 2025

Published online: 01 July 2025

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