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Spatial modelling of seaweed farming potential areas in Chengalpattu district using a Fuzzy AHP-GIS framework

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Seaweeds, with their diverse applications in food, energy, medicine and the chemical industry, hold immense potential as a renewable resource. However, the escalating demand for seaweed products has surpassed the sustainable yield from natural sources. This supply-demand gap necessitates the exploration and expansion of seaweed cultivation. While marine ecosystems currently dominate seaweed farming practices, investigating alternative cultivation environments is essential, as brackishwater offers an untapped opportunity for the sustainable production of this valuable resource. This study aims to systematically identify and assess potential areas suitable for seaweed farming in the Chengalpattu district brackishwater ecosystem using the Fuzzy Analytic Hierarchy Process (FAHP) in conjunction with geospatial techniques. FAHP combines AHP with fuzzy logic to better handle uncertainty and subjectivity in decision-making. Twenty-two representative locations along the coast in the brackishwater ecosystem were identified, and samples were collected and assessed at monthly intervals. This comprehensive study involved a meticulous evaluation of several key criteria *viz*., water quality, environmental factors, resource accessibility and relevant constraints. To facilitate a nuanced and spatially explicit analysis, each criterion was further sub-classified and systematically mapped using ArcGIS. Results revealed a total of 141.56 hectares as potential areas for seaweed farming, with 91.93 hectares classified as highly suitable and 49.63 hectares as moderately suitable. The findings contribute to the advancement of sustainable aquaculture practices by promoting the cultivation of seaweed in underutilised brackishwater environments. This strategic approach not only caters to the escalating market demand for seaweed but also cultivates economic prospects and livelihood enhancement for coastal communities.

[**Keywords**: Brackishwater, Livelihood, Seaweed farming, Site selection]

Introduction

Seaweeds are nutrient-rich resources that contribute significantly to food, employment and prosperity[1-2]. They possess diverse applications in nutrition, industry, biomedicine, agriculture and personal care, making them highly versatile[3-5]. Seaweeds are recognised as the "Medical Food of the 21st Century" due to their wide range of applications, including use as laxatives, in the production of pharmaceutical capsules, treatment of goitre, cancer, bone-replacement therapy and their role in cardiovascular surgeries[6-8]. The global seaweed industry is primarily driven by Asian countries, with China, Indonesia, the Philippines, South Korea, North Korea, Japan and Malaysia collectively dominating the majority of worldwide production[9]. Despite India's vast coastline and rich biodiversity of 871 seaweed species, India's contribution to this market remains minimal[10]. Seaweed farming in India is still a largely untapped resource[11-12]. The global production of seaweed was about 36.5 million tons (wet weight), worth around 17 billion USD, and Indian contribution to global production is only about 0.01 %, according to FAO[13].

Seaweed farming in India has gained momentum only in recent years, with states such as Tamil Nadu, Gujarat, Odisha and Andhra Pradesh, as well as the islands of Lakshadweep and Andaman Nicobar taking the lead[14]. Many self-help groups and fisherwomen have shown keen interest in taking up seaweed cultivation as an alternate livelihood option[12]. Given the substantial international demand for seaweed biomass coupled with India's vast coastline and growing interest in seaweed cultivation, it holds significant potential as a prosperous sector generating employment opportunities and subsistence income[14-15].

Furthermore, seaweed farming presents a sustainable solution to various environmental challenges, offering a multitude of ecological benefits, *viz*. bioremediation, carbon sequestration, and habitat provision for the coastal ecosystems[1]. The numerous benefits of seaweed farming highlight the critical importance of effective and strategic site selection. Identifying suitable locations for seaweed farms is a complex endeavour, encompassing a wide array of factors, including environmental considerations, economic viability, social impacts, and regulatory compliance[16-17]. Given the intricate nature of site selection, the development and implementation of systematic, science-based, and transparent methodologies are imperative. These approaches will streamline the decision-making process and ensure that seaweed farming operations are conducted in an environmentally responsible and sustainable manner[16,18-19].

Advancements in Geographic Information Systems (GIS) and Remote Sensing (RS) technologies have revolutionised spatial analysis by enabling the observation and examination of phenomena across diverse scales and resolutions[11]. This multi-scale perspective facilitates a more nuanced understanding of spatial dynamics, a crucial factor in the development and implementation of successful planning and management strategies[20]. Furthermore, Multi-Criteria Decision Making (MCDM) techniques, such as the Analytic Hierarchy Process (AHP) and its fuzzy counterpart (FAHP), are increasingly recognised as powerful methods for site selection[21-22].

AHP uses pair-wise comparisons to assign weights to different criteria and alternatives based on expert opinions[21,23]. FAHP extends AHP by incorporating fuzzy logic to handle the uncertainty and vagueness in human judgment. FAHP is more advantageous than the AHP method. FAHP can capture the linguistic preferences of experts more accurately and realistically than AHP, which uses crisp numbers. FAHP can use fuzzy numbers or linguistic terms such as "very high", "high", "medium", "low", and "very low" to express the relative importance of criteria or alternatives[24-26]. FAHP can reduce the inconsistency and subjectivity in pair-wise comparisons by using fuzzy membership functions and defuzzification methods. FAHP uses triangular or trapezoidal fuzzy numbers to represent the pair-wise comparison matrix and then uses the geometric mean or centroid method to calculate the weights of criteria or alternatives. FAHP can provide more stable and robust results than AHP when the weights of criteria or alternatives change due to sensitivity analysis[22,27-28].

Their efficacy extends across a wide spectrum of disciplines, where careful site assessment is paramount. A study by Raja *et al.*[20] demonstrated the practical implementation of advanced decision-making tools in sustainable resource management. Utilising a FAHP-based MCDM approach, their study identified optimal sites for cage farming in the Muttukadu lagoon, aiming to promote sustainable aquaculture and explore the potential for aquatourism. Through a rigorous evaluation of critical parameters, including water quality, environmental conditions, and accessibility, the study identified potential areas for cage farming in Muttukadu lagoon. The efficacy of the FAHP-based MCDM approach in pinpointing these potential sites underscores its value for analogous applications in promoting sustainable resource management and development initiatives.

Seaweed cultivation has predominantly focused on marine ecosystems. However, the potential of brackishwater environments, distinguished by their unique mix of freshwater and seawater, remains largely unexploited[1,11,20]. This underutilisation is attributable to a knowledge gap among seaweed farmers regarding the specific location for farming, cultivation techniques and potential yields associated with these ecosystems[29-30]. Consequently, a valuable resource for food production and environmental sustainability is being overlooked[1-2]. Identifying of potential farming areas in the brackishwater ecosystem in a scientific manner will help plan and develop seaweed farming sustainably without multi-user conflict. Hence, this study aims to identify the potential areas suitable for seaweed farming in the Chengalpattu district brackishwater ecosystem, using the FAHP method.

Materials and Methods

Study area

The Chengalpattu district in the northern part of Tamil Nadu was strategically chosen for this study due to its extensive coastline and diverse brackishwater environments, *viz*., Muttukadu lagoon, Buckingham canal, Kalpakkam brackishwater, Palar brackishwater, and Odiyur brackishwater. Its proximity to major urban centres like Chennai offers both ecological and economic advantages. The region's tropical wet and dry climate provides ideal conditions for the growth and proliferation of a diverse range of seaweed species. Seaweeds like *Gracilaria* and *Ulva* spp., are found in abundance in the area and left unutilised, making Chengalpattu an ideal location for this study. The coastal sub-watershed boundary of the Chengalpattu district is taken up as the study area (12°24′48″ N to 12°47′16″ N and 79°48′9″ E to 80°15′14″ E). The district is bounded on the north by Chennai district, on the west by Kancheepuram and Tiruvannamalai districts, and on the south by Villupuram district. Representative sampling locations have been identified along the coast (Fig. 1), and samples have been collected at monthly intervals from January 2020 – December 2023.

Seaweed farming site selection mapping

Seaweed farming site selection was carried out using the FAHP. Water quality criteria *viz*. salinity, pH, Dissolved Oxygen (DO), water temperature, nitrite, nitrate, ammonia, phosphate, turbidity, Biochemical Oxygen Demand (BOD), calcium, magnesium, sodium, and potassium were considered for the study based on relevant literature. Environmental criteria, *viz*. water depth, wind speed, and water current, were also considered. Resource accessibility criteria such as distance to the seed source, distance to the road, and distance to the market are considered for analysis. Constrain criteria were considered for wildlife habitats, bar mouth, navigation, docks and fishing zones, and

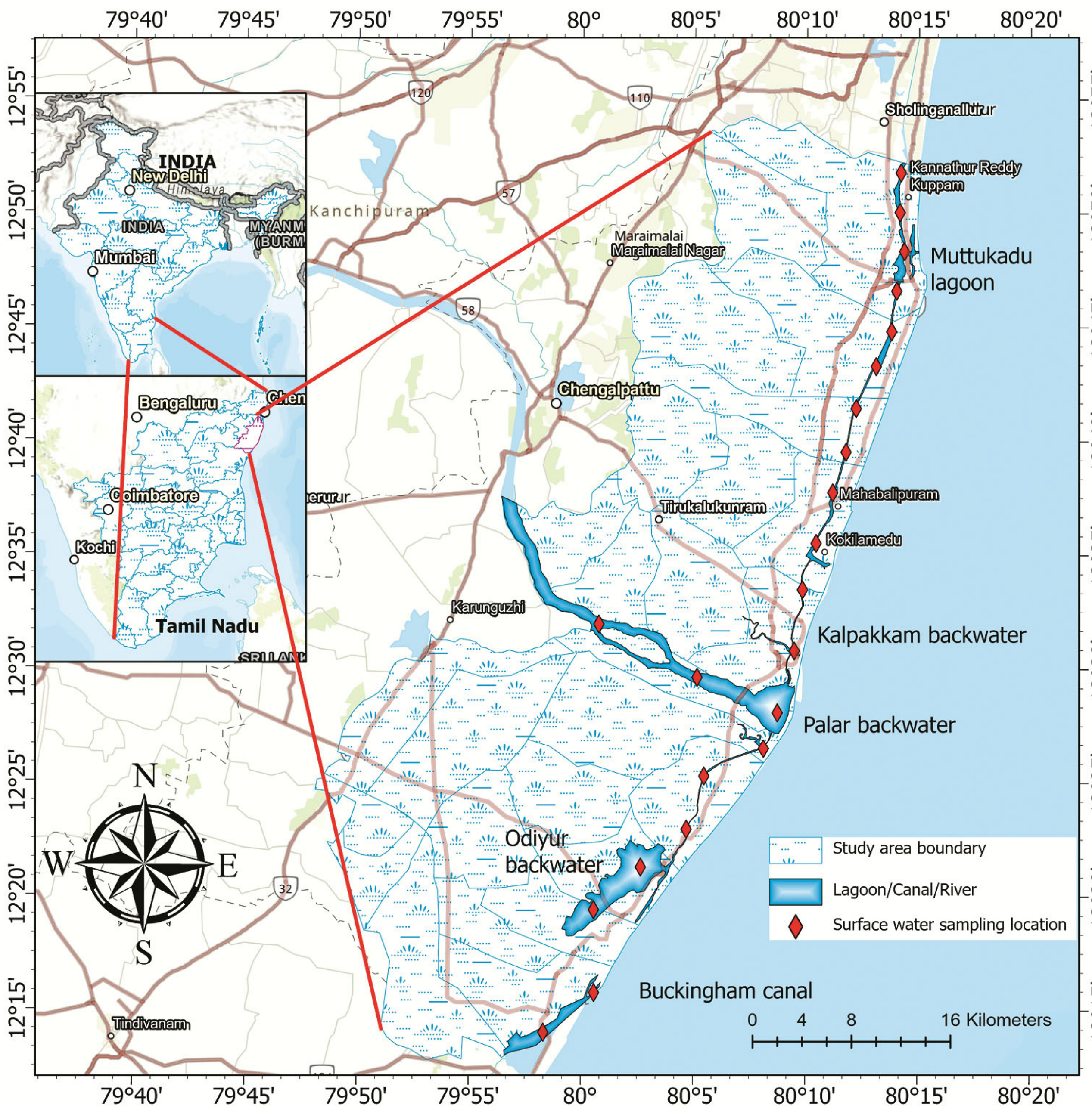

Fig. 1 — Study area map with sampling locations

buffer zones were generated for constrains[1-2,18-21,31-32]. The seaweed farming site selection criteria optimum range is given in Table 1. The methodology used for the study is given in Figure 2.

Water quality, environmental and accessibility criteria assessment

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 LAQUA twin Horiba probe, 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 (PO_4-P) and ammonia-nitrogen (NH_4-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, a final DO measurement was recorded. The BOD value is calculated by determining the difference between the initial and final DO levels. All analyses were conducted within two days at the Muttukadu Experimental Stations (ICAR–Central Institute of Brackishwater Aquaculture, Tamil Nadu, India) following APHA[33] guidelines.

Critical environmental factors, including wind speed, water depth, and water current, were rigorously assessed based on a comprehensive literature review and expert opinions. Water depth was precisely measured using a water level meter, while water current velocity was evaluated using a digital water current meter. Turbidity levels were analysed using a nephelometric turbidity meter. Wind speed data was obtained from the Indian Meteorological Department

Table 1 — Seaweed farming site selection criteria optimum range

S. No	Parameters	Highly suitable	Moderately suitable	Not suitable
Water quality criteria				
1	pH	7 – 8	6 – 6.9, 8.1 – 9	< 6, > 9
2	DO (mg/L)	> 6.1	4.5 – 6	< 4.5
3	Salinity (ppt)	19 – 25	15 – 18, 26 – 32	> 32
4	Water temperature (°C)	28 – 30	30.1 – 32	> 33
5	NO_3 (mg/L)	0.6 – 1.5	0.1 – 0.5	< 0.1, > 1.5
6	NO_2 (mg/L)	0.1 – 0.2	0.3 – 0.5	> 0.5
7	NH_4-N (mg/L)	< 0.5	0.5 – 1	> 1
8	PO_4-P (mg/L)	0 – 0.2	0.3 – 0.4	> 0.4
9	BOD (mg/L)	3 – 5	5.1 – 8	> 8
10	Turbidity (NTU)	< 20	20 – 50	> 50
11	Calcium (mg/L)	235 – 350	170 – 234, 351 – 400	> 400
12	Magnesium (mg/L)	700 – 900	520 – 699, 901 – 1,000	> 1,000
13	Sodium (mg/L)	6000 – 8000	4,500 – 5,999, 8001 – 10,000	> 10,000
14	Potassium (mg/L)	225 – 300	165 – 224, 301 – 320	> 320
Environmental criteria				
1	Wind speed (m/s)	1 – 2	2 – 4	> 4
2	Water depth (m)	0.6 – 1.5	1.6 – 2	> 2
3	Water current (m/s)	0.06 – 0.10	0.11 – 0.30	> 0.30
Accessibility criteria				
1	Distance to road (m)	< 500	500 – 2,000	> 2,000
2	Distance to market (m)	< 1000	1000 – 10,000	> 10,000
3	Distance to seed source (m)	< 1000	1000 – 10,000	> 10,000
Constrain criteria		Buffer distance		
1	Wildlife habitats	50 m		
2	Bar mouth	300 m		
3	Navigation	50 m		
4	Docks	50 m		
5	Fishing zone	50 m		

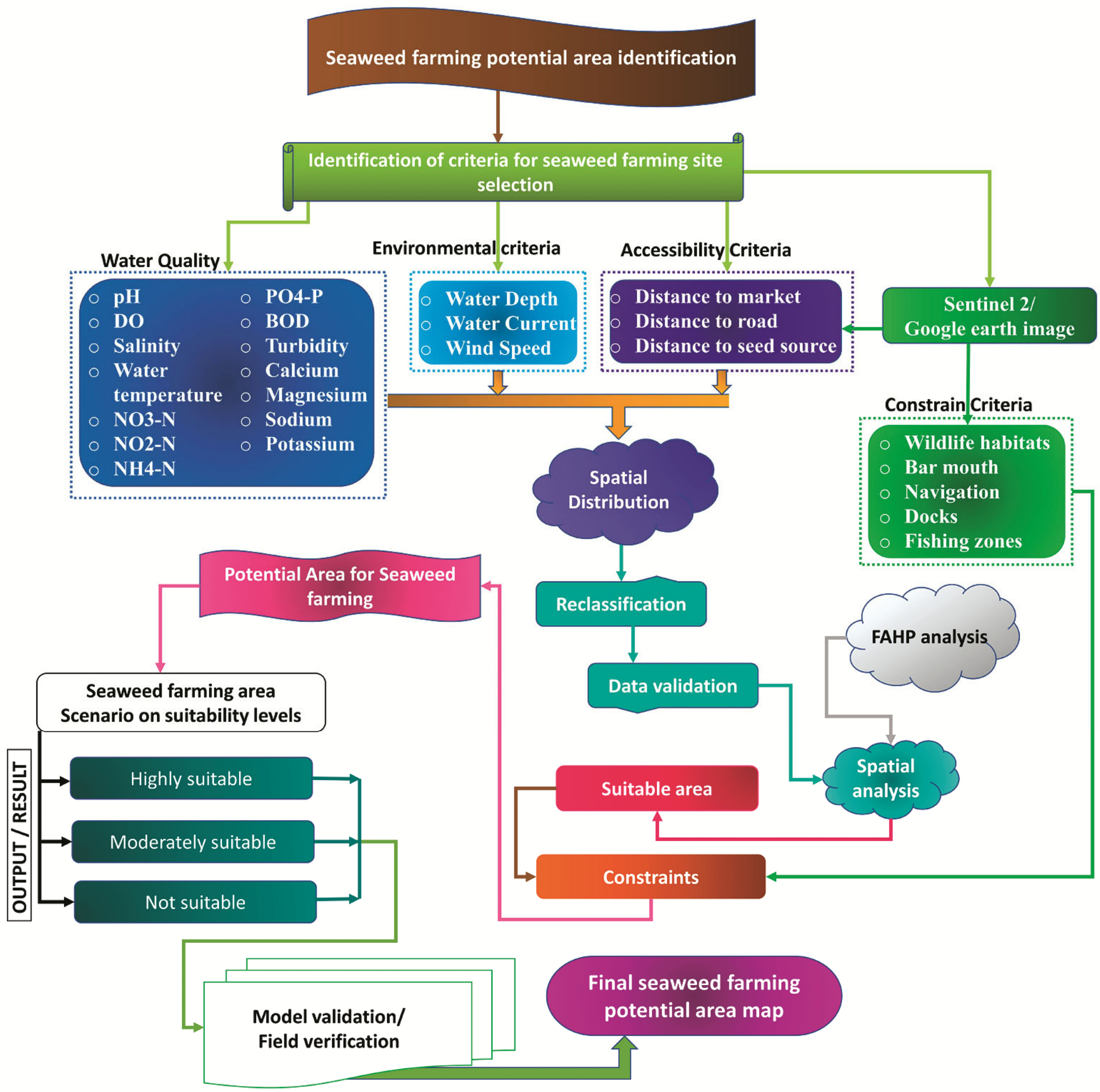

Fig. 2 — Seaweed culture potential area mapping methodology

(IMD) and spatially interpolated for enhanced visualisation and interpretation.

Accessibility factors, pivotal in the selection of optimal seaweed farming sites, were rigorously evaluated through a comprehensive review of relevant literature and consultation with subject matter experts. Key criteria encompassing proximity to markets, road networks, and seed sources were meticulously considered. Data about market locations and seed availability was acquired through a synergistic approach utilising both Google Earth imagery and on-site field surveys. Road maps were digitised from toposheets to facilitate spatial analysis. The ArcGIS software platform was leveraged for buffer generation and in-depth spatial assessment.

The analysis leverages a multi-source data approach, integrating information from Google Earth, the India Meteorological Department (IMD), and field surveys, each with inherent strengths and limitations. Google Earth's visual representation of land features is valuable, yet potential temporal limitations and varying image resolution necessitate careful interpretation, particularly in precise measurements. The IMD, as the official meteorological data source, provides reliable information, though accuracy can be influenced by parameter specificity and regional observation network density. Field surveys when rigorously designed and executed, offer high-quality data, but their temporal and spatial constraints, along with potential observer bias, warrant consideration. To address these inherent limitations, the study employs a multi-faceted methodological approach. Data triangulation, encompassing cross-referencing information from diverse sources, enhances data quality by identifying and reconciling discrepancies. Ground truthing, which involves validating remotely sensed or other data against field observations, strengthens accuracy and exposes potential biases.

Fuzzy Analytic Hierarchy Process (FAHP)

The Fuzzy Analytic Hierarchy Process (FAHP) represents a significant advancement in multi-criteria decision-making, refining the capabilities of the classic Analytic Hierarchy Process (AHP)[34]. While AHP provides a structured framework for decision analysis, its efficacy can be challenged by real-world scenario's inherent complexities and uncertainties. Fuzziness and vagueness often cloud decision-maker's judgments, leading to imprecision in preference elicitation and subsequent ranking of alternatives. In practical decision-making contexts, it is seldom the case that all decision data can be assessed with absolute certainty. While certain aspects may lend themselves to precise quantification, others remain inherently ambiguous or subjective. This inherent ambiguity poses a significant challenge to traditional AHP, particularly in establishing consistent preferences. The uncertainty embedded in human judgments can introduce complexities in both the pair-wise comparison process and the subsequent prioritisation of alternatives. To address this limitation, FAHP leverages the power of fuzzy set theory[34]. By allowing for the representation and manipulation of imprecise or linguistic data, FAHP enables decision-makers to express their preferences in a more nuanced and realistic manner. This, in turn, enhances the robustness and accuracy of the decision-making process. The versatility and effectiveness of FAHP have been demonstrated through numerous applications across diverse fields. Researchers have successfully employed FAHP to tackle decision-making challenges characterised by uncertainty and subjectivity[34-37]. FAHP represents a valuable extension of AHP, adeptly handling the complexities and ambiguities inherent in real-world decision-making. By incorporating fuzzy set theory, FAHP provides a more robust and flexible framework for evaluating alternatives and reaching informed decisions, particularly in situations where precise quantification is challenging or impractical. The FAHP weightage scale and weightage value for each factor are given in Tables 2 & 3.

Table 2 — Scale for FAHP pair-wise comparison matrix

Category	The intensity of relative importance
Equal	(1, 1, 1)
Equal to moderate	(1, 2, 3)
Moderate	(2, 3, 4)
Moderate to strong	(3, 4, 5)
Strong	(4, 5, 6)
Strong to very strong	(5, 6, 7)
Very strong	(6, 7, 8)
Very strong to extremely strong	(7, 8, 9)
Extremely strong	(9, 9, 9)

Table 3 — Fuzzy AHP-based weightage for seaweed farming potential area

Criteria	Fuzzy AHP			Chen weigh-tage
	Fuzzy number			
	Minimal	Modal	Maximal	
Water quality				
pH	0.7858	1.2687	1.9987	0.084
DO	1.0535	1.7354	2.6402	0.113
Salinity	1.2170	2.0184	3.1804	0.131
Water temperature	1.2133	2.0620	3.2946	0.133
NO_3	0.2908	0.4844	0.7677	0.023
NO_2	0.2872	0.4790	0.7605	0.023
PO_4-P	0.2872	0.4790	0.7605	0.023
NH_4-N	0.2872	0.4790	0.7605	0.023
Turbidity	0.5100	0.8345	1.3283	0.052
BOD	0.7385	1.2589	2.0190	0.083
Calcium (Ca)	0.7271	1.1851	1.8439	0.078
Magnesium (Mg)	0.7271	1.1851	1.8439	0.078
Sodium (Na)	0.7271	1.1851	1.8439	0.078
Potassium (K)	0.7271	1.1851	1.8439	0.078
Environmental criteria				
Wind speed	0.2563	0.3333	0.4408	0.055
Water current	0.5125	0.6667	0.8817	0.211
Water depth	1.5375	2.0000	2.6450	0.734
Accessibility criteria				
Dist. to road	0.9889	1.5066	2.1866	0.535
Dist. to market	0.3945	0.5979	0.8633	0.146
Dist. to seed source	0.6295	0.9491	1.4266	0.319
Seaweed farming potential area				
Water quality criteria	1.1229	1.6238	2.3003	0.590
Environmental criteria	0.6200	0.8936	1.2801	0.301
Accessibility criteria	0.3423	0.4918	0.6929	0.109

Results and Discussion

Water quality

Water quality is an important factor which plays a crucial role in the farmed species. Optimum water quality provides higher productivity. The spatial distribution of Chengalpattu district's surface water quality is given in Figures 3 & 4.

Water temperature in the study area ranged from 29.8 to 31.78 °C. Water temperature was given the highest weightage of 13.3 %, among the water quality

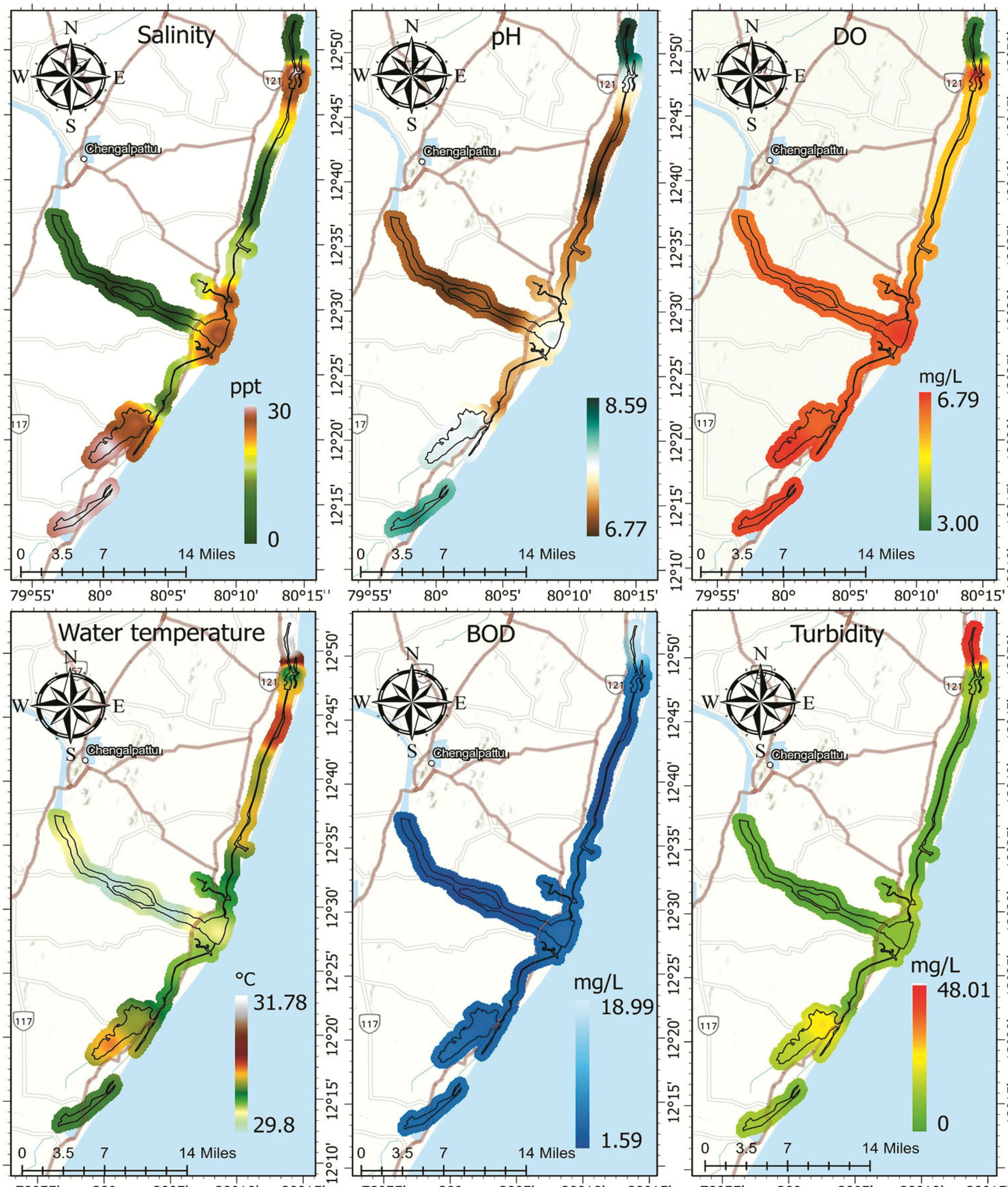

Fig. 3 — Spatial distribution of surface water physico-chemical (water quality) parameters, Chengalpattu district

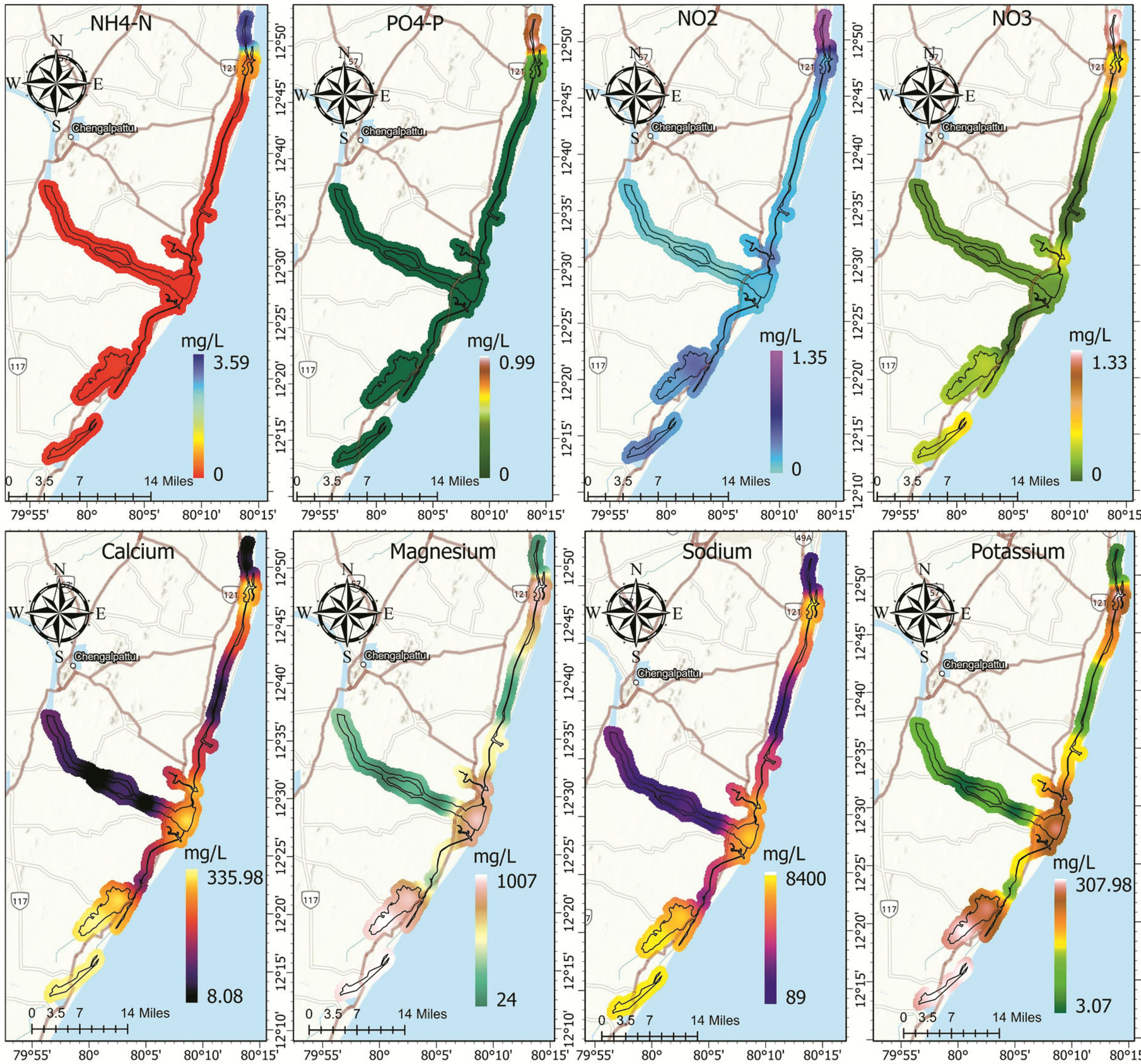

Fig. 4 — Spatial distribution of nutrients and key ions (water quality) in the brackishwater ecosystem of Chengalpattu district

criteria. Extreme water temperatures above the suitable range can impact seaweed growth. Whether too low or too high, extreme temperatures hinder photosynthesis, metabolic activities and reproductive processes. This results in reduced growth rates, altered biochemical compositions and decreased overall productivity[38-39].

Water salinity in the study area ranges from 0 – 30 ppt. Water salinity was given a weightage of 13.1 %. Salinity levels outside the suitable range can adversely affect the growth of seaweeds. Salinity below 15 ppt or above 33 ppt disrupts osmotic balance and nutrient uptake and eventually causes dehydration or cell damage. This leads to reduced growth rates, lower biomass production, and increased vulnerability to environmental pressures[1,38-40]. DO in the study area ranges from 3.0 – 6.79 mg/L. DO was given a weightage of 11.3 %. Insufficient DO levels below 4 mg/L can hinder seaweed growth and survival. Low oxygen availability limits photosynthesis, cellular respiration, and metabolic processes in seaweeds. As a result, growth is stunted, and seaweed such as *Gracilaria* spp., *Caulerpa* spp., and *Ulva* spp., becomes more susceptible to diseases and other environmental stressors[1,40].

The water pH in the study area ranges from 6.77 – 8.59. Water pH was given a weightage of 8.4 %. pH levels above 9 negatively impact seaweed growth.

The elevated pH alters the chemical composition of the water, affecting nutrient availability and metabolic processes within the seaweed. This can result in reduced growth, physiological stress, and lower overall productivity[1,40-41].

In the study area, calcium, magnesium, sodium and potassium ranged from 8.08 – 335.98 mg/L, 24 – 1007 mg/L, 89 – 8,400 mg/L, and 3.07 – 307.98 mg/L, respectively. These are important ions for seaweed growth as these affect the water quality, nutrient availability, and osmotic balance in seaweeds. Turbidity in the study area ranged from 0 – 48.01 NTU. High turbid areas block sunlight and impact the growth rate of seaweeds, resulting in an overall low growth rate. The nutrients in the Chengalpattu district brackishwater column *viz*. NH_4-N ranges from 0 – 3.59 mg/L, PO_4-P is about 0 – 0.99 mg/L, NO_2 ranges from 0 – 1.35 mg/L and NO_3 ranges from 0 – 1.33 mg/L. BOD ranges from 1.59 – 18.99 mg/L. Unsuitable nutrient concentrations, such as very high or very low levels of NO_3, NO_2, NH_4-N, PO_4-P, and BOD, can affect seaweed growth. Insufficient nutrients limit growth and productivity, leading to nutrient deficiency symptoms. Excessive nutrient concentrations can cause eutrophication, algal blooms, and negative interactions with seaweed, such as increased competition or unfavourable water quality conditions[42-44]. The spatial distribution of brackishwater physico-chemical parameters of Chengalpattu district is given in Figure 4.

Understanding and identifying sites with optimum ranges for these parameters are crucial for successful seaweed cultivation. It allows for optimal growth, biomass production, and overall health of seaweeds. It's important to note that the specific impacts may vary depending on the seaweed species, local conditions, and interactions with other environmental factors[4,43-44].

Environmental criteria

Water depth in the study area ranges from 0.20 – 2.0 m. For the environmental criteria, water depth was given the highest weightage of about 73.4 %. Low water depth exposes seaweed seedlings to sunlight and damages them. Hence, an optimum water depth is required for higher production[17,45]. The water current in the study area ranges from 0.10 – 0.52 m/s. Water current weightage is about 21.1 %. Water current helps in nutrient exchange and keeps the system sustainable. High water current induces stress in seaweeds, hindering their growth rate[46]. In areas with low wind speed and water current, the water circulation rate is very low, with only a limited nutrient available for the seaweeds to grow, resulting in a lower growth rate[47]. Wind speed in the study area ranges from 2.8 – 4.7 m/s, and the weightage given for wind speed is about 5.5 %. Moderate wind speed generates current flow and provides a healthy ecosystem for seaweed growth, and high wind speed damages raft and seaweed seedlings. Strong winds can displace or drift seaweed rafts, affecting their spatial distribution and making it challenging to maintain and manage the seaweed rafts in the culture site[48].

Calm waters with low wind speed and water currents would increase the risk of fouling and disease outbreaks in the seaweeds. Without sufficient water movement, sediments and organic matter may accumulate on the seaweeds, leading to reduced productivity and increased susceptibility to diseases[49,50]. The spatial distribution map of environmental criteria is given in Figure 5.

Accessibility criteria

Distance to the road in the study area is about 1 – 900 m and is given the highest weightage of 53.5 %. Being closer to the roads allow for easier transportation of equipment, other supplies, and harvested seaweed to and from the seaweed farming location. It reduces logistical challenges and associated costs, facilitating efficient operations. Distance to seed source ranges from 0 – 13.99 km, it was given a weightage of 31.9 %; as the lesser the distance, the higher the quality and easier stocking.

Brackishwater seaweeds are typically cultivated in a salinity range of 22 – 30 ppt, and they exhibit remarkable adaptability, tolerating salinity levels up to 32 ppt without any adverse effects on their growth[1,11,51]. In the brackishwaters of the Chengalpattu district, various seaweed species like *Gracilaria tenuistipitata* (formerly known as *Agarophyton tenuistipitatum*), *Gracilaria salicornia*, *Ulva lactuca*, *Ulva prolifera* and *Ulva intestinalis* thrive seasonally[1-2,9,20]. These locally available seaweeds present a valuable opportunity for initial stocking in seaweed cultivation. By utilising these species, farmers can significantly reduce seedling costs and foster the growth of indigenous seaweed farming practices. This approach aligns with the findings of several research studies[1,52-53], highlighting the potential of local seaweed resources for sustainable aquaculture development. Seaweed

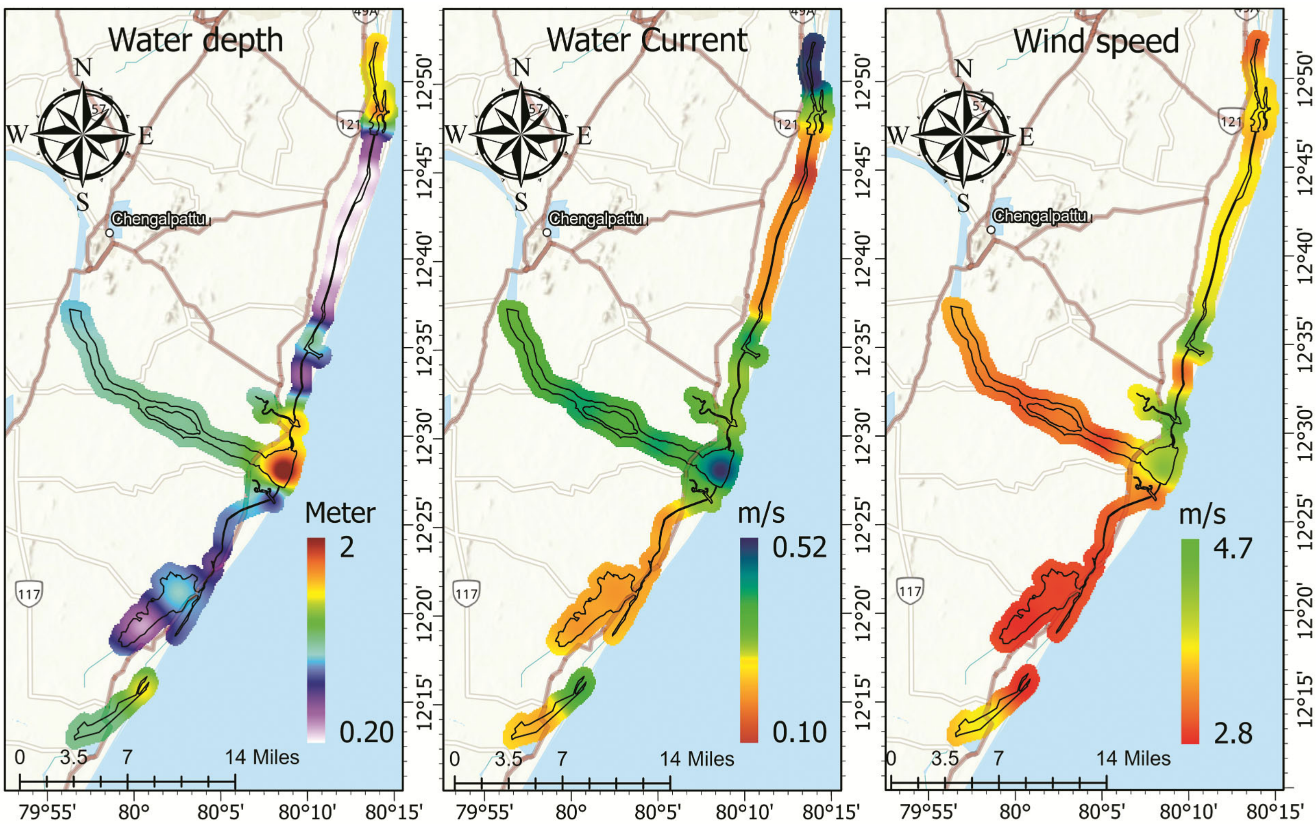

Fig. 5 — Spatial distribution of environmental criteria for seaweed farming in Chengalpattu district

possesses diverse commercial applications like culinary uses (nori, kombu), industrial hydrocolloids (agar, carrageenan), agricultural inputs (fertiliser, animal feed), cosmetics, and emerging fields like pharmaceuticals & biofuels[7,38,53].

Nearby local market availability helps in the procurement of miscellaneous farming materials. Shorter distances to the market result in lower transportation costs, reducing overall production expenses. The distance to the market was given a weightage of 14.6 %. It ranges from 0.50 – 5.99 km in the study area. The spatial distribution map of accessibility criteria is given in Figure 6. The market price for dried seaweed *Gracilaria* spp. and *Ulva* spp. in India typically ranges between Rs. 25 to 40 kg^{-1}, with variations influenced primarily by the proximity to processing facilities. However, for seaweed sourced from remote locations, the market price is standardised at Rs. 25 kg^{-1} to account for higher transportation costs. In these cases, processing companies frequently absorb the entire transportation cost to ensure a fair price for farmers, fostering sustainable sourcing practices despite logistical challenges[52].

Sustainable seaweed cultivation necessitates a comprehensive evaluation of diverse constraint factors to safeguard ecological integrity and foster long-term industrial viability. The identification of suitable farming zones, with minimal disruption to existing ecosystems, is crucial for preserving ecologically sensitive habitats. Constrain factors have been considered for habitats, tourist spots, bar mouth, navigation, docks and fishing areas. Through diligent consideration of these multifaceted constraints, a sustainable and thriving seaweed cultivation system can be established, fostering harmony between environmental preservation, economic development, and community well-being[32,54].

Optimum sites for seaweed farming

The results show the total potential area identified in Chengalpattu district is about 141.56 ha, with 91.93 ha as highly potential and 49.63 ha as moderately potential for seaweed farming. The spatial map for seaweed farming site selection using FAHP is given in Figure 7.

Following the identification of potential seaweed farming areas using the Geographic Information

System (GIS)-based Multi-Criteria Decision Analysis (MCDA) framework, a rigorous field validation process was implemented to assess the model's predictive accuracy and confirm site suitability. Key parameters, including water depth, water quality, accessibility and environmental factors, were meticulously measured and evaluated against the optimal ranges established for seaweed cultivation. The comprehensive field validation process demonstrated a high degree of congruence between the model's predictions and the actual conditions observed in the field.

The FAHP method, along with this methodology, could help identify potential seaweed farming areas for other coastal regions. Several studies have demonstrated the efficacy of a GIS-based multi-criteria approach in the context of site selection for seaweed farming. For instance, Segbefia *et al.*[51] applied a similar approach to identify potential areas for seaweed farming in Ghana's complex coastal environments using a geospatial multi-criteria approach. Jamaluddin *et al.*[55] used a GIS-based multi-criteria approach to assess areas suitable for farming of *Eucheuma cottonii* in Takalar, Regency, South Sulawesi, Indonesia. Their research affirmed that this method provides more accurate information in complex waters and promotes sustainable development. Seaweed farming is a highly income-yielding activity involving simple, low-cost, low-maintenance technology with a short grow-out cycle. Recognising seaweed's potential for environmental and economic benefits, the Government of India has allocated Rs. 640 crores under the Pradhan Mantri Matsya Sampada Yojana (PMMSY) to promote seaweed cultivation, targeting over 1.12 million tons by 2025. This aligns with the GFCM 2030 strategy for sustainable fisheries and aquaculture[13,56].

The coastal environment of Chengalpattu district presents unique challenges and opportunities for seaweed farming. Preliminary estimates by the Central Marine Fisheries Research Institute (CMFRI) suggest a potential of about 23,970 ha for seaweed farming along the entire Indian coastline. Of this, Chengalpattu district holds about 273 ha of potential area for seaweed farming[57]. These areas are strategically located outside the Coastal Regulation Zone (CRZ) at a buffer distance of 1 km or less[57,58]. The turbulent marine conditions, characterised by

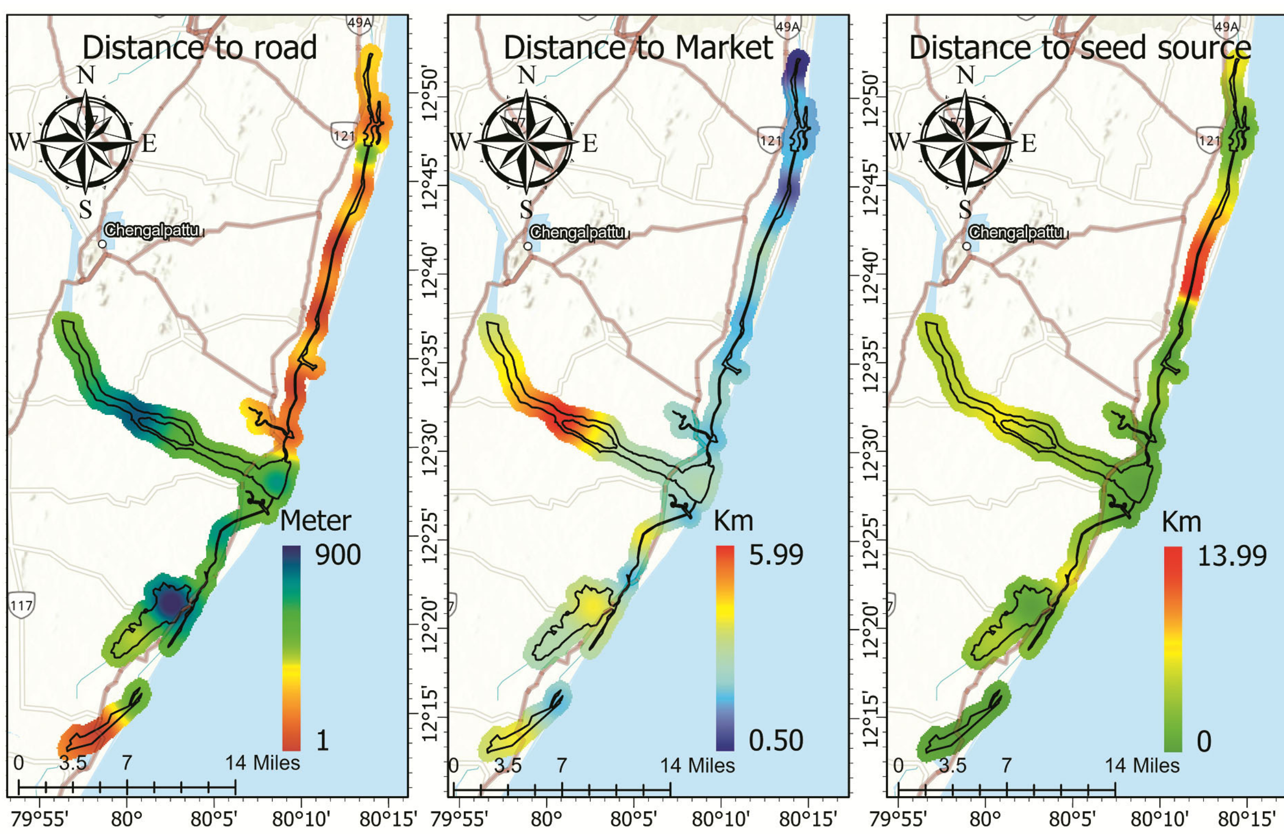

Fig. 6 — Spatial distribution of accessibility criteria for seaweed farming in Chengalpattu district

Fig. 7 — Seaweed farming potential area map using FAHP method

rough seas and substantial wave action, limit farming to inherently robust seaweed species. In contrast, brackishwater environments, such as estuaries and lagoons, offer calmer conditions that are more conducive to seaweed farming. This study identified about 141.56 ha suitable for seaweed cultivation within brackishwater ecosystems in Chengalpattu district. Seaweed farming in brackishwater environments exhibits greater temporal flexibility compared to marine environments. Brackishwater seaweed farming can be undertaken throughout much of the year whereas marine seaweed farming is constrained by the cyclical occurrence of cyclones and monsoons, which significantly influence sea conditions[1,2,21].

To fully realise the potential of seaweed farming in Chengalpattu district and across India, the National Institution for Transforming India (NITI) Aayog has outlined a comprehensive strategy encompassing regulatory frameworks, social security, investment incentives, infrastructure development, and research initiatives[58]. Recognising the sector's vulnerability, NITI Aayog proposes a risk cover encompassing crop, infrastructure, and life insurance. This safety net will attract investment and encourage wider participation. Integrating seaweed farmers into existing schemes like Pradhan Mantri Fasal Bima Yojana (PMFBY), Pradhan Mantri Kisan Samman Nidhi (PM-KISAN), and Kisan Credit Card (KCC) will provide income support and access to formal credit. Promoting farmer collectives like Self-Help Groups (SHGs) and Farmer Producer Organizations (FPOs) will further empower farmers by facilitating access to credit, technology, and markets. NITI Aayog also recommends incentivising investments through measures such as encouraging Foreign Direct Investment (FDI) and Public-Private Partnerships (PPP) in processing and supply chain infrastructure. This will attract capital and expertise, boosting production capacity and creating value-added products. A dynamic data portal with geo-tagged suitable cultivation sites will promote transparency and informed decision-making, streamlining licensing and approvals[58,59]. Integrating seaweed and its products into e-National Agriculture Market (e-NAM) and agricultural mandis will ensure fair pricing and market access, connecting farmers directly with buyers. NITI Aayog also emphasised the importance of robust infrastructure. Setting up seed banks in coastal states will ensure access to quality planting material. Creating logistics and primary processing centers at the cluster level will streamline the value chain, reducing transportation costs and improving post-harvest handling. Aggregation and marketing centres at the district level will facilitate efficient market linkages. Finally, establishing Centers of Excellence (CoEs) for seaweed will play a pivotal role in knowledge dissemination and skill development[58].

The cultivation of seaweed in Chengalpattu district presents a compelling opportunity for coastal folks' livelihood, economic growth and sustainable development. However, realising this potential necessitates a strategic framework that integrates the identified potential area with the national recommendations put forth by NITI Aayog, which is crucial. By adopting the comprehensive strategy outlined by NITI Aayog, which encompasses regulatory clarity, risk mitigation measures, investment incentives, infrastructure development, and research initiatives, India can effectively foster thriving seaweed cultivation sector[58-60]. This will not only bolster coastal livelihoods and contribute to national economic prosperity but also position India as a prominent competitor in the global seaweed market. Ultimately, the successful cultivation of seaweed in Chengalpattu district serves as a microcosm for the broader potential of seaweed farming across India, demonstrating the significant economic and ecological benefits achievable through strategic planning and sustainable practices.

This study significantly advances brackishwater seaweed farming by integrating cutting-edge geospatial technologies and comprehensive decision-making models. The successful application of a GIS-MCDA framework, following established methodologies[16,20,61], enabled the identification of potential cultivation areas within the complex brackishwater ecosystems of the Chengalpattu district. Furthermore, this study uniquely incorporates hydrodynamic factors like water current and wind speed, recognising their critical influence on seaweed farm resilience as highlighted by de *et al.*[62] and Stelzenmüller *et al.*[48]. The emphasis on native seaweed species, consistent with recommendations by Spillias *et al.*[63] and Sarkar *et al.*[1], promotes biodiversity conservation and minimises the risk of invasive species introductions.

Beyond scientific inquiry, this research contributes to multiple Sustainable Development Goals (SDGs)[64]. Spatial analysis of seaweed farming potential areas facilitates evidence-based decision-making, minimising environmental impact and ensuring sustainable resource management (SDG 14). Seaweed farming enhances food security (SDG 2) through increased production of nutritious food sources[57]. This study demonstrates the transformative potential of geospatial techniques and multi-criteria decision analysis for sustainable and responsible seaweed farming. By integrating water quality, environmental criteria, constraints, and accessibility considerations, this study provides a robust framework for identifying and prioritising suitable cultivation areas. This research not only enhances the understanding of seaweed growth dynamics but also paves the way for a thriving and sustainable seaweed farming industry in India, contributing to multiple facets of sustainable development.

Conclusion

The results revealed that a substantial area of 141.56 ha holds potential for seaweed farming. Of this, the FAHP analysis shows that the highly suitable area is about 91.93 ha and 49.63 ha is moderately potential. This developed model can serve as a valuable tool for policymakers and stakeholders, enabling them to actively promote brackishwater seaweed farming as a viable and sustainable alternative livelihood option for coastal fisherwomen in India. This study provides a systematic and transparent method for site selection of seaweed farming in brackishwater ecosystems. It offers valuable insights into the potential and challenges of seaweed farming development and management in India. While the study's findings are promising, it is essential to acknowledge potential limitations. The suitability analysis was predicated on specific criteria and may necessitate adaptation for diverse geographical regions or evolving environmental conditions. Future research endeavours could focus on validating the model's predictions through the incorporation of supplementary factors, encompassing socioeconomic and market dynamics.

The identification of suitable areas for seaweed farming presents opportunities for the sustainable enhancement of livelihoods within coastal communities, particularly for fisherwomen. By fostering brackishwater seaweed cultivation, policymakers can contribute to economic empowerment, bolster food security, and promote environmental conservation. The outcomes can inform the development of targeted interventions and capacity-building programs to support the growth of this nascent yet promising sector.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Authors Contributions

PNR, RJ, RA, KA & CPB: Design, conceptualization, planning of the work, supervision and writing - review & editing; RNR: Writing - original draft, data collection, formal analysis, mapping, interpretation, manuscript preparation, and writing - review & editing; and SAK: Data collection and formal analysis.

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