Ocean and Coastal Management 248 (2024) 106964

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

A comprehensive study on ecological insights of *Ulva lactuca* seaweed bloom in a lagoon along the southeast coast of India

Nila Rekha Peter *, Nishan Raja Raja, Jayakumar Rengarajan, Aravind Radhakrishnan Pillai, Ambasankar Kondusamy, Aravind Kumar Saravanan, Balasubramanian Changaramkumarath Paran, Kuldeep Kumar Lal

ICAR-Central Institute of Brackishwater Aquaculture, 75 Santhome High Road, R. A. Puram, MRC Nagar, Chennai, 600 028, India

ARTICLE INFO

Keywords:
Algal bloom
Mavic 3 pro
Bay of Bengal
Sentinel 2
Seaweed
Ulva lactuca

ABSTRACT

Ulva lactuca, commonly known as sea lettuce is a green macroalgae (chlorophyta) and its uncontrolled proliferation forms a bloom, which causes ecological imbalances and adversely impacts brackishwater ecosystems. Algal bloom can harm the environment and aquatic organisms, but it can also be beneficial if harvested and utilized for industrial purposes. A massive bloom of green macroalgae was observed in the Muttukadu lagoon, located along the southeast coast of India in the Bay of Bengal. A comprehensive study was taken up to assess the spatial distribution, proximate, nutrients, minerals, heavy metals, and factors inducing the bloom. For this study, high-resolution satellite images (Sentinel 2) were used. The spatial distribution of seaweed was mapped using Floating Algae Index (FAI), Modified Floating Algae Index (MFAI), Normalized Difference Red Edge (NDRE) Index and Seaweed Index (SI) models. Results were validated using the MAVIC 3 pro drone and field survey. The SI model was found to be more accurate compared to other models. The bloom exhibited notable temporal dynamics, with peak coverage observed in the last week of May 2023 with a spread area of about 100.05 ha, the bloom intensity was found to be high till the last week of June 2023, after which it gradually declined. The proximate composition (%) of *Ulva lactuca* showed the moisture content is about 80.00 ± 2.98, crude protein 24.17 ± 1.80, crude lipid 0.81 ± 0.05, Total Ash 37.45 ± 1.44, Fiber (8.92 ± 0.41), and Acid Insoluble Ash (16.18 ± 1.16). The mineral concentration was in the order Ca > Na > Mg > K > P. Iron (Fe) was observed to be high compared to other micronutrients, with a concentration of 1164.40 mg/kg. Rich nutrients and low heavy metal concentration significantly can boost the selling cost of *Ulva lactuca* providing livelihood support for the coastal fisherfolk.

1. Introduction

Ulva lactuca is found in a variety of marine and estuarine habitats worldwide, often thriving in intertidal zones, rocky shores, and shallow coastal waters. Its common name comes from its resemblance to lettuce and its vivid green colour (Dominguez and Loret., 2019; Guiry, 2013; Pang et al., 2010; Kaliaperumal and Kalimuthu, 1997). Its ability to tolerate a wide range of environmental conditions and its rapid growth rate contributes to its ubiquity in marine and brackishwater ecosystems (Guidone and Thornber., 2013; Hu et al., 2010).

Ulva lactuca has a simple morphology consisting of a bi-layered cell structure. This Chlorophyta species has a green to dark green colour and a flat, blade-like thallus that is a cell sheet embedded in a hard gelatinous cover. It is the main species of the Ulva genus. It has a thin green sheet that grows from a round base. It lives in many places near the shore, where it can make big layers on top of the water. It is useful as food, animal feed, fertilizer, and a source of carrageenan (Pappou et al., 2022; Bruhn et al., 2011).

Ulva lactuca is distributed globally and can be found in various regions such as Europe, both coasts of North America, Central America, the Caribbean Islands, South America, Africa, Indian Ocean Islands, South-west Asia, China, Pacific Islands, Australia and New Zealand (Qi et al., 2016; Tang and Gobler., 2011; Yaich et al., 2011; Teichberg et al., 2010). This species plays a significant ecological role as a primary producer within marine/brackishwater food webs, converting sunlight, carbon dioxide, and nutrients into organic matter through

* Corresponding author.
E-mail addresses: p.rekha@icar.gov.in, nila_71@yahoo.com (N.R. Peter).

https://doi.org/10.1016/j.ocecoaman.2023.106964
Received 25 October 2023; Received in revised form 21 November 2023; Accepted 1 December 2023

photosynthesis, and generating oxygen as a byproduct. This process not only contributes to the overall productivity of coastal waters but also provides food and habitat for various organisms (Mofeed, 2017; Tabarsa et al., 2012; Yaich et al., 2011). Despite its ecological importance, a large bloom of *Ulva lactuca* poses challenges to the environment. It thrives over a wide temperature and salinity range, and in brackishwater environments with high nitrogen and phosphorus contents, along with relatively low pH and water temperature, it can bloom rapidly. This proliferation can lead to a decrease in biodiversity, even affecting other algae species, and can impair local tourism and invade beaches. The decomposition of *Ulva lactuca* can produce acidic vapours that are harmful to both animals and humans (Allen et al., 2013; Diaz et al., 2013; Nan et al., 2008). However, it also contains commercially valuable components such as bioactive compounds, food or biofuel, offering potential opportunities for sustainable utilization (Chávez-Sánchez et al., 2017).

Monitoring these algal blooms is crucial, and remote sensing plays a vital role. It provides an effective, cost-efficient way to detect and monitor these events in real time (Haro et al., 2023; Pratama and Albasri., 2021). The advantage of remote sensing is its ability to cover large areas, enabling regional surveys and the identification of features of algal bloom. It also allows for repetitive coverage, which is useful when collecting data on algal blooms. (Haro et al., 2023; Pratama and Albasri., 2021; Taddia et al., 2020; Ody et al., 2019; Siddiqui et al., 2019; Hu, 2009). There are several techniques used in remote sensing for mapping algal blooms in marine and brackishwater ecosystems. These include the Floating Algae Index (FAI), Modified Floating Algae Index (MFAI), Seaweed Index (SI), Normalized Difference Red Edge (NDRE) Index and Seaweed Enhancing Index (SEI) (Ibrahim et al., 2016; Abudabos et al., 2013; Van der Wal et al., 2013).

Despite its ubiquity and ecological importance, comprehensive studies assessing its distribution and nutrient composition in the brackishwater ecosystem are surprisingly sparse. This lack of holistic understanding hinders our ability to fully comprehend the ecological role of *Ulva lactuca* and its potential for sustainable utilization. Hence this study was taken up to assess the spatial distribution of *Ulva lactuca* and analyzes the proximate, nutrient, mineral, and heavy metal composition of the seaweed and its implications for sustainable utilization and development in Muttukadu lagoon.

2. Materials and methods

2.1. Study area

Muttukadu backwater is located 36 km south of Chennai city and runs parallel to the east coast, the Bay of Bengal. It is also called an estuary, creek or lagoon and is one of the eight crucial lagoon systems on the east coast of India, Tamil Nadu. The study area is located from 12°49′30″N to 12°47′0″N and 80°13′40″E to 80°15′0″E. Fourteen representative sampling points were identified, and water samples were collected. The study area map with the representative sampling locations is given in Fig. 1.

2.2. Hydrodynamic condition assessment

The tidal range was mapped using Sentinel 2. As the water recedes from high tide to low tide, it creates a distinguishable damp mark on the surface, which is observable through satellite imagery (Sentinel-2). This mark serves the purpose of delineating the boundary between high tide and low tide. Tidal elevation difference was assessed at selective locations for Low Tide (LT) and High Tide (HT) in Muttukadu lagoon. The water flow direction during tides was recorded using a field survey.

2.3. Nutrient enrichment and algal growth

The pre-bloom and algal phase, nutrient concentrations viz. nitrogen

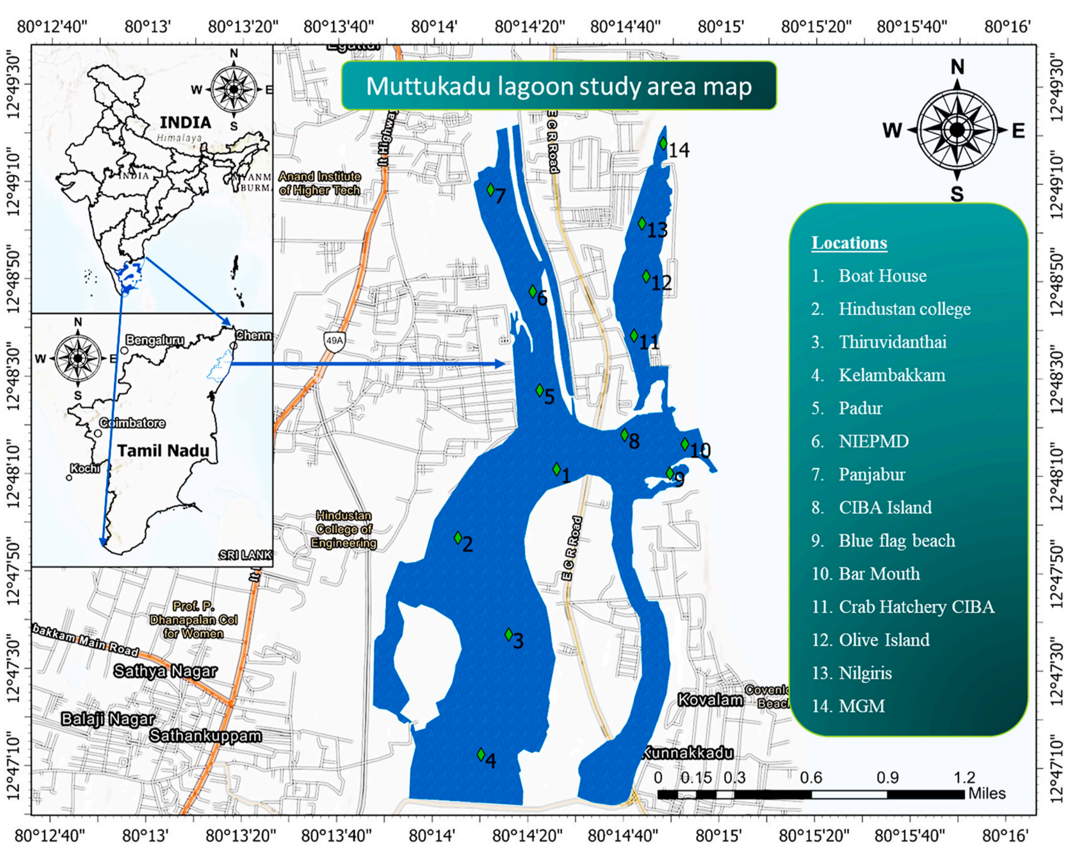

Fig. 1. Study area map.

and phosphorus in the lagoon ecosystem were compared with the seaweed bloom intensity (Chávez-Sánchez et al., 2017; Teichberg et al., 2010). Throughout the bloom it was observed to be spread from sampling locations 1–4. These nutrients are known to be essential for algal growth, including that of *Ulva lactuca.* Comparing these baseline nutrient concentrations with measurements taken during the peak of the bloom provided a clear picture of the nutrient enrichment that occurred in conjunction with the bloom.

2.4. Water quality analysis assessment

Water samples were collected and analysed at monthly intervals from May 2023–July 2023. Water pH and Dissolved oxygen were determined using probes (Horiba pH meter and Lutron DO–5510, respectively). Water temperature, and salinity were examined using mercury thermometer and hand held refractometer. Phosphate phosphorous (PO_4–P) and ammonia-nitrogen (NH_4–N) were analysed using phosphomolybdic acid-ascorbic acid and phenol hypochlorite, respectively. Nitrite nitrogen (NO_2–N) was examined using the sulphanilamide NED technique in the laboratory at the Muttukadu Experimental Stations, (ICAR – Central Institute of Brackishwater Aquaculture, Muttukadu, Chengalpattu district, Tamil Nadu, India), all samples were analysed within two days (APHA, 2005).

2.5. *Ulva lactuca* seaweed mapping

The spatial distribution of *Ulva lactuca* was mapped using a Sentinel 2 satellite image. The methodology used for the study is given in Fig. 2. The study area has been delineated and the satellite image was processed to reduce the sunlight effect on the satellite image using deglint. Then the land and water were masked, and the land surface was removed from the satellite image.

The depth invariant index was used to reduce the water depth effect in the satellite image. The depth effect on satellite images was reduced using Equ (1) (Manuputty et al., 2017; Siregar et al., 2018).

$$\text{Depth Invariant Index (DII)} = \ln(L_i - L_{si}) - \left(\frac{K_i}{K_j}\right)\ln\left(L_j - L_{sj}\right) \tag{1}$$

where.

Li and *Lj* are the radiance values of two spectral bands,

Lsi and *Lsj* are the radiance values of the same bands over a reference bottom and.

Ki and *Kj* are the attenuation coefficients of the same bands.

After the satellite image was processed for DII seaweed distribution was estimated using various models viz. Floating Algae Index (FAI), Modified Floating Algae Index (MFAI), Normalized Difference Red Edge (NDRE) Index and Seaweed Index (SI) (Haro et al., 2023; Ody et al., 2019; Siddiqui et al., 2019; Hu, 2009).

2.5.1. Floating algae index

The floating algae index (FAI) formula is based on the assumption that floating algae have higher reflectance in the near-infrared band than in the red and blue bands, while water has lower reflectance in the near-infrared band than in the red and blue bands. The FAI formula is given in Equations (2)–(4) (Liu et al., 2021; Siddiqui et al., 2019; Hu, 2009).

$$FAI = Rrc\ (NIR) - R'rc\ (NIR) \tag{2}$$

$$R'rc\ (NIR) = \frac{(Rrc\ (Red) - Rrc\ (Blue))(\lambda_{NIR} - \lambda_{Blue})}{\lambda_{Red} - \lambda_{Blue}} - Rrc\ (Blue) \tag{3}$$

FAI calculated using sentinel 2 is given below

$$FAI = Rrc\ (B8A) - \frac{(Rrc\ (B4) - Rrc\ (B2))(\lambda_{B8A} - \lambda_{B2})}{\lambda_{B4} - \lambda_{B2}} - Rrc\ (B2) \tag{4}$$

where.

Rrc (*B2*), *Rrc* (*B4*), and *Rrc* (*B8A*) are the reflectance values of the blue, red, and near-infrared bands of Sentinel-2, respectively, and λ_{B2}, λ_{B4}, and λ_{B8A} are the corresponding wavelengths.

$\lambda_{B2} = 0.49$ μm

$\lambda_{B4} = 0.66$ μm

$\lambda_{B8A} = 0.86$ μm

2.5.2. Modified Floating Algae Index

The Modified Floating Algae Index (MFAI) helps in detecting floating macroalgae. It is a modification of the Floating Algae Index (FAI) that adjusts the spectral features of the sensor to improve the detection accuracy. The MFAI formula is given in Equations (5) and (6) (Descloitres et al., 2021; Ody et al., 2019; Hu, 2009).

$$MFAI = R_{NIR} - \frac{(R_{RED} - R_{GREEN})(\lambda_{NIR} - \lambda_{GREEN})}{\lambda_{RED} - \lambda_{GREEN}} - R_{GREEN} \tag{5}$$

The MFAI for sentinel 2 is given in Equation (6).

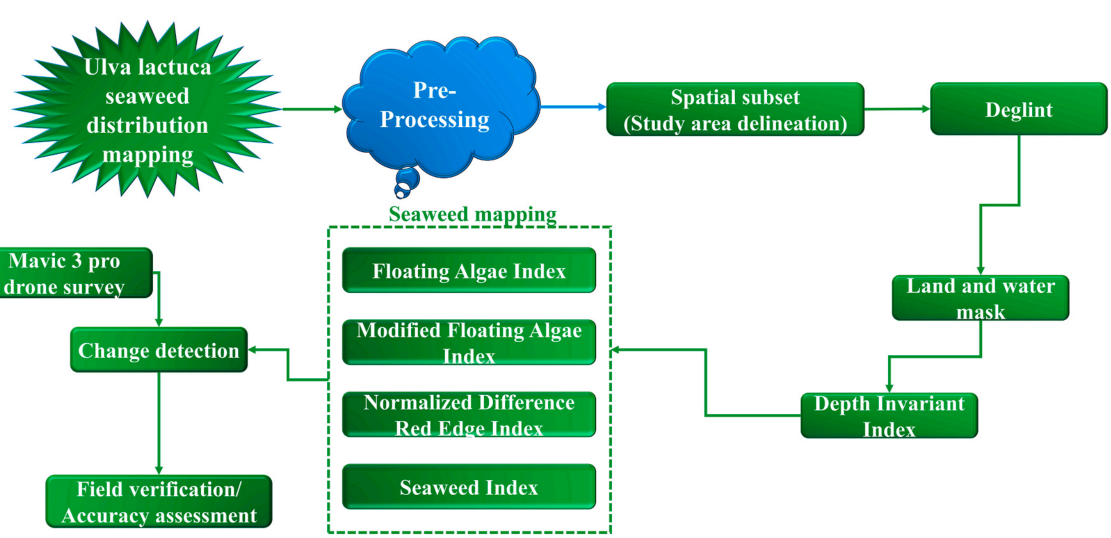

Fig. 2. Seaweed mapping methodology.

$$MFAI = Rrc\ (B8A) - \frac{(Rrc\ (B4) - Rrc\ (B3))(\lambda_{B8A} - \lambda_{B3})}{\lambda_{B4} - \lambda_{B3}} - Rrc(B3) \quad (6)$$

where.

Rrc (B3) *Rrc* (B4) and *Rrc* (B8A) are the reflectance values of the green, red and near-infrared bands of Sentinel-2, respectively, and λ_{B3} and λ_{B8A} are the corresponding wavelengths.

$\lambda_{B3} = 0.56$ μm

$\lambda_{B4} = 0.66$ μm

$\lambda_{B8A} = 0.86$ μm.

The MFAI formula is an improved version of FAI that uses the green band instead of the blue band to avoid the strong absorption by water in the blue band.

The values of λ_{B2}, λ_{B3}, λ_{B4}, and λ_{B8A} are the wavelengths of the blue, green, red, and near-infrared bands of the Sentinel-2 satellite. The values of λ_{B2}, λ_{B3}, λ_{B4}, and λ_{B8A} are the same for Sentinel-2A and Sentinel-2B, as they have identical sensors and specifications.

2.5.3. Normalized difference red edge index

NDRE stands for normalized difference red edge index, and it is a spectral index that can be used to detect chlorophyll content of vegetation using the red edge band (Che et al., 2021)

$$NDRE = \frac{(NIR) - (RE)}{(NIR) + (RE)} \quad (7)$$

Where.

NIR and *RE* are the reflectance values of the near-infrared and red edge bands of a satellite image, respectively.

$$NDRE = \frac{Rrc\ (B8A) - Rrc\ (B5)}{Rrc\ (B8A) + Rrc\ (B5)} \quad (8)$$

The red edge band is a narrow band that covers the transition zone between the red and near-infrared regions of the spectrum, where the reflectance of vegetation changes sharply due to chlorophyll absorption. NDRE is used to detect seaweed patches, as they have different chlorophyll content than land vegetation and open water.

2.5.4. Seaweed index

The seaweed index was used to detect seaweed patches using Sentinel-2 satellite data.

$$SI = \frac{(NIR) - (SWIR)}{(NIR) + (SWIR)} \quad (9)$$

$$SI = \frac{Rrc\ (B8A) - Rrc(B11)}{Rrc\ (B8A) + Rrc\ (B11)} \quad (10)$$

where *Rrc* (*B8A*) and *Rrc* (*B11*) are the reflectance values of the near-infrared band (band 8A) and the shortwave-infrared band (band 11) of the Sentinel-2 satellite image. The details of the satellite images used in the study are given in Table 1.

2.6. Bloom monitoring using Mavic 3 pro drone

Drones are unmanned aerial vehicles that can be used to collect high-resolution data and images of marine/brackishwater environments. In this study, a DJI Mavic 3 Pro drone was used to assess the spatial distribution of *Ulva lactuca* seaweed on coastal ecosystems through aerial survey. The drone was flown at a height of 100 m above the lagoon water's surface. The specification of the Mavic 3 Pro drone is given in Table 2.

Table 1
Data used for seaweed mapping.

Satellite Platform	Product Type	Date of Acquisition	Spatial Resolution
Sentinel-2A	MSI L2A	2023-07-09	10, 20 m
Sentinel-2A	MSI L2A	2023-06-29	10, 20 m
Sentinel-2B	MSI L2A	2023-06-14	10, 20 m
Sentinel-2B	MSI L2A	2023-05-25	10, 20 m

2.7. Validation of the seaweed distribution models

The performance of the models FAI, MFAI, NDRE and SI for seaweed distribution in Muttukadu lagoon was evaluated using four criteria viz. accuracy, precision, recall and F1 score. These criteria were derived from the confusion matrix, which shows the agreement between the observed and predicted classes of seaweed occurrence and non-occurrence. All the criteria were calculated using Equations (10)–(13) (Xing et al., 2023).

$$\text{Accuracy} = \frac{\text{TPS} + \text{TNS}}{\text{TPS} + \text{TNS} + \text{FPS} + \text{FNS}} \quad (10)$$

$$\text{Precision} = \frac{\text{TPS}}{\text{TPS} + \text{FPS}} \quad (11)$$

$$\text{Recall} = \frac{\text{TPS}}{\text{TPS} + \text{FNS}} \quad (12)$$

$$\text{F1 score} = \frac{(2 * \text{Precision} * \text{Recall})}{(\text{precision} + \text{Recall})} \quad (13)$$

Where.

TPS – True Positive Sample.
TNS – True Negative Sample.
FPS – False Positive Sample.
FNS – False Negative Sample.

2.8. Seaweed collection

2.8.1. Proximate, nutrient, mineral, and heavy metal analysis

During the *Ulva lactuca* bloom, a comprehensive assessment was conducted to analyze its proximate composition and heavy metal concentration. They are essential for evaluating the use of *Ulva lactuca* as food, biofuel, fertilizer, and other industrial purposes. By examining the proximate composition, including factors like moisture, protein, lipid, and carbohydrate content, insights were gained into the nutritional value and energy content of the algal biomass. The methods used for

Table 2
Mavic 3 pro drone specification.

S. No	Specification	Details
1	Drone take-off weight	<249 g
2	Dimensions (L × W × H)	251 × 362 × 70 mm (unfolded with propellers)
3	Max Speed (At sea level, no wind)	16 m/s (S Mode), 10 m/s (N Mode), 6 m/s (C Mode)
4	Max Flight Distance	18 km (with Intelligent Flight Battery and measured while flying at 43.2 kph in windless conditions)
5	Max Wind Speed Resistance	10.7 m/s (Level 5)
6	Global Navigation Satellite System (GNSS)	GPS + Galileo + BeiDou
7	Sensor	1/1.3-inch CMOS Effective Pixels: 48 MP
8	Lens	FOV: 82.1° Format Equivalent: 24 mm Aperture: f/1.7 Focus Range: 1 m to ∞
9	ISO Range	Video: 100–6400 (Auto), 100–6400 (Manual) Photo: 100–6400 (Auto), 100–6400 (Manual)
10	Max Image Size	8064 × 6048

assessing the proximate composition in *Ulva lactuca* are given below. The moisture in *Ulva lactuca* was assessed by drying the sample in an oven and determining moisture content by the weight difference between dry and wet material. Weighed approx. 5–10 g of ground sample. The sample is placed in a drying oven at 105 °C for at least 12 h. Then the sample was cooled in the dryer. Again it was weighed, taking care not to expose the sample to the atmosphere. Crude Protein analysis was carried out using Kjeldahl's method, which evaluates the total nitrogen content of the sample after it has been digested in sulphuric acid with a mercury or selenium catalyst. Crude Lipid was assessed by ether extract method, and total ash content was determined by incinerating the sample at a high temperature for a longer duration to convert the sample into ash. The ash content is expressed as the percentage of the dry sample. Crude fibre analysis was carried out using the acid detergent fibre (ADF) method. Acid Insoluble Ash (AIA) was determined by treating the ash obtained from total ash analysis with hydrochloric acid and then measuring the weight of the remaining residue. Phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), copper (Cu), lead (Pb), chromium (Cr), mercury (Hg), selenium (Se), and zinc (Zn) were assessed using ICPOES (Inductively Coupled Plasma Optical Emission Spectrometry) equipment. It is essential to evaluate how *Ulva lactuca* can be used as food, biofuel, fertilizer, and other industrial purposes.

3. Results and discussion

3.1. *Ulva lactuca* bloom distribution

The result shows that the *Ulva lactuca* bloom started in May 2023 the bloom was at its peak from the last week of May up to June 2023 respectively. About 48–50 tonnes of *Ulva lactuca* are distributed in Muttukadu Lagoon as shown in Fig. 4. The bloom was first observed on May 25, 2023, with a moderate to very high intensity of spread across the lagoon. The bloom persisted till June 29, 2023, with varying degrees of intensity ranging from low to very high. However, the bloom started to decline from July 2023 onwards, the intensity was reduced to a lower range. Seaweed distribution area using various models is given in Table 3. The bloom distribution varied in each method as shown in Table 3.

Spatial distribution of seaweed during the bloom is given in Figs. 4–7.

The seaweed distribution reflectance varies for each method. For Ulva distribution during May 2023, the reflectance range for the FAI method is about −0.30–0.40 as shown in Fig. 3, where higher reflectance denotes seaweed distribution. The distribution of seaweed is observed in light to dark orange in colour. The FAI values for seaweed range from 0.01 to 0.2, depending on the density and biomass of the algae (Selvaraj et al., 2021). MFAI reflectance ranges from −0.24–0.51. The MFAI values for seaweed are higher than FAI values, as the red edge band is more sensitive to chlorophyll content. The MFAI values for seaweed range from 0.02 to 0.3 (Zhang et al., 2021). NDRE reflectance ranges from −1.89–0.71. The NDRE values for seaweed can vary depending on the species, season, and location. Selvaraj et al. (2021) found that NDRE values for two common New Zealand native seaweed species, *Ecklonia radiata* and *Carpophyllum maschalocarpum*, ranged from 0.1 to 0.4 across four locations and four seasons. SI method reflectance ranges from −2.19–0.76. The SI values for seaweed can be negative or positive, depending on the reflectance of the green band. A study by Zhang et al. (2021) found that the SI values for three types of seaweed in China, *Sargassum horneri*, *Gracilaria lemaneiformis*, and *Ulva prolifera*, ranged from −0.2 to 0.2. The spatial distribution of seaweed with its reflectance for various models is given in Figs. 3–6.

The bloom distribution and intensity in the lagoon, as shown in Table 4. The occurrence of *Ulva lactuca* blooms is the result of a complex interplay of both natural processes and human activities.

3.2. Validation

The drone images revealed the presence of *U.lactuca* bloom in the Muttukadu Estuary, with varying degrees of intensity and spatial coverage. Drone images provide a clear view of submerged seaweeds (Taddia et al., 2020). The Ulva bloom was more prevalent in the southern part of the estuary, where the salinity and nutrient levels were higher. While Sentinel-2 images captured the general pattern of Ulva distribution in the estuary, but missed some of the finer details and variations that were detected by the drone images. The drone coverage of *Ulva lactuca* is given in Fig. 7. The field survey images are given in Fig. 8.

The comparative analysis shows that the SI model has the highest accuracy of 91.60% among the four models, followed by MFAI, FAI and NDRE models with accuracies of 85.80%, 83.10% and 71.30%,

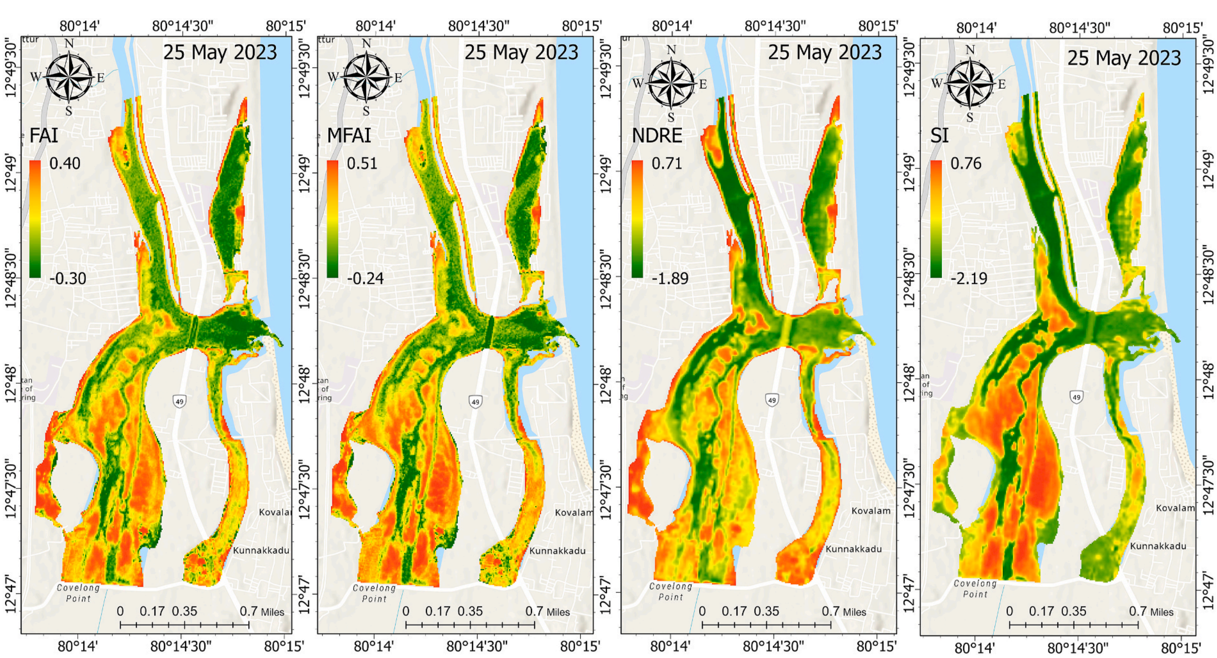

Fig. 3. *Ulva lactuca* distribution during May 2023.

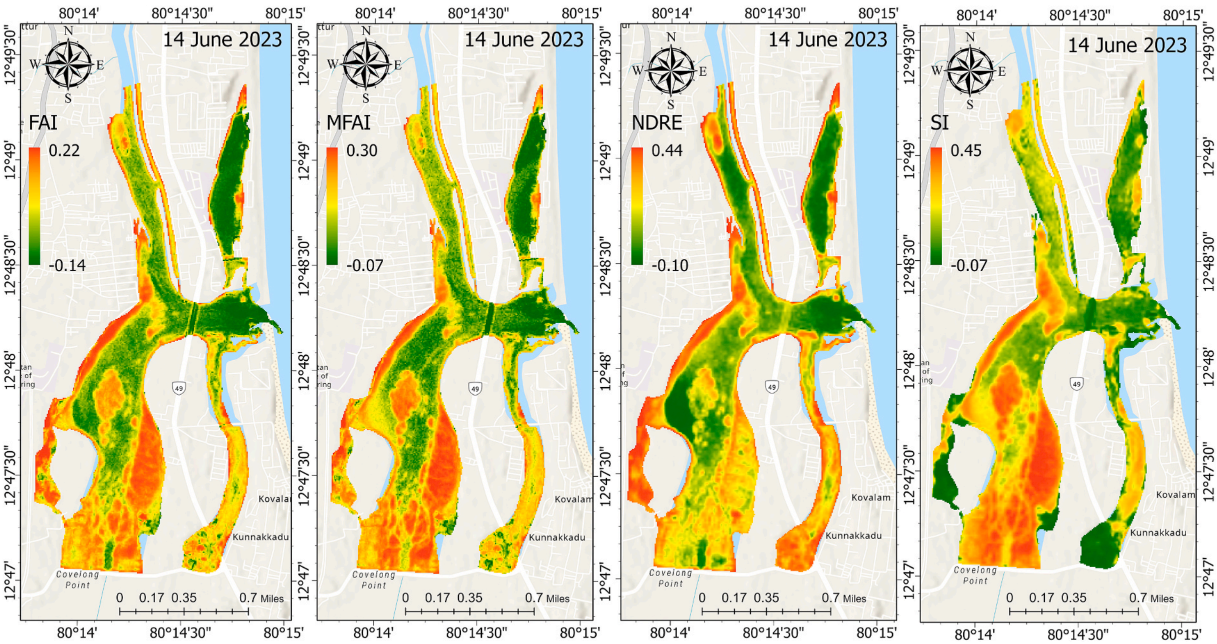

Fig. 4. *Ulva lactuca* distribution on June 14, 2023.

Table 3
Seaweed distribution coverage area using various model.

Satellite Image Acquisition Date	Seaweed distribution area in hectares			
	FAI	MFAI	NDRE	SI
May 25, 2023	123.06	154.22	112.13	100.05
June 14, 2023	141.15	173.39	109.87	76.22
June 29, 2023	93.81	127.40	106.44	96.71
July 09, 2023	79.94	115.51	80.16	80.68

respectively. The SI model also outperforms the other models in terms of precision and F1 score, as shown in Table 5. The recall values of the models are similar with small variation, except for the NDRE model which has a lower recall.

3.3. Hydrodynamic condition during bloom

The time interval between a high tide and a low tide is approximately 6 h and 12 min. The water level in the lagoon experiences an increase of 0.5–1 m during high tide. The Muttukadu lagoon tide map is given in Fig. 9.

Hydrodynamic conditions, specifically calm waters and low wave action can facilitate the accumulation of *Ulva lactuca* biomass, contributing to bloom formation (Haro et al., 2023; Pang et al., 2010; Tang and Gobler., 2011). In areas with minimal water movement, such as sheltered bays or estuaries, the macroalgae can become trapped or settle, leading to the aggregation of biomass. As more sea lettuce accumulates

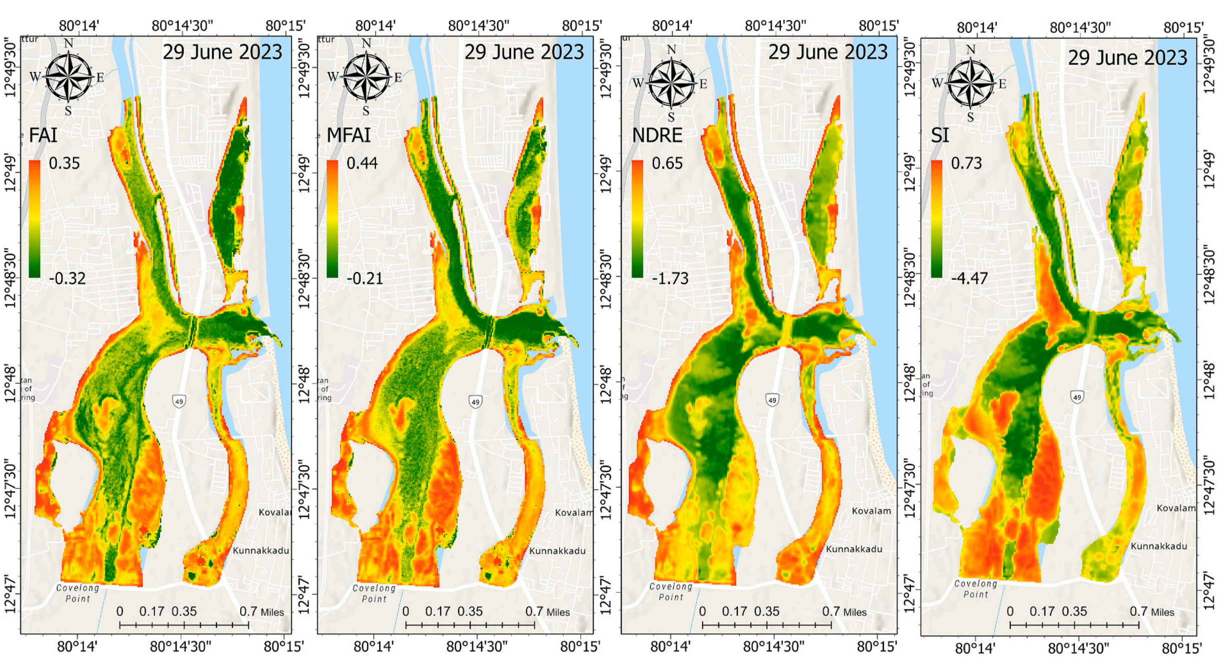

Fig. 5. *Ulva lactuca* distribution on June 29, 2023.

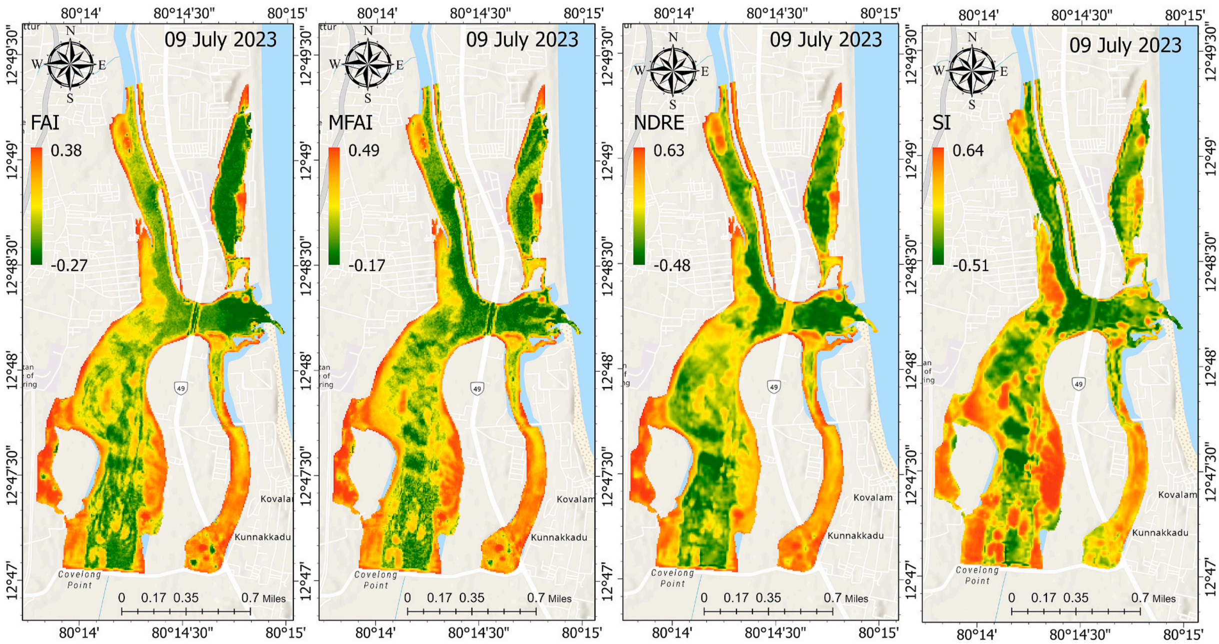

Fig. 6. *Ulva lactuca* distribution on July 9, 2023.

Fig. 7. Muttukadu lagoon seaweed bloom view in MAVIC 3 pro drone.

in a given area, it can create a positive feedback loop, as the dense mats of algae further reduce water movement, promoting even more biomass accumulation (Chávez-Sánchez et al., 2018; Teichberg et al., 2010). The direction of water movement during high tide and low tide is given in Fig. 10. The high tide and low tide view of Muttukadu lagoon is shown in Fig. 11. Tidal movements can cause the mixing of nutrient-rich water from deeper areas with surface waters. During the rising tide, nutrients that have settled in the sediments can be re-suspended and transported to the surface waters, providing a source of nutrients for algal growth, including *Ulva lactuca.* This can contribute to the initiation and sustenance of blooms (Pollard et al., 2018). During low tides, water can become trapped in shallow pools or tidal flats, leading to evaporation and the concentration of nutrients. When the tide rises again, there is a possibility of nutrient enrichment in the coastal area, potentially promoting the growth of *Ulva lactuca* and other algae. Tides generate water movement based on the influence of water currents and influence the distribution and aggregation of *Ulva lactuca.* During high tides, water movement can disperse the macroalgae and prevent their excessive accumulation. However, as the tide recedes, water movement slows down, potentially leading to the aggregation of *Ulva lactuca* biomass in certain areas, contributing to the formation of blooms.

Table 4
Ulva lactuca bloom distribution and intensity in Muttukadu Lagoon.

	Ulva lactuca bloom			
	May 25, 2023	*June 14, 2023*	*June 29, 2023*	*July 9, 2023*
Intensity of bloom	<u>Location</u> 1-Moderate 2-Very high 3-Very high 4-Very high	<u>Location</u> 1- Low 2- Moderate 3- Very high 4- Very high	<u>Location</u> 1- Moderate 2- Low 3- Very high 4- Very high	<u>Location</u> 1- Moderate 2- Low 3- High 4- Moderate

3.4. Nutrient enrichment and algal growth

Higher nutrient concentrations during the pre-bloom indicated a greater availability of resources for algal growth, potentially leading to more intense and extensive blooms. The evaluation of bloom potential involved assessing the relationship between the nutrient concentrations and the observed bloom intensity. Correlating the nutrient data with the

Fig. 8. Muttukadu lagoon algal bloom field survey.

Table 5
Accuracy assessment of seaweed distribution using various models.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 score (%)
FAI	83.10	78.22	91.08	84.16
MFAI	85.80	84.01	89.26	86.55
NDRE	71.30	69.48	78.56	73.74
SI	91.60	94.01	89.71	91.81

actual bloom conditions, the study reveals that higher nutrient enrichment results in higher bloom intensity as shown in Table 6. One of the primary drivers of *Ulva lactuca* blooms is nutrient enrichment, a process known as eutrophication. Eutrophication occurs when an excess of nutrients, particularly nitrogen and phosphorus, enters aquatic ecosystems. These nutrients originate from various sources, including agricultural runoff, sewage discharges, and industrial effluents. When these nutrients reach coastal waters, they serve as fertilizers, promoting the growth of algae. Elevated nutrient levels, particularly nitrogen and

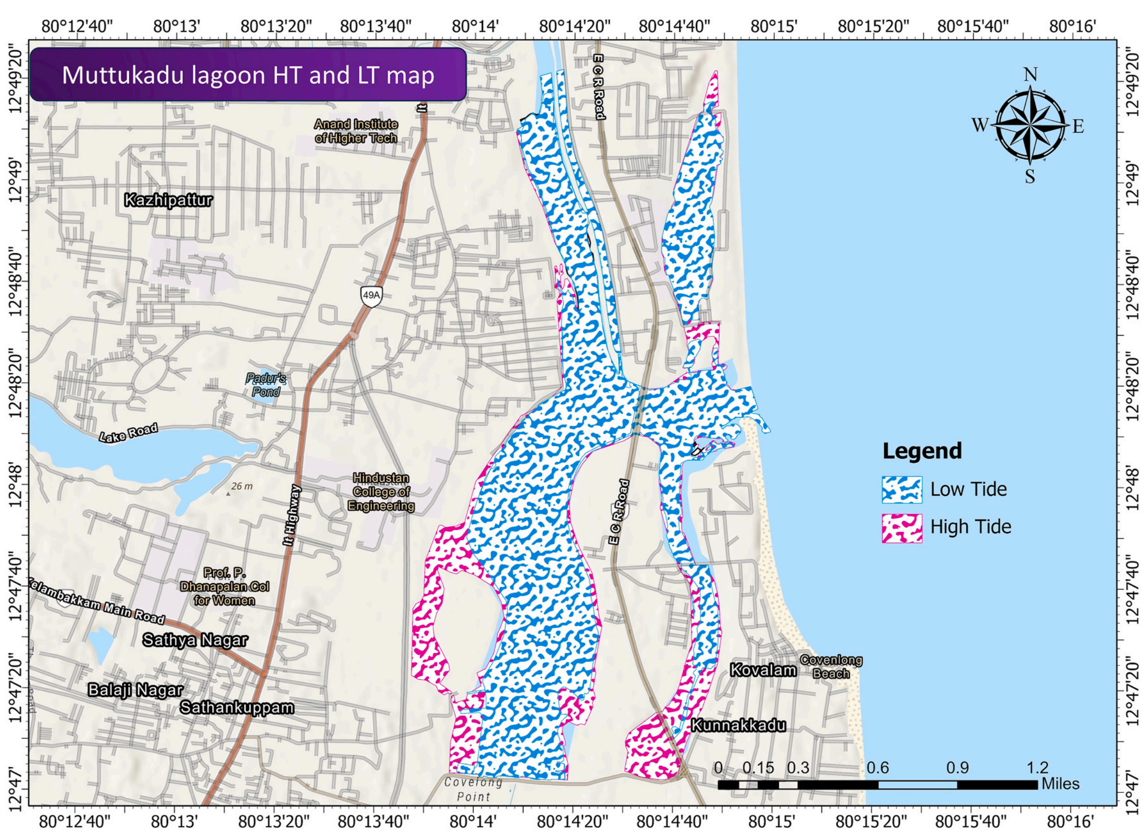

Fig. 9. Muttukadu Lagoon tide map.

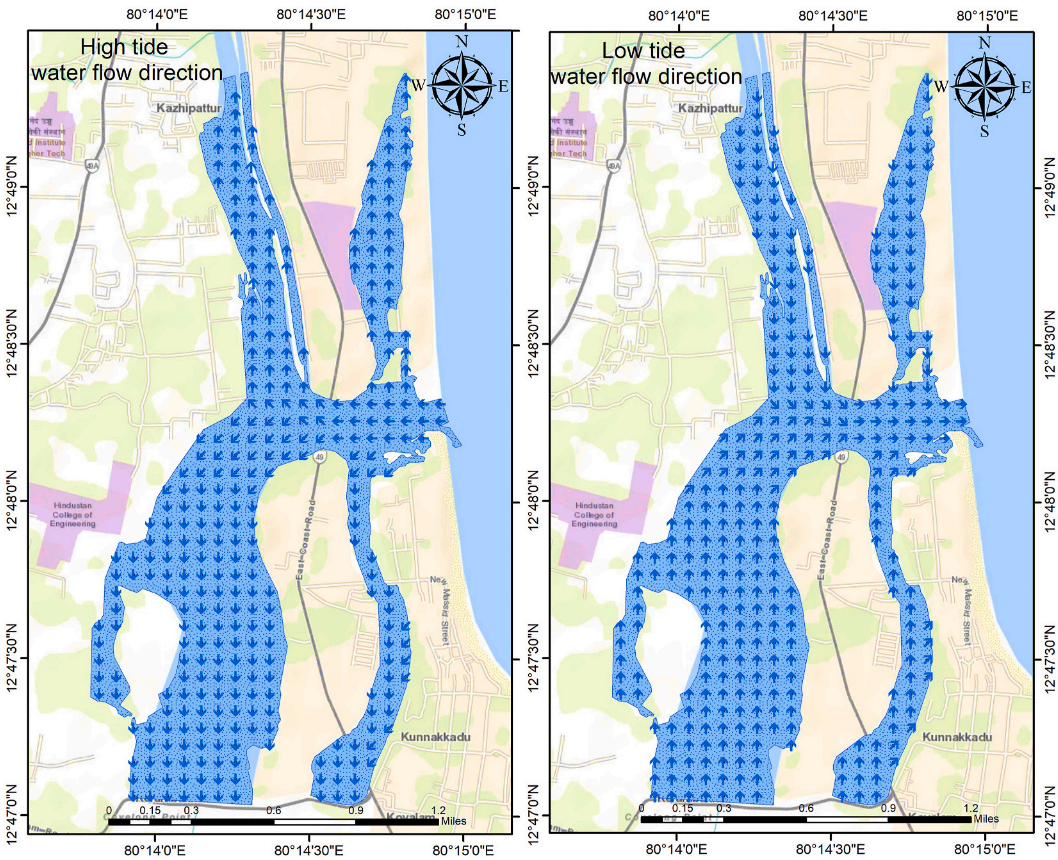

Fig. 10. Water flow direction during high tide and low tide in Muttukadu lagoon.

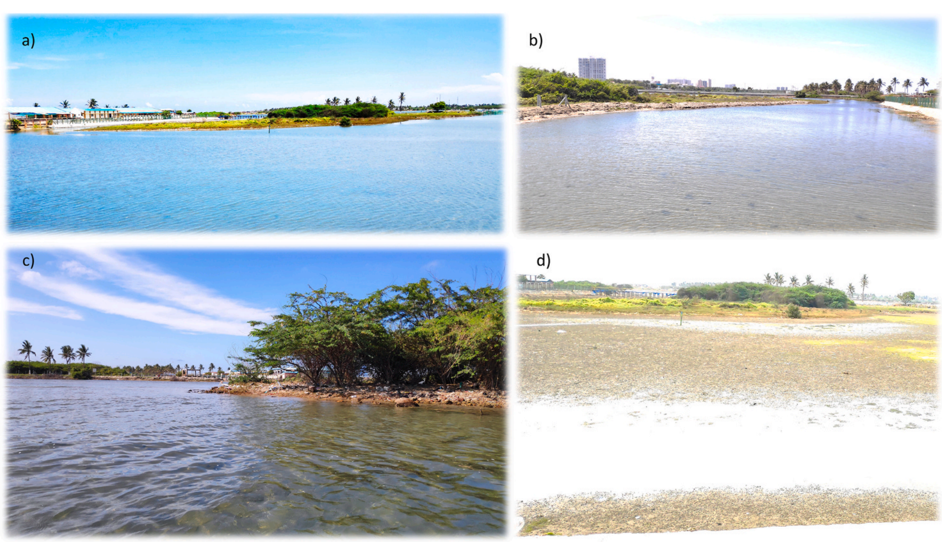

Fig. 11. Muttukadu lagoon tidal view a), b) & c) High tide view d) Low tide view.

phosphorus, are often associated with the initiation and sustenance of algal blooms, as these nutrients fuel the rapid growth of algae, including *Ulva lactuca (*Chávez-Sánchez et al., 2017; Ale et al., 2011).

In the presence of abundant nutrients, compared with other algae and macrophytes, *U. lactuca* rapidly proliferates, forming dense mats or aggregates. This phenomenon is often observed in areas where nutrient inputs are high, such as near agricultural lands or urban areas. As sea lettuce thrives on elevated nutrient levels, it can quickly dominate the ecosystem, leading to the development of blooms (Ibrahim et al., 2016; Abudabos et al., 2013; Van der Wal et al., 2013). The various bloom causes are given in Fig. 12.

3.5. *Muttukadu Lagoon water quality assessment*

Temperature and light availability also play a crucial role in the formation *of Ulva lactuca* blooms. Sea lettuce is well-suited to warm temperatures, as it is a mesophilic species that thrives in a wide range of temperatures commonly found in coastal waters. With rising sea surface

Table 6
Pre-Bloom Nutrient Concentrations and *Ulva lactuca* bloom Potential in Muttukadu Lagoon.

Location	Nitrogen Concentration (mg/L)	Phosphorus Concentration (mg/L)	*Ulva lactuca* bloom Potential
Site 1	2.4	0.20	Moderate
Site 2	4.1	0.29	Very High
Site 3	4.3	0.31	Very High
Site 4	4.4	0.33	Very High

temperatures due to climate change, coastal areas may experience extended periods of warmth, providing favourable conditions for *Ulva lactuca* to flourish. Furthermore, the growth of *Ulva lactuca* is dependent on photosynthesis, a process that relies heavily on light availability. Adequate sunlight is essential for the algae to produce energy and grow. Therefore, regions with high solar radiation and extended daylight hours can provide the necessary conditions for rapid *Ulva lactuca* growth, contributing to the initiation and progression of blooms. The water temperature in the study area was found to be in the range of 29.94–32.30 °C during pre-bloom (May 2023) and in the algal phase (June 2023) was about 31–32.15 °C. The concentration of NH_4–N, PO_4–P, and NO_2 in Pre bloom was 0.04–1.40 mg/L, 0.01–1.36 mg/L and 0.24–1.13 mg/L, the nutrient concentration was observed to be reduced largely during algal phase ranging from 0.002 to 0.38 mg/L, 0.01–0.35 mg/L, and 0–0.74 mg/L respectively.

DO in pre-bloom (May 2023) ranges from 6.10 to 7.10 mg/L, in the algal phase (June 2023). DO concentration ranges from 2.50 to 7.59 mg/L, in locations 1–4 DO was about 2.50–5.04 mg/L as shown in Fig. 13. As *Ulva lactuca* bloom grows and subsequently decay, a significant amount of organic matter is generated. During the decomposition process, microorganisms consume oxygen as they break down the organic material. In cases where the biomass of the bloom is exceptionally high, this decomposition process can consume large quantities of oxygen from the surrounding water. The excessive oxygen consumption associated with the decay of *Ulva lactuca* blooms can lead to hypoxic conditions, where oxygen levels in the water drop to levels that are detrimental to marine organisms. Hypoxia can stress or kill fish, invertebrates, and other aquatic life that depend on oxygen for survival. In severe cases, extended periods of hypoxia can lead to "dead zones" where large portions of the marine/brackishwater ecosystem become uninhabitable for coastal life.

3.6. Proximate and nutrient composition of Ulva lactuca

The high crude protein content of 24.17% indicates that *Ulva lactuca* is a good source of protein. The low crude lipid content of 0.81% suggests that the alga is low in fats. The total ash content of 37.45% indicates the presence of minerals and inorganic components. Fiber content at 8.92% suggests the presence of structural carbohydrates. The acid insoluble ash of 16.18% indicates the presence of minerals that are not soluble in acid. The proximate composition of *Ulva lactuca* is given in Table 7. Proximate analysis provides detailed information about the nutrient composition of *Ulva lactuca*, including its protein, carbohydrate, lipid, and mineral content. This information is essential for understanding the potential uses of this algae in various industries, such as food, feed, and biofuel.

Nutrient content of *Ulva lactuca* in terms of Phosphorus (P), Calcium (Ca), Magnesium (Mg), Potassium (K), and Sodium (Na) is about 1622.10 mg/kg, 20,063.80 mg/kg, 10,223.40 mg/kg, 9036.50 mg/kg, and 15,479.90 mg/kg respectively. The mineral concentration is given in Table 8. *Ulva lactuca* is commonly used as a sea vegetable in salads and is also served cooked, in soups along with meats and fish. Some of the countries where *Ulva lactuca* is used as food include Great Britain, Ireland, Scandinavia, China, and Japan.

Ulva lactuca has a wide range of potential industrial applications. The high phosphorous content in *Ulva lactuca* indicates its potential as a biofuel source. Calcium (Ca) is a mineral that is necessary for life. It is a rich source of bioactive compounds, particularly a polysaccharide known as Ulvan, which has been found to have anti-viral, antioxidant, anti-tumour, anti-coagulant, antihyperlipidemic, hepatoprotective, immuno-stimulating, anti-depressant and anti-anxiolytic activities. This makes *Ulva lactuca* a valuable resource for the chemical, biomedical and agricultural sectors. In the food and feed industries, *Ulva lactuca* is used as a source of phycocolloids. It can also serve as an ingredient for thickening and gelling agents. Moreover, due to its high cellulose content, *Ulva lactuca* is an ideal raw material for bioplastic production. It can be used to produce a variety of bioplastics, including polylactic acid (PLA) and polyhydroxyalkanoates (PHAs). Furthermore, the biomass of *Ulva lactuca* has various applications in the pharmaceutical and nutraceutical industries. *Ulva lactuca* is a versatile resource with numerous potential industrial applications (Farobie et al., 2022; Taddia et al., 2020; Pollard et al.., 2018; Ibrahim et al., 2016; Diaz et al., 2013).

The micronutrient concentration of Iron (Fe), Copper (Cu), Selenium (Se), and Zinc (Zn) in *Ulva lactuca* is about 1164.40 mg/kg, 13.85 mg/kg, BDL, and 16.34 mg/kg respectively. The micronutrients are given in Table 9. The micronutrients Iron (Fe), Copper (Cu), Selenium (Se), and Zinc (Zn) play crucial roles in various applications such as shrimp feed formulation, fertilizer formulation, nutrient drink formulation, and others. Micronutrients are essential for the growth and health of

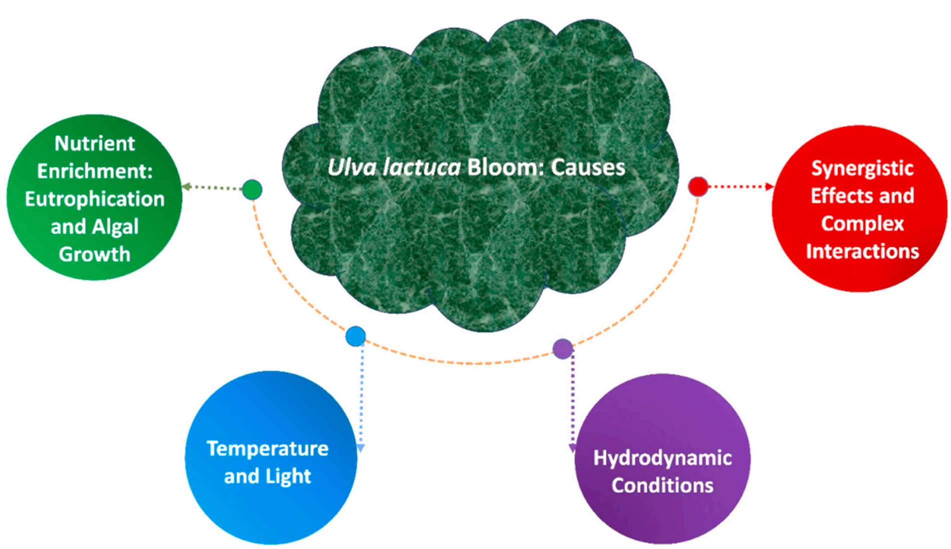

Fig. 12. *Ulva lactuca* bloom cause.

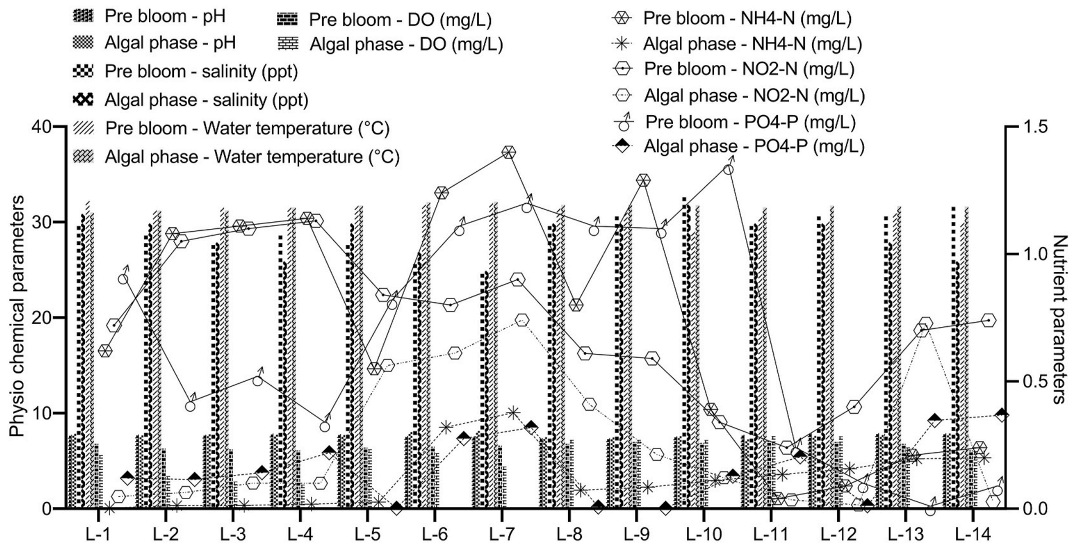

Fig. 13. Muttukadu lagoon water quality pre-bloom and algal phase.

Table 7
Proximate and nutrient composition of *Ulva lactuca*.

Proximate composition (%)	Wild
Moisture	80.00 ± 2.98
Crude protein	24.17 ± 1.80
Crude lipid	0.81 ± 0.05
Total Ash	37.45 ± 1.44
Fiber	8.92 ± 0.41
Acid Insoluble Ash	16.18 ± 1.16

shrimps. Iron is necessary for various metabolic processes, Copper acts as a co-factor for many enzymes, Selenium is an essential component of antioxidant enzymes, and Zinc plays a vital role in protein synthesis and energy metabolism. A combination of feed ingredients is needed to supply the nutrients and energy shrimp need for best growth. Micronutrients are also important in plant nutrition. They are typically added to fertilizers to ensure plants get all the necessary nutrients. For instance, Iron is essential for chlorophyll synthesis, Copper is involved in photosynthesis, Selenium improves growth and stress resistance, and Zinc is required for enzyme function in plants. These micronutrients are also beneficial to human health and are often added to nutrient drinks. Iron is necessary for the production of haemoglobin (Farobie et al., 2022; Allen et al., 2013; Bruhn et al., 2011; Yaich et al., 2011), Copper aids in iron absorption, Selenium has antioxidant properties, and Zinc supports immune function (Ibrahim et al., 2016; Hu et al., 2010; Nan et al., 2008).

The heavy metal concentration in *Ulva lactuca* for lead (Pb), chromium (Cr), and mercury (Hg) is about BDL, 7.1 mg/kg and BDL

Table 8
Minerals (mg/kg) composition in wild seaweeds.

S. No	Species	(P)	(Ca)	(Mg)	(K)	(Na)
1	*Ulva lactuca*	1622.10	20,063.80	10,223.40	9036.50	15,479.90

Phosphorous (P), Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na).

Table 9
Micronutrients (mg/kg) in *Ulva lactuca*.

S. No	Species	(Fe)	(Cu)	(Se)	(Zn)
1	*Ulva lactuca*	1164.40	13.85	BDL	16.34

Iron (Fe), Copper (Cu), Selenium (Se), Zinc (Zn), BDL- Below Detection Level (<1).

Table 10
Heavy metals (mg/kg) in *Ulva lactuca*.

S. No	Species	(Pb)	(Cr)	(Hg)
1	*Ulva lactuca*	BDL	7.1	BDL

Lead (Pb), Chromium (Cr), Mercury (Hg), BDL- Below Detection Level (<1).

respectively. The heavy metals concentration is given in Table 10. Heavy metals can accumulate in seaweeds from the surrounding water. While some heavy metals are essential for biological processes, others can be harmful or even toxic to organisms and humans when present in high concentrations (Chávez-Sánchez et al., 2017; Mofeed, 2017; Bruhn et al., 2011). Therefore, monitoring the levels of heavy metals in seaweeds like *Ulva lactuca* is important for assessing the health of coastal ecosystems and the potential risks to human health from consuming these seaweeds. *Ulva lactuca has* the ability to absorb and remove excess nutrients such as nitrogen and phosphorus from the water, making it a good candidate for bioremediation in aquatic ecosystems.

3.7. Sustainable harvesting of seaweed for coastal livelihoods

Harvesting *Ulva lactuca* helps in managing the bloom while providing economic opportunities for local communities as shown in Fig. 14. Controlled harvesting of the macroalgae can reduce its biomass and prevent excessive growth that leads to blooms. Additionally, the harvested seaweed can be used for various purposes, including food, animal feed, fertilizer, and even in the production of biofuels and cosmetics (Farobie et al., 2022; Dominguez and Loret., 2019). Community-based management approaches that involve local stakeholders in sustainable harvesting practices can help strike a balance between ecological conservation and socio-economic development. Proper regulations and guidelines should be established to ensure that harvesting remains within sustainable limits and does not contribute to overexploitation.

4. Conclusion

The study on the *Ulva lactuca* bloom in Muttukadu Lagoon from May to July 2023 provides valuable insights into the spatial distribution and temporal dynamics of algal blooms. The distribution of *Ulva lactuca* bloom was mapped using four models viz. SI, FAI, MFAI and NDRE. The accuracy of these models was verified by comparing them with field and drone surveys, as well as using accuracy, precision, recall and F1 score.

Fig. 14. *Ulva lactuca* harvest as an additional livelihood activity for coastal community.

The seaweed index (SI) was found to be more accurate compared to other models, it helps in effectively monitoring these blooms, with an accuracy of over 91.60%. The peak bloom coverage was observed in the last week of May 2023 and extends till the last week of June 2023. The spatial distribution of water quality revealed that *Ulva lactuca* acts as a bioremediation agent by reducing the nutrient concentration in the water, which can help improve the water quality and prevent eutrophication. The study also highlighted the potential for sustainable utilization of *Ulva lactuca* biomass, as it has rich nutrient content and low heavy metal concentration.

The study revealed algal blooms can pose ecological challenges butalso provide opportunities for renewable resource utilization with scientific monitoring and management strategies. This helps in maintaining the balance of coastal ecosystems and promote the sustainable use of resources like *Ulva lactuca* for various industrial purposes and livelihood support for coastal communities.

Consent for publication

All authors agree to give their consent for publication.

Ethical approval

To the best of our knowledge, the manuscript does not need ethical approval in the method section.

CRediT authorship contribution statement

Nila Rekha Peter: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nishan Raja Raja:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jayakumar Rengarajan:** Conceptualization, Formal analysis, Methodology, Project administration, Software, Supervision, Validation, Writing – review & editing. **Aravind Radhakrishnan Pillai:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Ambasankar Kondusamy:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Supervision, Validation, Writing – review & editing. **Aravind Kumar Saravanan:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Balasubramanian Changaramkumarath Paran:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Kuldeep Kumar Lal:** Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing 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 paper.

Data availability

Data will be made available on request.

Acknowledgement

We acknowledge the funds and facilities provided by the Director of ICAR–CIBA for carrying out this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106964.

References

Abudabos, A.M., Okab, A.B., Aljumaah, R.S., Samara, E.M., Abdoun, K.A., Al-Haidary, A. A., 2013. Nutritional value of green seaweed (Ulva lactuca) for broiler chickens. Ital. J. Anim. Sci. 12 (2), e28. https://doi.org/10.4081/ijas.2013.e28.

Ale, M.T., Mikkelsen, J.D., Meyer, A.S., 2011. Differential growth response of *Ulva lactuca* to ammonium and nitrate assimilation. J. Appl. Phycol. 23, 345–351. https://doi.org/10.1007/s10811-010-9546-2.

Allen, E., Browne, J., Hynes, S., Murphy, J.D., 2013. The potential of algae blooms to produce renewable gaseous fuel. Waste Manag. 33 (11), 2425–2433. https://doi.org/10.1016/j.wasman.2013.06.017.

APHA, 2005. Standard Methods of Water and Wastewater, twenty-first ed. American Public Health Association, Washington, DC, pp. 2–61. ISBN: 0875530478.

Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, I., Jensen, P.D., 2011. Bioenergy potential of *Ulva lactuca*: biomass yield, methane production and combustion. Bioresour. Technol. 102 (3), 2595–2604. https://doi.org/10.1016/j.biortech.2010.10.010.

Chávez-Sánchez, T., Piñón-Gimate, A., Serviere-Zaragoza, E., López-Bautista, J.M., Casas-Valdez, M., 2018. Ulva blooms in the southwestern Gulf of California: reproduction and biomass. Estuarine. Coastal and Shelf Science 200, 202–211. https://doi.org/10.1016/j.ecss.2017.11.007.

Chávez-Sánchez, T., Piñón-Gimate, A., Serviere-Zaragoza, E., Sánchez-González, A., Hernández-Carmona, G., Casas-Valdez, M., 2017. Recruitment in Ulva blooms in relation to temperature, salinity and nutrients in a subtropical bay of the Gulf of California. Bot. Mar. 60 (3), 257–270. https://doi.org/10.1515/bot-2016-0066.

Che, S., Du, G., Wang, N., He, K., Mo, Z., Sun, B., Mao, Y., 2021. Biomass estimation of cultivated red algae Pyropia using unmanned aerial platform based multispectral imaging. Plant Methods 17 (1), 1–13. https://doi.org/10.1186/s13007-021-00711-y.

Descloitres, J., Minghelli, A., Steinmetz, F., Chevalier, C., Chami, M., Berline, L., 2021. Revisited estimation of moderate resolution sargassum fractional coverage using decametric satellite data (s2-msi). Rem. Sens. 13 (24), 5106. https://doi.org/10.3390/rs13245106.

Diaz, M., Darnhofer, I., Darrot, C., Beuret, J.E., 2013. Green tides in Brittany: what can we learn about niche–regime interactions? Environ. Innov. Soc. Transit. 8, 62–75. https://doi.org/10.1016/j.eist.2013.04.002.

Dominguez, H., Loret, E.P., 2019. *Ulva lactuca*, a source of troubles and potential riches. Mar. Drugs 17 (6), 357. https://doi.org/10.3390/md17060357.

Farobie, O., Syaftika, N., Masfuri, I., Rini, T.P., Es, D.P.L., Bayu, A., et al., 2022. Green algae to green fuels: Syngas and hydrochar production from *Ulva lactuca* via sub-critical water gasification. Algal Res. 67, 102834 https://doi.org/10.1016/j.algal.2022.102834.

Guidone, M., Thornber, C.S., 2013. Examination of Ulva bloom species richness and relative abundance reveals two cryptically co-occurring bloom species in Narragansett Bay, Rhode Island. Harmful Algae 24, 1–9. https://doi.org/10.1016/j.hal.2012.12.007.

Guiry, M.D., 2013. AlgaeBase. World-wide Electronic Publication. http://www.algaebase.org.

Haro, S., Bermejo, R., Wilkes, R., Bull, L., Morrison, L., 2023. Monitoring intertidal golden tides dominated by Ectocarpus siliculosus using Sentinel-2 imagery. Int. J. Appl. Earth Obs. Geoinf. 122, 103451 https://doi.org/10.1016/j.jag.2023.103451.

Hu, C., 2009. A novel ocean color index to detect floating algae in the global oceans. Remote Sens. Environ. 113 (10), 2118–2129. https://doi.org/10.1016/j.rse.2009.05.012.

Hu, C., Li, D., Chen, C., Ge, J., Muller-Karger, F.E., Liu, J., et al., 2010. On the recurrent Ulva prolifera blooms in the yellow sea and east China sea. J. Geophys. Res.: Oceans 115 (C5). https://doi.org/10.1029/2009JC005561.

Ibrahim, W.M., Hassan, A.F., Azab, Y.A., 2016. Biosorption of toxic heavy metals from aqueous solution by *Ulva lactuca* activated carbon. Egyptian journal of basic and applied sciences 3 (3), 241–249. https://doi.org/10.1016/j.ejbas.2016.07.005.

Kaliaperumal, N., Kalimuthu, S., 1997. Seaweed potential and its exploitation in India. Seaweed Research and Utilisation 19 (1&2), 33–40.

Liu, M., Ling, H., Wu, D., Su, X., Cao, Z., 2021. Sentinel-2 and Landsat-8 observations for harmful algae blooms in a small eutrophic lake. Rem. Sens. 13 (21), 4479. https://doi.org/10.3390/rs13214479.

Manuputty, A., Gaol, J.L., Agus, S.B., Nurjaya, I.W., 2017. The utilization of depth invariant index and principle component analysis for mapping seagrass ecosystem of Kotok Island and Karang Bongkok, Indonesia. In: IOP Conference Series: Earth and Environmental Science, vol. 54. IOP Publishing, 012083, 1. https://iopscience.iop.org/article/10.1088/1755-1315/54/1/012083.

Mofeed, J., 2017. Biosorption of heavy metals from aqueous industrial effluent by non-living biomass of two marine green algae *Ulva lactuca* and Dunaliella salina as Biosorpents. Catrina: Int. J. Environ. Sci. 16 (1), 43–52. https://doi.org/10.21608/cat.2017.14267.

Nan, C., Zhang, H., Lin, S., Zhao, G., Liu, X., 2008. Allelopathic effects of Ulva lactuca on selected species of harmful bloom-forming microalgae in laboratory cultures. Aquat. Bot. 89 (1), 9–15. https://doi.org/10.1016/j.aquabot.2008.01.005.

Ody, A., Thibaut, T., Berline, L., Changeux, T., Andre, J.M., Chevalier, C., et al., 2019. From in situ to satellite observations of pelagic sargassum distribution and aggregation in the tropical North Atlantic ocean. PLoS One 14 (9), e0222584. https://doi.org/10.1371/journal.pone.0222584.

Pang, S.J., Liu, F., Shan, T.F., Xu, N., Zhang, Z.H., Gao, S.Q., et al., 2010. Tracking the algal origin of the Ulva bloom in the Yellow Sea by a combination of molecular, morphological and physiological analyses. Mar. Environ. Res. 69 (4), 207–215. https://doi.org/10.1016/j.marenvres.2009.10.007.

Pappou, S., Dardavila, M.M., Savvidou, M.G., Louli, V., Magoulas, K., Voutsas, E., 2022. Extraction of bioactive compounds from *Ulva lactuca*. Appl. Sci. 12 (4), 2117. https://doi.org/10.3390/app12042117.

Pollard, M., Whitfield, A.K., Hodgson, A.N., 2018. Possible influences of a macroalgal bloom in eelgrass beds on fish assemblages in the lower Knysna Estuary, South Africa. Afr. J. Aquat. Sci. 43 (3), 319–323. https://doi.org/10.2989/16085914.2018.1515063.

Pratama, I., Albasri, H., 2021. Mapping and estimating harvest potential of seaweed culture using Worldview-2 Satellite images: a case study in Nusa Lembongan, Bali−Indonesia. Aquat. Living Resour. 34, 15. https://doi.org/10.1051/alr/2021015.

Qi, L., Hu, C., Xing, Q., Shang, S., 2016. Long-term trend of Ulva prolifera blooms in the western Yellow Sea. Harmful Algae 58, 35–44. https://doi.org/10.1016/j.hal.2016.07.004.

Selvaraj, S., Case, B.S., White, W.L., 2021. Effects of location and season on seaweed spectral signatures. Frontiers in Ecology and Evolution 9, 581852. https://doi.org/10.3389/fevo.2021.581852.

Siddiqui, M.D., Zaidi, A.Z., Abdullah, M., 2019. Performance evaluation of newly proposed seaweed enhancing index (SEI). Rem. Sens. 11 (12), 1434. https://doi.org/10.3390/rs11121434.

Siregar, V.P., Agus, S.B., Subarno, T., Prabowo, N.W., 2018. Mapping shallow waters habitats using OBIA by applying several approaches of depth invariant index in North Kepulauan Seribu. In: IOP Conference Series: Earth and Environmental Science, vol. 149. IOP Publishing, 012052. https://doi.org/10.1088/1755-1315/149/1/012052, 1.

Tabarsa, M., Rezaei, M., Ramezanpour, Z., Waaland, J.R., 2012. Chemical compositions of the marine algae Gracilaria salicornia (Rhodophyta) and *Ulva lactuca* (Chlorophyta) as a potential food source. J. Sci. Food Agric. 92 (12), 2500–2506. https://doi.org/10.1002/jsfa.5659.

Taddia, Y., Russo, P., Lovo, S., Pellegrinelli, A., 2020. Multispectral UAV monitoring of submerged seaweed in shallow water. Applied Geomatics 12, 19–34. https://doi.org/10.1007/s12518-019-00270-x.

Tang, Y.Z., Gobler, C.J., 2011. The green macroalga, Ulva lactuca, inhibits the growth of seven common harmful algal bloom species via allelopathy. Harmful Algae 10 (5), 480–488. https://doi.org/10.1016/j.hal.2011.03.003.

Teichberg, M., Fox, S.E., Olsen, Y.S., Valiela, I., Martinetto, P., Iribarne, O., et al., 2010. Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with Ulva spp. Global Change Biol. 16 (9), 2624–2637. https://doi.org/10.1111/j.1365-2486.2009.02108.x.

Van der Wal, H., Sperber, B.L., Houweling-Tan, B., Bakker, R.R., Brandenburg, W., López-Contreras, A.M., 2013. Production of acetone, butanol, and ethanol from biomass of the green seaweed *Ulva lactuca*. Bioresour. Technol. 128, 431–437. https://doi.org/10.1016/j.biortech.2012.10.094.

Xing, Q., Liu, H., Li, J., Hou, Y., Meng, M., Liu, C., 2023. A novel approach of monitoring Ulva pertusa green tide on the basis of UAV and deep learning. Water 15 (17), 3080. https://doi.org/10.3390/w15173080.

Yaich, H., Garna, H., Besbes, S., Paquot, M., Blecker, C., Attia, H., 2011. Chemical composition and functional properties of *Ulva lactuca* seaweed collected in Tunisia. Food Chem. 128 (4), 895–901. https://doi.org/10.1016/j.foodchem.2011.03.114.

Zhang, X., Xu, D., Han, W., Wang, Y., Fan, X., Loladze, I., et al., 2021. Elevated CO2 affects kelp nutrient quality: a case study of Saccharina japonica from CO2-enriched coastal mesocosm systems. J. Phycol. 57 (1), 379–391. https://doi.org/10.1111/jpy.13097.