Restoration of degraded coastal wetlands focusing on seagrass meadows in Gulf of Mannar, Tamil Nadu - *to strengthen climate adaptation and to enhance livelihood sustainability*

(Work Order: TNSWA1/25733/2022, Dated 12.02.2024)

Final Report

Submitted to

Principal Chief Conservator of Forests &
Member Secretary
Tamil Nadu State Wetland Authority
Panagal Maligai
Saidapet
Chennai - 600 015

By

Suganthi Devadason Marine Research Institute (SDMRI)
(Recognized by Manonmaniam Sundaranar University and U.G.C. &
Recognized Scientific and Industrial Research Organization by the DSIR, GOI)
44 - Beach Road, Tuticorin - 628 001, Tamil Nadu
Tel: 0461 - 2336488, 2323007; E.mail: director@sdmri.in
Web: http://www.sdmri.in

30.04.2025

Restoration of degraded coastal wetlands focusing on seagrass meadows in Gulf of Mannar, Tamil Nadu - *to strengthen climate adaptation and to enhance livelihood sustainability*

(Work Order: TNSWA1/25733/2022, Dated 12.02.2024)

Final Report

Submitted to

Principal Chief Conservator of Forests &
Member Secretary
Tamil Nadu State Wetland Authority
Panagal Maligai
Saidapet
Chennai - 600 015

By

Suganthi Devadason Marine Research Institute (SDMRI)
(Recognized by Manonmaniam Sundaranar University and U.G.C. &
Recognized Scientific and Industrial Research Organization by the DSIR, GOI)
44 - Beach Road, Tuticorin - 628 001, Tamil Nadu
Tel: 0461 - 2336488, 2323007; E.mail: director@sdmri.in
Web: http://www.sdmri.in

30.04.2025

Contents

S No	Chapters	Page
i	List of researchers and support staff engaged in the seagrass restoration work	3
ii.	Executive summary	4
1.	Introduction	8
1.1.	Background	8
1.2.	Threats to seagrasses	9
1.3.	Seagrass beds in India	10
1.4.	Seagrass beds in the Gulf of Mannar	10
1.5.	Need for seagrass restoration	11
2.	Scope of the work	12
3.	Seagrass Restoration (Methodology & Work Done)	12
3.1.	Seagrass restoration technique	12
3.2.	Site selection and baseline assessment	13
3.3.	Work done	13
3.4.	Benthic community structure in the selected sites	23
3.5.	Transplantation of seagrasses	25
4.	Monitoring and maintenance	49
4.1.	Fixing of monitoring stations and monitoring methods	49
4.2.	Assessment of environmental parameters	50
4.3.	Seagrass cover and shoot density in the restored area	51
4.4.	Seagrass-associated fish in the restored area	56
4.5.	Seagrass-associated macrofauna in the restored area	61
4.6.	Physico-chemical parameters at the restoration sites	66
5.	Comparison with a nearby degraded site	73
6.	Removal of PVC pipes	76
7.	Comparison with Alternative Methodologies	77
8.	Conclusion and Remarks	78
9.	References	80
	Photos	87

i. List of researchers and support staff engaged in the seagrass restoration work

The following SDMRI research and field staffs are engaged in seagrass restoration work.

1. Dr. J.K. Patterson Edward, Director, SDMRI - Responsible Person (Coordination & Overall Supervision)
2. Dr. G. Mathews, Associate Professor & Dive Master (Senior Technical Staff)
3. Dr. K. Diraviya Raj, Associate Professor & Dive Instructor (Senior Technical Staff)
4. Dr. R.L. Laju, Assistant Professor & Open Water Diver (Junior Technical Staff)
5. Dr. A. Arasamuthu, Research Associate & Open Water Diver (Junior Technical Staff)
6. Dr. P. Dinesh Kumar, Research Associate & Open Water Diver (Junior Technical Staff)
7. Mr. T. Vignesh, Research Fellow & Open Water Diver
8. Mr. G. Praveen, Research Fellow & Open Water Diver
9. Dr. N. Gladwin Gnana Asir, Assistant Professor (Technical Staff - Mapping)
10. Mr. A. Sahayamani, Field Assistant
11. Mr. N. Stephen, Field Assistant
12. Mr. Emerson, Field Assistant

In addition, the services of 8-10 skilled and trained manpower from coastal community were also used.

ii. Executive summary

- Under the Tamil Nadu State Wetland Authority project, seagrass restoration work was carried out during 15.05.2024 to 05.07.2024 (Phase - I) and during 23.10.2024 to 07.11.2024 (Phase - II) covering 2,000 sq.m area near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park.

- Manual transplantation of seagrass sprigs method was used to restore degraded seagrass areas around Koswari Island using a total of 2,000 Nos. PVC frames (1 X 1 m).

- Using SCUBA diving, the restoration sites were selected within 1 acre of degraded area near Koswari Island, and their coordinates were marked with GPS. Restoration was conducted in seven blocks. Block 1 had of 200 frames while blocks 2-7 had 300 each. Block 1 (restoration site 1) is located slightly far from Koswari Island with a distance of 3 km whereas blocks 2 to 7 (restoration site 2) lie close to island within 1 km. Each block had of 4-8 nos. of clusters with each cluster separated with an approximate distance of about 30 to 40 meters.

- Four common seagrass species were transplanted namely *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis*. The percentage contributions of the transplanted seagrass species are 45% by *Oceana serrulata*, 20% by *Thalassia hemprichii*, 30% by *Syringodium isoetifolium* and 5% by *Halodule uninervis.*

- Due to some unexpected adverse weather conditions like the elevated sea surface temperature, turbulence and poor underwater visibility, the seagrass restoration work was carried out in two phases i.e. between 15.05.2024 and 05.07.2024 (Phase - I) and between 23.10.2024 and 07.11.2024 (Phase - II).

- The entire seagrass restoration work near the Koswari Island was supervised by the Forest Staff of Tuticorin Wildlife Range.

- Monitoring and maintenance of the restoration sites were started immediately after the completion of the first phase of restoration in July 2024 upto February 2025. Four permanent monitoring stations were fixed within the two restoration sites and marked with GPS. Stations 1 to 3 were fixed in the restoration site 2 and station 4 was fixed in restoration site 1.

- Data on seagrass percentage cover, shoot density, associated biodiversity and environmental parameters was collected monthly from July 2024 to February 2025 applying standard underwater protocols.

- Seagrass cover in the restoration area kept on increasing gradually after the transplantation as the average increase in seagrass cover was from 20.8 to 33.8% from July 2024 to February 2025.

- Among the four species transplanted, the average cover of *Oceana serrulata* increased from 7.9 to 11.8%; the cover of *Thalassia hemprichii* increased from 6.2 to 9.6%; the cover of *Syringodium isoetifolium* increased from 5.9 to 10.1%; and the cover of *Halodule uninervis* increased from 0.8 to 2.4% during the study period.

- The average shoot density of seagrasses also increased at the restoration area gradually from 67.5 to 124.2 no.m^{-2} between July 2024 and February 2025.

- Among the four species, shoot density of *Oceana serrulata* increased from 23.5 to 41.7 no.m^{-2}; for *Thalassia hemprichii* it increased from 17.6 to 31.3 no.m^{-2}, for *Syringodium isoetifolium* it increased from 18.9 to 37.6 no.m^{-2} and for *Halodule uninervis* it increased from 7.5 to 13.7 no.m^{-2}.

- The density fish in the restored area increased gradually from July 2024 to February 2025 as the seagrass cover increased. The overall density of fish increased from 10.5 to 42.4 during the study period. The most common fish species in the restored area include *Eubleekeria splendens*, *Parupeneus indicus, Scarus* sp., and *Siganus canaliculatus.*

- The average density of benthic macrofauna in the restoration sites increased from 0.95 to 5.23 no.m^{-2} between July 2024 and February 2025. Among the five taxa assessed, molluscs were the dominant category as the average density of molluscs increased from 0.39 to 1.74 no.m^{-2} during the study period followed by echinoderms which increased from 0.23 to 1.45 no.m^{-2}.

- Environmental parameters assessed in the restoration sites were within the optimum levels and did not reach extreme levels during the monitoring period.

- After the establishment of transplanted seagrasses, PVC pipes were removed from the sea bottom in February 2025.

Seagrass restoration activities under Tamil Nadu State Wetland Authority Project in Gulf of Mannar carried out in Koswari Island between 15.05.2024 and 05.07.2024 (Phase - I) and between 23.10.2024 and 07.11.2024 (Phase - II)

Days	Date	Number of PVC quadrats (1 x 1m) with seagrass shoots deployed	Name of Forest staff accompanying the field team	Designation of the Forest staff accompanying the field team
	Phase - I			
1	15.05.24	50	Mr. Esaki Muthu	Anti Poaching Watcher(APW)
2	16.05.24	50	Mr. Manikandan	Forest Guard
3	17.05.24	60	Mr. Ajith	APW
4	18.05.24	60	Mr.Mahesh Kumar	APW
5	20.05.24	65	Mr. Selva Kumar	APW
6	21.05.24	71	Mr. Selva Kumar	APW
7	22.05.24	75	Mr. Selva Kumar	APW
8	23.05.24	69	Mr. Selva Kumar	APW
9	19.06.24	50	Mr. Esaki Muthu	APW
10	20.06.24	62	Mr. Esaki Muthu	APW
11	21.06.24	50	Mr. Esaki Muthu	APW
12	24.06.24	26	Mr. Esaki Muthu	APW
13	28.06.24	51	Mr. Esaki Muthu	APW
14	29.06.24	50	Mr. Esaki Muthu	APW
15	01.07.24	65	Mr. Esaki Muthu	APW
16	02.07.24	71	Mr. Esaki Muthu	APW
17	03.07.24	75	Mr. Manikandan	Forest Guard
18	05.07.24	55	Mr. Esaki Muthu	APW
	Phase - II			
1.	23.10.24	53	Mr. R. Manikandan	Forest Guard
2.	24.10.24	80	Mr. Madasamy	Forest Diver
3.	25.10.24	88	Mr. Rajkumar	Forest Diver
4.	26.10.24	95	Mr. Madasamy	Forest Diver
5.	28.10.24	97	Mr. R. Manikandan	Forest Guard
6.	29.10.24	91	Mr. Ajith	APW

7.	30.10.24	82	Mr. Esaki Muthu	APW
8.	04.11.24	90	Mr. J. Selva Kumar	APW
9.	05.11.24	80	Mr. Esaki Muthu	APW
10.	06.11.24	102	Mr. Rajkumar	Forest Diver
11.	07.11.24	87	Mr. Madasamy	Forest Diver
	Total =	**2000**		

1. Introduction

1.1. Background

Coastal and marine habitats play important ecological and economic roles that are beneficial to humans. Their services include protection against natural disasters, preventing erosion along shorelines, regulating coastal water quality, nutrient recycling, trapping sediment, and providing habitats for commercially important and endangered marine organisms, and food security for many coastal communities around the world. Seagrass beds are one of such dynamic ecosystems with numerous benefits. Seagrasses are marine flowering plants that have the adaptation to grow successfully in tidal and subtidal marine environments (Short et al., 2016). Seagrasses, the only angiosperms in the marine ecosystems to grow submerged in the nearshore regions, (Touchette, 2007) have 72 species as reported from the seas around the world (Short et al., 2007). Seagrasses thrive better in less nutrient waters with minimal hydrodynamic energy where light can penetrate.

Seagrasses offer significantly huge economic benefits valued at more than US$ 19,000 per hectare per year (www.oceanhealthindex.org). There are several regional estimates to highlight the economic importance of seagrasses. The economic contribution of seagrass habitats to secondary production in the Gulf waters of South Australia has been estimated to be AU$ 114 million per year (McArthur and Boland, 2006). In Derawan Island, Indonesia, estimates of the economic value of fish and marine biota inhabiting the seagrass ecosystem area respectively are US$ 13,488.80 and US$ 35,744.69 per hectare per year (Kurniawan et al., 2020). The total economic value of the seagrass ecosystem in Nain Island, Indonesia has been estimated as US$ 1,997,848 yr-1 (Pandelaki et al., 2020). Seagrasses contribute about 20% of the global fisheries by supporting biodiversity (Unsworth et al., 2019). When compared to unvegetated areas, seagrass beds have been estimated to support 55,000 more fish per hectare (Jänes et al. 2020). Further, it has been estimated that the economic value of seagrass beds amounts to US$ 481.77 CO_2/acre in the form of blue carbon (Nurdianto and Resosudarmo, 2016).

Seagrass ecosystems play important ecological roles such as direct contribution through primary production, providing a surface for epiphytic growth, and providing shelter to a wide range of biodiversity. Seagrass beds harbor a great number of marine organisms and act as nursery habitats for the juveniles of several species (Horinouchi et al. 2009). Many of the commercially exploited marine organisms are obligate inhabitants of seagrass beds for part or whole of their life cycles (Barry et al. 2021). Epiphytic organisms that depend on seagrass leaves include algae, fungi, protozoa, sponges, bryozoans, hydroids, and ascidians (Jiang et al. 2020). Different species of commercially important fish and crustaceans thrive exclusively in the seagrass beds as they get habitat for critical spawning, nursery, and refuge (Heise and Bortone 1999). Due to their capacity to sustain a huge amount of commercial fishery resources, seagrass beds are often fishing hotspots for coastal fishermen. Seagrasses are often found adjacent to coral reefs and mangroves highlighting the connection between these ecosystems. As seagrass beds remove nutrients from the seawater, they are important to maintain the quality of coastal waters to help the other ecosystems to thrive better. Seagrasses trap sediment and slow down the water movement, causing suspended sediment to fall out and thus help the nearby coral reef ecosystems (Mckenzie et al., 2003). The trapping and stabilization of sediments by seagrasses prevent abrasion or burial of coral reefs during natural calamities such as storms (Nakamura, 2009). Sediment banks accumulated by seagrass beds provide a substrate for the colonization of mangroves (Ogden and Gladfelter, 1983).

Blue Carbon is a viable tool in the mitigation of climate change effects in future climatic conditions (Serrano al. 2021). Along with other habitats such as mangroves, salt marshes and macroalga beds, seagrasses have been reported to help in tackling the emissions of greenhouse gases and nutrients by storing extensive amounts of carbon. Seagrass meadows are responsible for 10-15% of global oceanic organic carbon storage (Duarte et al., 2005) and provide efficient habitats for long-term burial of sedimentary organic carbon (Serrano et al., 2016), which is thought to be the highest accumulation rate of blue carbon and potentially stored in sediment for centuries to millennia (Mcleod et al., 2011; Serrano et al., 2012). Seagrasses capture carbon dioxide through photosynthesis and accumulate in plant biomass (Cebrian 1999). This biomass accumulates as organic carbon in sediments (Duarte et al., 2011). Seagrass canopies also trap suspended organic matter, retaining it in the sediment as accumulated organic matter (Hendriks et al., 2008). According to an estimate, global seagrass beds store 140 Mg organic carbon per hectare, which is 40 times higher than what the land forests store (Serrano al. 2021). According to another estimate, about 19.9 Pt carbon is stored in the top 1 m of global seagrass beds, which is equivalent to the total CO_2 emissions from fossil fuel and cement production in 2014 (Kerr, 2017).

1.2. Threats to seagrasses

The rapid population growth and expansion of the urban areas are exerting substantial pressure on critical coastal ecosystems, which include seagrass beds. In spite of their critical importance, seagrass ecosystems around the world continue to suffer damages. According to an estimate, seagrass die-off is 0.9% year^{-1} on account of various natural and human-induced factors (Waycott et al. 2009). Due to their sensitivity to poor water quality, coastal development activities, and nutrient enrichment, global seagrass beds have declined during the past several decades (Green et al. 2021). Factors like natural fragmentation by the action of waves and currents, destructive fishing methods, pollution, and recreational activities have also been linked with seagrass destruction (Dunic et al., 2021). The rate of decline of seagrass beds has been severe as it has been reported to have declined at a rate of 110 km^2 year^{-1} between 1980 and 2006 with 15% of seagrass species being now considered under threat (Waycott et al. 2009). The loss of seagrass beds would directly affect the ecosystem services they provide and compromise the extent and quality of the associated biodiversity, fisheries, coastal protection, and carbon storage. The loss of seagrass beds would have a significant impact on the socio-economics of the dependent livelihood (Tan et al. 2020).

1.3. Seagrass beds in India

The tropical Indo-Pacific region is widely recognized as the richest region in the world in terms of biodiversity (Förderer et al., 2018). Indian coastal waters enjoy the tropical climate and hence are characterized by a considerable extent of seagrass beds. Though seagrasses are widely available and are known to provide significant ecological and economic benefits, they remain a poorly studied biota in India when compared with mangrove ecosystems. Though seagrass patches are observed throughout the east and west coasts of the country, major seagrass beds occur along the coasts of Gulf of Mannar and Palk Bay in Tamil Nadu, at the Lakshadweep Islands in the Arabian Sea, and at the Andaman and Nicobar Islands in the Bay of Bengal (Jagtap, 1991; Jagtap et al., 2003; Parthasarathy et al., 1991; Thangaradjou and Kannan, 2010; Mathews et al., 2010). Chilika Lake in Odisha, Pulicat Lake in Tamil Nadu and some areas in Goa and Maharashtra along the west coast also have seagrasses. The total extent of seagrass beds in the country has been estimated as 516.59 km^2 (Geevarghese et al., 2018).

1.4. Seagrass beds in the Gulf of Mannar

Tamil Nadu has the second-largest coastline of 1,076 km in India. It comprises the Coromandel Coast, the Palk Bay, the Gulf of Mannar, and the West Coast. These coastlines, particularly those of the Gulf of Mannar, are endowed with a variety of marine ecosystems including seagrass beds. The Gulf of Mannar is well known for its seagrass cover of over 160 km^2 (NAFCC Report 2019) with 13 species. The Gulf of Mannar is a biodiversity hotspot with significant extent of seagrass beds and thousands of fishermen along its coast thrive with the seagrass-associated fishery resources. Encompassing the 21 islands and the surrounding shallow waters, the total seagrass area cover within the Gulf of Mannar Marine National Park has been reported as 76 km^2 (Mathews et al., 2010). The reported biodiversity in the Gulf of Mannar is 4,223 species (Balaji et al., 2012) and seagrasses play a significant role in supporting this rich biodiversity by sheltering several species of fishes, sea horses, sea turtles, sea cucumbers, sea urchins, starfishes, gastropods, bivalves, ascidians, sponges, crustaceans, etc. (Mathews et al., 2010). Seagrasses in the Gulf of Mannar are observed upto a depth of 18 m but the percentage cover, shoot density, biomass, diversity, and the density of associated organisms are comparatively higher in the shallow waters within the area between islands and the mainland (Mathews et al., 2010). It has been reported that seagrass beds around the islands of the Gulf of Mannar provide a significant grazing ground for the sea *cow Dugong dugon*. The most dominant seagrass species in Gulf of Mannar are *Thalassia hemprichii, Syringodium isoetifolium* and *Oceana serrulata* (Mathews et al., 2010).

Seagrasses along the coast of the Gulf of Mannar are affected by several climatic and non-climatic threats and have been degraded significantly during the past couple of decades. Temperature anomalies, increased CO_2 levels and sea level rise caused by climate change affect the seagrasses of Gulf of Mannar. Though seagrasses are rooted strongly to the sea bottom, strong currents and waves are capable of uprooting them. During the period between July and September, and tonnes and tonnes of seagrass blades washed ashore can be sighted along the shores of the Gulf of Mannar (Mathews et al., 2010). Being mostly turbid and known for high sedimentation, seagrass beds in the Gulf of Mannar are affected by reduced light (Balaji, 2018). Seagrasses are also fed upon by various herbivorous animals including sea cow, green sea turtles, fishes, etc. As animal foraging is a natural process in the food web, it does not affect the seagrasses in a great manner. Nutrient enrichment and algal blooms have also been reported to affect the seagrass beds in the Gulf of Mannar (Raj et al., 2020). Input sources like flooding and fresh water runoff also affect the seagrass beds whenever they happen. Hundreds of huge mechanized trawlers are operated in the Gulf of Mannar doing bottom trawling which severely affects seagrasses (Mathews et al., 2010). Apart from that, other destructive activities such as the uses of shore seine, push net operation, surface supplied diving, and bottom settling gill nets, etc. also affect the integrity of seagrass beds in the Gulf of Mannar. Both domestic and industrial pollution also contribute to the degradation of seagrasses. Anchoring, bottom-laid gill nets, walking on seagrass beds, etc. also cause considerable damage to seagrass beds of the Gulf of Mannar.

1.5. Need for seagrass restoration

The loss of seagrass beds would bring about serious repercussions affecting coastal communities and the fight against climate change. Hence, the loss of seagrass biomass should be compensated by wide-scale restoration efforts to sustain their ecological functions. Due to the severe intensity of the decline of global seagrass beds, research on seagrass restoration measures has been taken up seriously during the past few decades. Various seagrass restoration techniques with different success rates have been attempted in different parts of the world (Fonseca, 1992; Paling et al, 2009; Edward et al. 2019). The conservation and restoration of seagrass beds have been used as a mitigation measure to tackle climate change impacts as seagrass beds efficiently act as carbon sinks (Nellemann et al. 2009). Seagrass restoration would enhance the key ecological services of seagrasses such as the increase and sustenance of fishery resources, enhanced biodiversity, increased productivity, improved carbon storage capacity, and more. These services benefit the dependent coastal communities to sustain their livelihood options, offer food and shelter to thousands of dependent marine organisms and help in the fight against climate change effects.

2. Scope of the work

Selection of suitable site for seagrass restoration near Koswari Island in Tuticorin coast of Gulf of Mannar

a) Collection of baseline data such as environmental parameters in the selected site

b) Selection of donor site to collect seagrass sprigs for transplantation

c) Transplantation of sprigs in 2,000 sq.m area using 2,000 PVC quadrats, each of 1 x 1 m. (About 50% transplantation area in 1 acre.)

d) Each quadrat was tied with six rows of jute strings and each row to have 20 shoots. Thus there were a total of 120 shoots in a quadrat.

e) Fixing of the quadrats (containing the sprigs) underwater in the sediment was done using hook-shaped iron clamps (30 cm in length).

f) Monitoring of restored sites - to assess seagrass cover and shoot density, fishes, macrofauna and environmental parameters.

g) Maintenance of restoration sites - to remove any solid wastes, torn pieces of nets and seaweeds and to replace the quadrats disturbed by fishing activities, if any.

h) Mapping of seagrass in the restoration site

i) Reports - First Progress Report, Second Progress Report, Draft Final Report, Final Report

3. Seagrass Restoration (Methodology & Work Done)

3.1. Seagrass restoration technique

Seagrass restoration was carried out to bring back the ecological services that seagrasses provide, and so the restoration sites are expected to offer services equivalent to those the nearby natural seagrass beds provide. Continuous research carried out on seagrass restoration has brought considerable improvements in its success (Paling et al., 2009). Among the many seagrass restoration methods, shoot-based techniques have been predominant, which include small-scale pilot studies to large-scale transplantation trials involving manual and mechanical planting (Tan et al., 2020). In India, the exploration of seagrass areas is yet incomplete as new seagrass patches are still discovered by recent underwater explorative studies (Bilgi et al., 2022). Very few studies have been carried out on seagrass restoration in Indian waters and that too only in the Gulf of Mannar and Palk

Bay (Bensam and Udhayashankar, 1990; Thangaradjou, 2000; Edward et al., 2008; Thangaradjou and Kannan, 2008; Edward et al., 2019; Balaji et al., 2020). Among the several attempts in the Gulf of Mannar and Palk Bay, the manual transplantation of seagrass sprigs using PVC quadrats developed by Suganthi Devadason Marine Research Institute (SDMRI) has been proven to be a successful method, which involves a low-tech and low-cost technique (Edward et al., 2019). Several experiments were carried out by SDMRI on seagrass restoration in the Gulf of Mannar before the manual transplantation of sprigs was found to be feasible (Edward et al. 2008). The sprigs method was initiated by Perrow and Anthony (2002), in which mature seagrass sprigs are collected from a healthy donor site and transplanted at restoration sites. This method has been perfected to suit the conditions in the Gulf of Mannar by Edward et al. (2019). It is a skill-based activity and hence only professional divers with a scientific understanding of seagrass ecology can execute it properly. This method has been proved to offer several positive outcomes as the restored area becomes similar to natural seagrass beds within two years.

3.2. Site selection and baseline assessment

Selection of proper site for seagrass restoration is very important to get good results. Compromised success rates in seagrass restoration projects are mainly due to poor site selection, high sedimentation, reduced light, strong waves and currents, animal foraging, etc. To avoid these issues, two degraded seagrass sites (Table 1; Figs. 1-3) with a history of seagrass presence near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park were selected. It was made sure that the selected restoration sites were free from sources of physical stress such as erosion, deposition, etc. The sea floor at the restoration sites is dominated by a mixture of silt and clay. Donor site (Table 2; Figs. 4-5) was selected close to the restoration sites so that the sprigs can have similar environmental conditions. Healthy seagrass beds with a seagrass cover more than 60% were selected to act as donor sites. To reduce the stress to the donor sites and to allow their recovery, collection of sprigs was restricted to less than 5% biomass of the donor site. The benthic community structure of the selected seascapes was estimated by the Line Intercept Transect (LIT) method (English et al., 1997). Two transects were laid on the benthic substrate to measure the percentage coverage of benthic variables in the restoration sites. Physico-chemical parameters were also assessed using standard protocols.

3.3. Work done

Seagrass restoration with a total of 2,000 PVC frames of 1 x 1 m planned for covering 2,000 sq.m of transplantation area was successfully completed.

Out of the 2,000 PVC frames, 1,055 PVC frames of 1 x 1 m were used to restore 1,055 sq.m area i.e. completion of over 50% of seagrass restoration work during the period 15.05.2024 to 05.07.2024.

The deployment of the remaining 945 PVC frames of 1x1 m for restoring 945 sq.m area was completed during the period 23.10.2024 to 07.11.2024.

The seagrass restoration covering 2,000 sq.m transplantation area was completed on 07.11.2024.

The seagrass restoration work was delayed due to the elevated sea surface temperature, rough climatic conditions, turbulence and poor underwater visibility.

Monitoring of the restoration sites was carried out from July 2024 to February 2025 and is continued.

<u>Seagrass restoration sites</u>

Seagrass restoration was conducted in two sites near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park. The seagrass restoration sites were selected through an underwater assessment (Table 1; Figs. 1-3).

Fig.1: Map showing the two seagrass restoration sites near Koswari Island in Gulf of Mannar

Table 1: Details of seagrass restoration sites

Seagrass restoration site	GPS	Depth (m)	Nearest Island	Distance between Island and restoration site (km)	Nearest village	Distance between village shore and restoration site (km)
Site 1 Near Koswari Island, Tuticorin coast of Gulf of Mannar	8°54'12.07"N 78°12'57.41"E	2.5 - 5.0m	Koswari	3.0	Pattinamaruthoor	4.5
Site 2 Near Koswari Island, Tuticorin coast of Gulf of Mannar	8°52'35.37"N 78°13'27.82"E	3.0 – 4.5m	Koswari	1.0	Tharuvaikulam	5.5

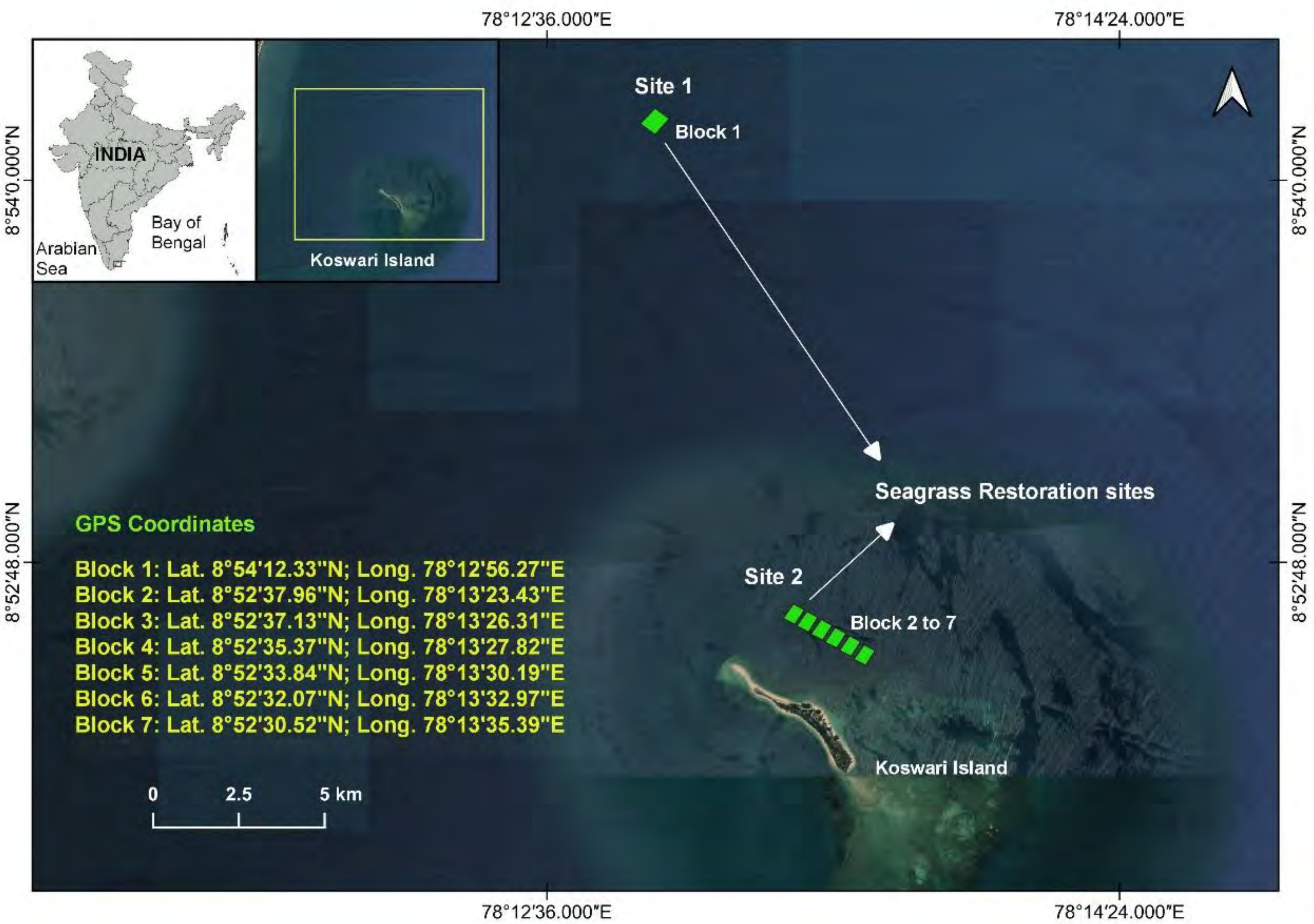


Fig.2: Map showing the two seagrass restoration sites near Koswari Island with details of seven blocks in Gulf of Mannar

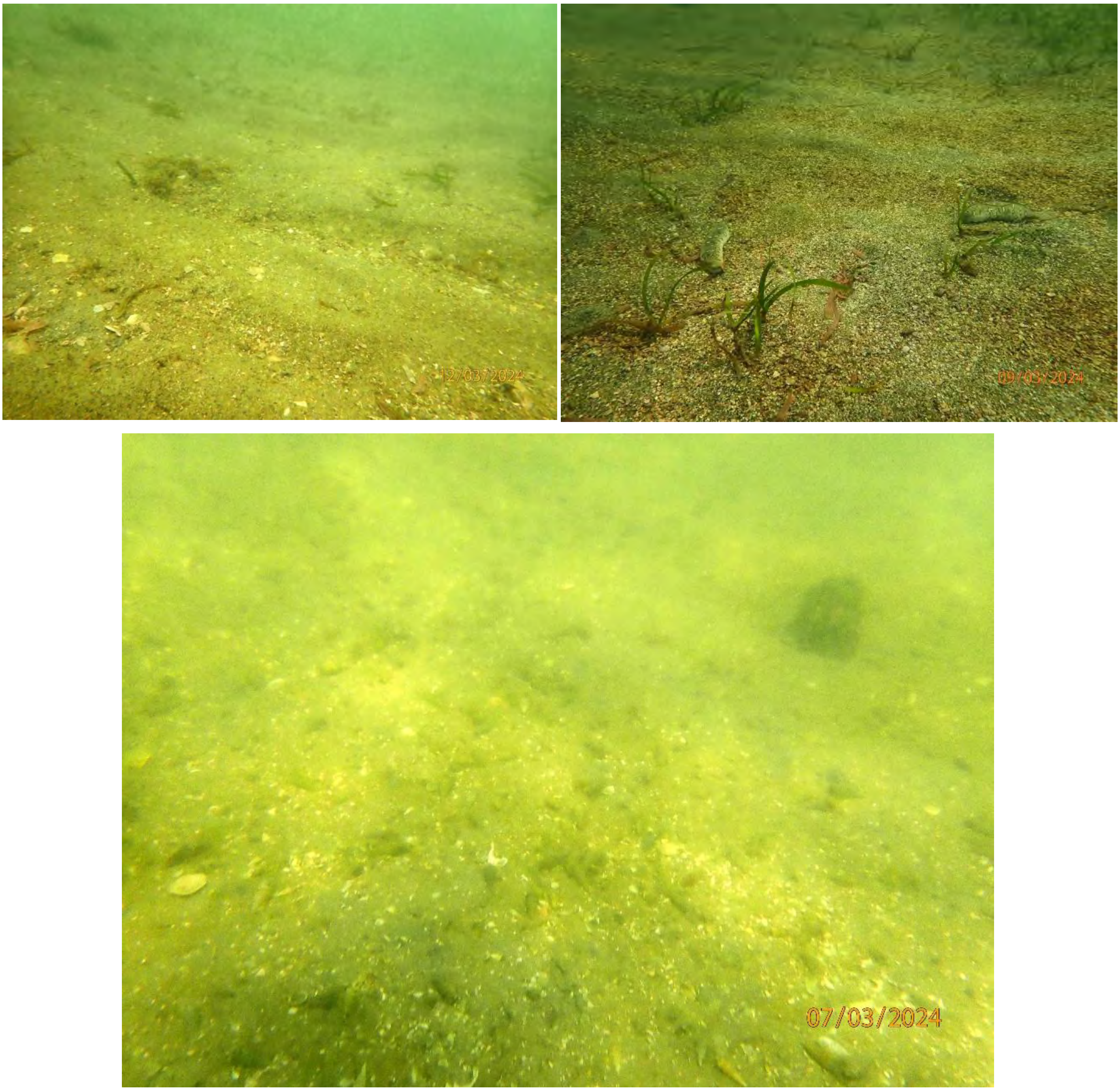


Fig.3: Underwater photos showing the nature of seagrass restoration sites

Seagrass donor site

Seagrass donor site with healthy luxuriant seagrass beds was selected near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park. The seagrass donor site was selected through an underwater assessment (Table 2; Figs. 4-5).

Table 2: Details of seagrass donor site

Seagrass Donor site	GPS	Depth	Nearest Island	Distance from restoration site (km)	Donor site status	Dominant species
Near Tharuvaikulam village, Tuticorin coast of Gulf of Mannar	8°53'5.88"N 78°11'35.17"E	2.0 - 3.0 m	Koswari	3.0	Dense seagrass meadows	*Oceana serrulata, Syringodium isoetifolium, Thalassia hemprichii , Halodule uninervis*

Fig. 4: Donor site with healthy dense seagrass bed

Fig.5: Donor site with healthy dense seagrass bed

Description of four selected species

Species descriptions and morphological characters are adopted from https://www.marinespecies.org/index.php and https://www.seagrasswatch.org/

Oceana serrulata **(Fig. 6)**

Kingdom: Plantae
Division: Tracheophyta
Subdivision: Spermatophytina
Class: Magnoliopsida
Order: Alismatales
Family: Cymodoceaceae
Genus: *Oceana*
Species: *Oceana serrulata*

Morphology

Linear strap-like leaves, 5-9 mm wide; serrated leaf tip; leaf sheath is broad, triangular with a narrow base; leaf scars do not form a continuous ring around the stem; found on shallow subtidal reef flats and sand banks.

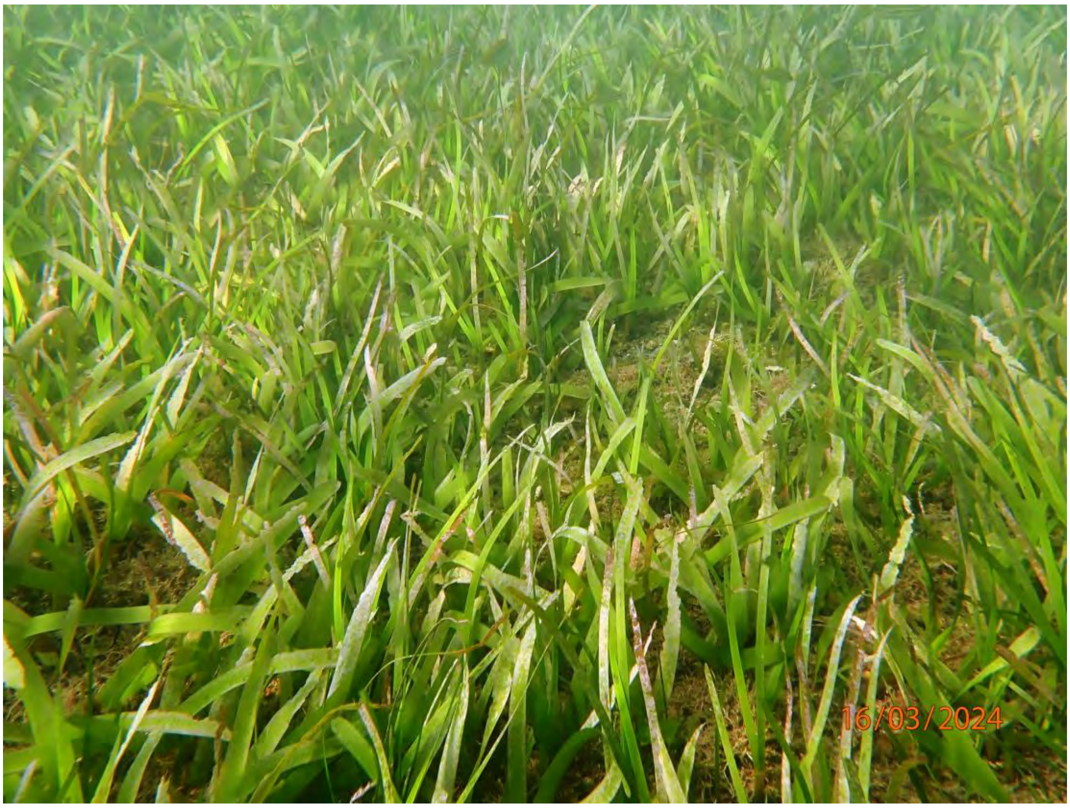


Fig.6: ***Oceana serrulata***

***Thalassia hemprichii* (Fig. 7)**

Kingdom: Plantae
Division: Tracheophyta
Subdivision: Spermatophytina
Class: Magnoliopsida
Order: Alismatales
Family: Hydrocharitaceae
Genus: *Thalassia*
Species: *Thalassia hemprichii*

Morphology

Short black bars of tannin cells in leaf blade; thick rhizome with scars between shoots; hooked/curved leaves; leaves 10-40 cm long; common on shallow reef flats.

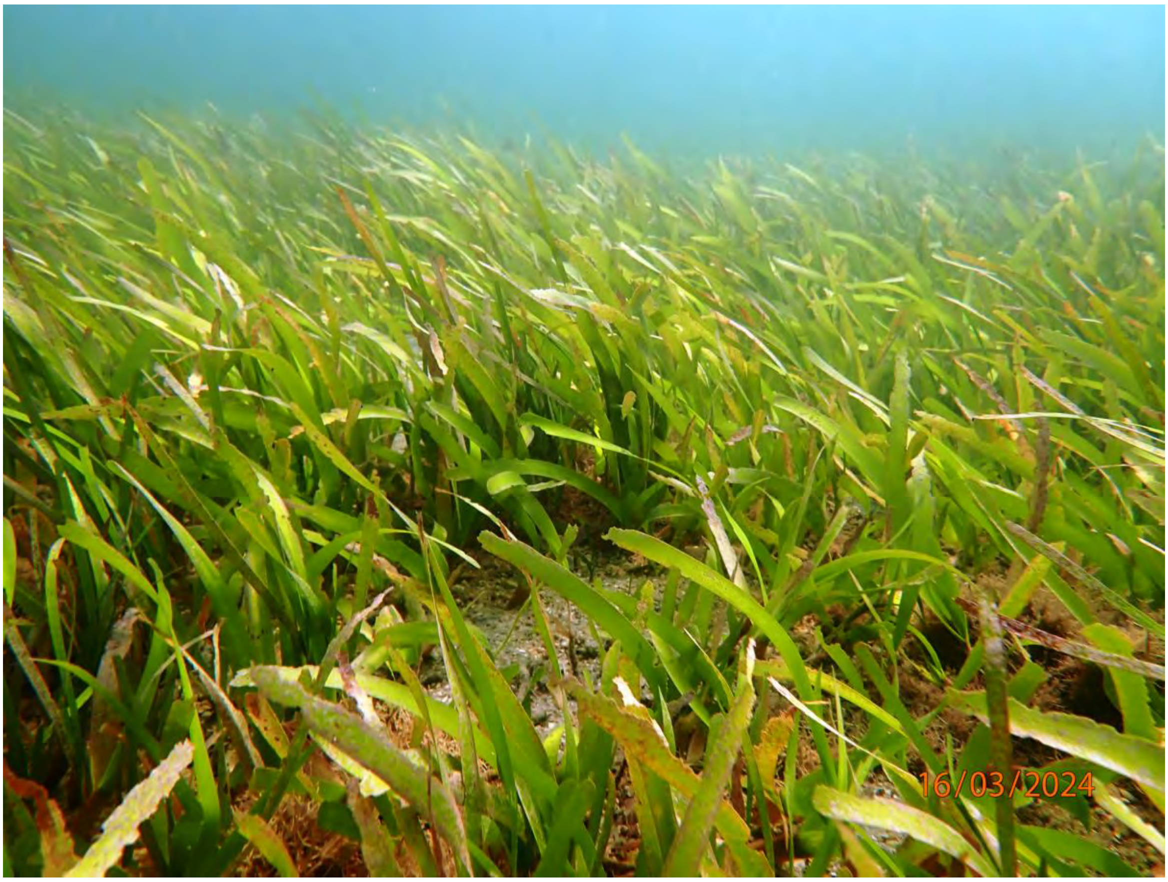


Fig.7: *Thalassia hemprichii*

***Syringodium isoetifolium* (Fig. 8)**

Kingdom: Plantae
Division: Tracheophyta
Subdivision: Spermatophytina
Class: Magnoliopsida
Order: Alismatales
Family: Cymodoceaceae
Genus: *Syringodium*
Species: *Syringodium isoetifolium*

Morphology

Cylindrical in cross section (spaghetti like); leaf tip tapers to a point; leaves 7-30 cm long; found on shallow subtidal reef flats and sand banks.

Fig.8: *Syringodium isoetifolium*

***Halodule uninervis* (Fig. 9)**

Kingdom: Plantae
Division: Tracheophyta
Subdivision: Spermatophytina
Class: Magnoliopsida
Order: Alismatales
Family: Cymodoceaceae
Genus: *Halodule*
Species: *Halodule uninervis*

<u>Morphology</u>

Usually larger than *Halodule pinifolia*; trident leaf tip; 1 central longitudinal vein; rhizome usually pale ivory, with clean black leaf scars; dugong preferred food; found on shallow/intertidal sand or mud banks.

Fig.9: *Halodule uninervis*

3.4. Benthic community structure in the selected sites

Restoration Site 1

Live coral cover was absent in the seagrass restoration site. Low occurrence of seagrass cover was observed with 0.52%. Among the benthic categories, abiotic factors namely sand and silt made the predominant part on the sea floor with 87.93%. The other benthic categories were: Soft corals, 0.0%; DCA, 0.58%; algae, 4.11%; and Others, 6.86% (Fig. 10).

Restoration Site 2

Live coral cover and soft coral communities were not observed in the restoration site and relatively low coverage of seagrass was found with 0.28%. Among the benthic categories, abiotic was the dominant component with 88.11% comprising silt, clay and sand followed by others with 7.11%. Low abundance of algae was found in this site with 3.85% (Fig. 11).

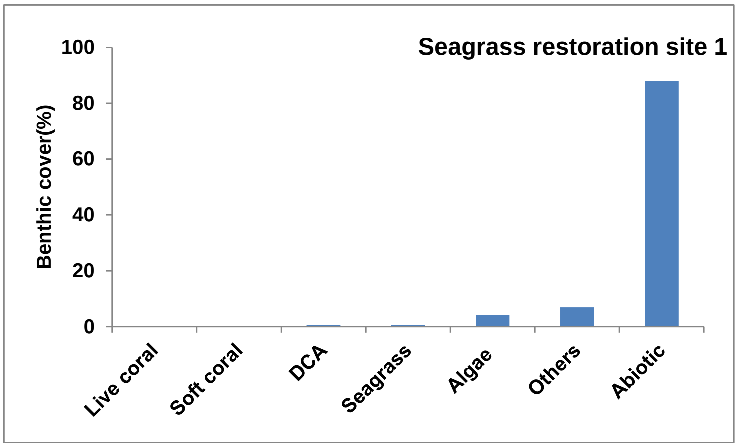


Fig.10: Benthic community structure in the seagrass restoration site 1

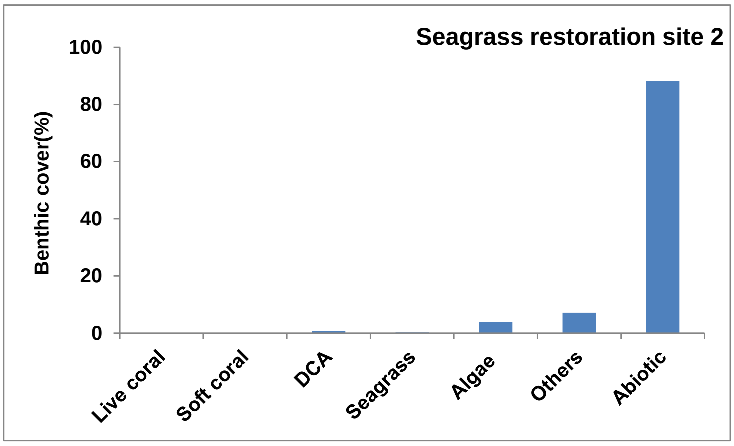


Fig.11: Benthic community structure in the seagrass restoration site 2

Donor site

The donor site is located 3 km away from restoration site and it had no live and soft coral communities. High density of seagrass cover was observed with 70.11%. Other benthic categories were: abiotic, 20.76%; DCA, 0.11%; algae, 4.28%; and Others, 4.78% (Fig. 12).

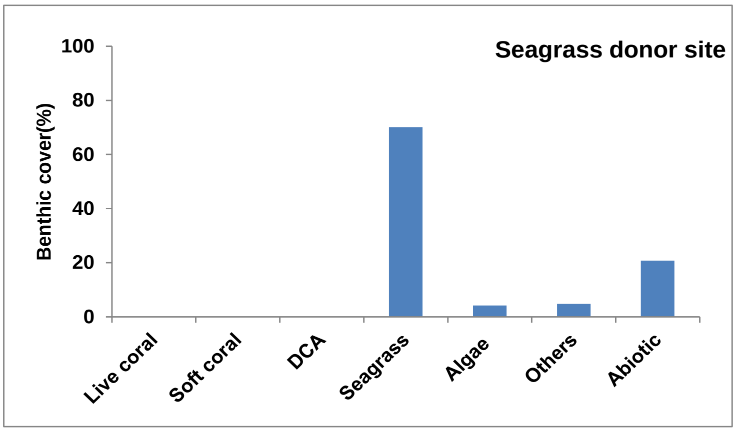


Fig. 12: Benthic community structure in the seagrass donor site

Physico-chemical parameters

Seagrass restoration sites

At site 1, among the physical parameters, water temperature was 29.2 and 29.1°C respectively in surface and bottom waters; salinity was around 35 ppt; EC was 31.2 and 31.0 mS/cm respectively; turbidity was 5.5 and 5.8 NTU respectively; pH was 7.9 and 8.0 respectively; TSS was 85 and 102 mg/l respectively. Among the chemical parameters, DO was 4.9 and 4.8 mg/l respectively; COD was 1.35 and 1.38 mg/l respectively; BOD was 1.6 and 1.6 mg/l respectively; calcium level was 395 and 380 mg/l respectively; magnesium level was 1145 and 1128 mg/l respectively; nitrate level was 1.2 and 1.3 µg/l respectively; nitrite level was 0.39 and 0.95 µg/l respectively; chloride level was 16.8 and 16.8 g/l respectively; oil and grease level was 0.12 and 0.18 mg/l respectively. Sedimentation rate was 28.12 $mg/cm^2/day$.

At site 2, among the physical parameters, water temperature was 29.3 and 29.0°C respectively in surface and bottom waters; salinity was around 35 ppt; EC was 33.0 and 32.0 mS/cm respectively; turbidity was 5.3 and 5.6 NTU respectively; pH was 7.8 and 8.0 respectively; TSS was 92 and 107 mg/l respectively. Among the chemical parameters, DO was 5.1 and 4.9 mg/l respectively; COD was 1.38 and 1.42 mg/l respectively; BOD was 1.8 and 1.9 mg/l respectively; calcium level was 410 and 390 mg/l respectively; magnesium level was 1150 and 1175 mg/l respectively; nitrate level was 1.3 and 1.4 µg/l respectively; nitrite level was 0.42 and 0.81 µg/l respectively; chloride level was 16.6 and 16.7 g/l respectively; oil and grease level was 0.13 and 0.15 mg/l respectively. Sedimentation rate was 30.47 $mg/cm^2/day$.

Donor site

Similarly, at seagrass donor site, among the physical parameters, water temperature was 29.2 and 29.1° C respectively; salinity was around 35 ppt; EC was 32 and 31.0 mS/cm respectively; turbidity was 5.5 and 5.7 NTU respectively; pH was 7.9 and 8.0 respectively; TSS was 88 and 104 mg/l respectively. Among the chemical parameters, DO was 4.8 and 4.8 mg/l respectively; COD was 1.36 and 1.38 mg/l respectively; BOD was 1.7 and 1.6 mg/l respectively; calcium level was 400 and 395 mg/l respectively; magnesium level was 1156 and 1185 mg/l respectively; nitrate level was 1.2 and 1.3 µg/l respectively; nitrite level was 0.36 and 0.34 µg/l respectively; chloride level was 16.5 and 16.4 g/l respectively; oil and grease level was 0.14 and 0.16 mg/l respectively. The details of the physico-chemical parameters in the seagrass restoration and donor sites are given in Table 3.

Table 3: Physical and chemical parameters of seagrass restoration and donor sites

Parameters	Seagrass restoration sites				Donor site	
	Site 1		Site 2			
	Surface	Bottom	Surface	Bottom	Surface	Bottom
Temperature (^{0}C)	29.2	29.1	29.3	29.0	29.2	29.1
Salinity (ppt)	35	35	35	35	35	35
EC (mS/cm)	31.2	31	33	32	32	31
Turbidity (NTU)	5.5	5.8	5.3	5.6	5.5	5.7
pH Value	7.9	8	7.8	8	7.9	8
TSS (mg/l)	85	102	92	107	88	104
Sedimentation (mg/cm^2/day)	28.12		30.47		29.5	
DO (Dissolved oxygen)	4.9	4.8	5.1	4.9	4.8	4.8
COD (mg/l)	1.35	1.38	1.38	1.42	1.36	1.38
BOD (mg/l)	1.6	1.6	1.8	1.9	1.7	1.6
Calcium (mg/l)	395	380	410	390	400	395
Magnesium (mg/l)	1145	1128	1150	1175	1156	1185
Nitrates (µg/l)	1.2	1.3	1.3	1.4	1.2	1.3
Nitrites (µg/l)	0.39	0.95	0.42	0.81	0.36	0.34
Chloride (g/l)	16.8	16.8	16.6	16.7	16.5	16.4
Oil & grease (mg/l)	0.12	0.18	0.13	0.15	0.14	0.16

3.5. Transplantation of seagrasses

Restoration of seagrasses was carried out during 15.05.2024 to 05.07.2024 (Phase - I) and during 23.10.2024 to 07.11.2024 (Phase - II) covering 2,000 sq.m area near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park.

The seagrass restoration work was delayed between the phases due to the elevated sea surface temperature, rough climatic conditions, turbulence and poor underwater visibility. The entire seagrass restoration work near the Koswari Island was supervised by the Forest Staff of Tuticorin Wildlife Range. Four seagrass species namely *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis* were used for restoration in Koswari Island. *Oceana serrulata, Thalassia hemprichii,* and *Syringodium isoetifolium* are the most abundant seagrass species in the Gulf of Mannar (Mathews et al. 2010; Edward et al. 2019) followed by *Halodule uninervis* and hence were used for restoration. By using the above species, the less abundant ones are left undisturbed. And, these four species have been proven to be highly successful for the adopted restoration method (Edward et al. 2019). Approximately, the percentage composition of *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium and Halodule uninervis* in the Gulf of Mannar is 40, 20, 20 and 5% respectively. In this project, the composition of the transplanted seagrass species are 45% by *Oceana serrulata*, 20% by *Thalassia hemprichii* and 30% by *Syringodium isoetifolium* and 5% by *Halodule uninervis*. All selected seagrass species reproduce both sexually and asexually. They reproduce sexually through underwater pollination, and asexually through rhizomes. However, there are no studies on seagrass reproduction in the Gulf of Mannar or Palk Bay, or even for any seagrass area in India. We did not record any flowering and seeding of seagrasses at donor sites during collection and nor in the restoration sites after the transplantation during the project timeline.

In manual seagrass transplantation method, an apical shoot with intact roots is attached at a regular interval to a biodegradable jute twine, and the twine is tied to a 1 X 1 m PVC quadrat. A minimum of six rows of jute twines are tied firmly with each quadrat with a minimum of 20 shoots per twine. The quadrats and jute twines help in keeping the shoots intact and also safe from being washed away by the waves, tides and current. PVC frames are pre-drilled to make them negatively buoyant by taking seawater in. After taking these quadrats with seagrass transplants under the water, divers place them at the restoration site and nail them firmly using hook-shaped iron rods. It is made sure that the seagrass roots are in contact with the bottom and that disturbance from waves, tides, and currents is minimized. The PVC frames are left in place until the shoots are firmly rooted to the sediments and it is ensured that all the sprigs maintain contact with the seafloor. Altogether 2,000 PVC frames (1 X 1 m) were constructed. Long pipes were cut into desirable size to make 1 X 1 m frame. Initial work was done at the laboratory in Tuticorin and the final fabrication was done in the field. Using SCUBA diving, restoration was conducted in seven blocks within 1 acre of degraded seagrass areas in the two selected sites. Block 1 (site 1) consists of 200 frames while blocks 2-7 consist of 300 each. Block 1 is located slightly far from Koswari Island at a distance of 3 km, whereas blocks 2 to 7 (site 2) lie close to Island within 1 km. Each block consists of 4-8 nos. of clusters with each cluster separated with a distance of about 30 to 40 meters.

Out of the 2,000 PVC frames, 1,055 PVC frames of 1 x 1 m were used to restore 1,055 sq.m area i.e. completion of over 50% of seagrass restoration work during the period 15.05.2024 to 05.07.2024. The deployment of the remaining 945 PVC frames of 1x1 m for restoring 945 sq.m area was completed during the period 23.10.2024 to 07.11.2024.

Construction of PVC frames

Long PVC pipes were cut into desirable size to make 1 X 1 m frame. A total of 2,000 PVC frames (1 X 1 m) were fabricated. Initial work was done at the laboratory in Tuticorin and the final fabrication was completed in the field (Fig.13 & 14).

Fig.13: Construction of PVC frames in the field

Fig.14: Construction of PVC frames in the field

Seagrass collection from dense donor sites for transplantation

Four seagrass species (*Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis*) were collected from the nearby healthy and dense donor seagrass beds. Due care was taken not to disturb the donor seagrass beds and also not to waste seagrass shoots (Figs.15- 18).

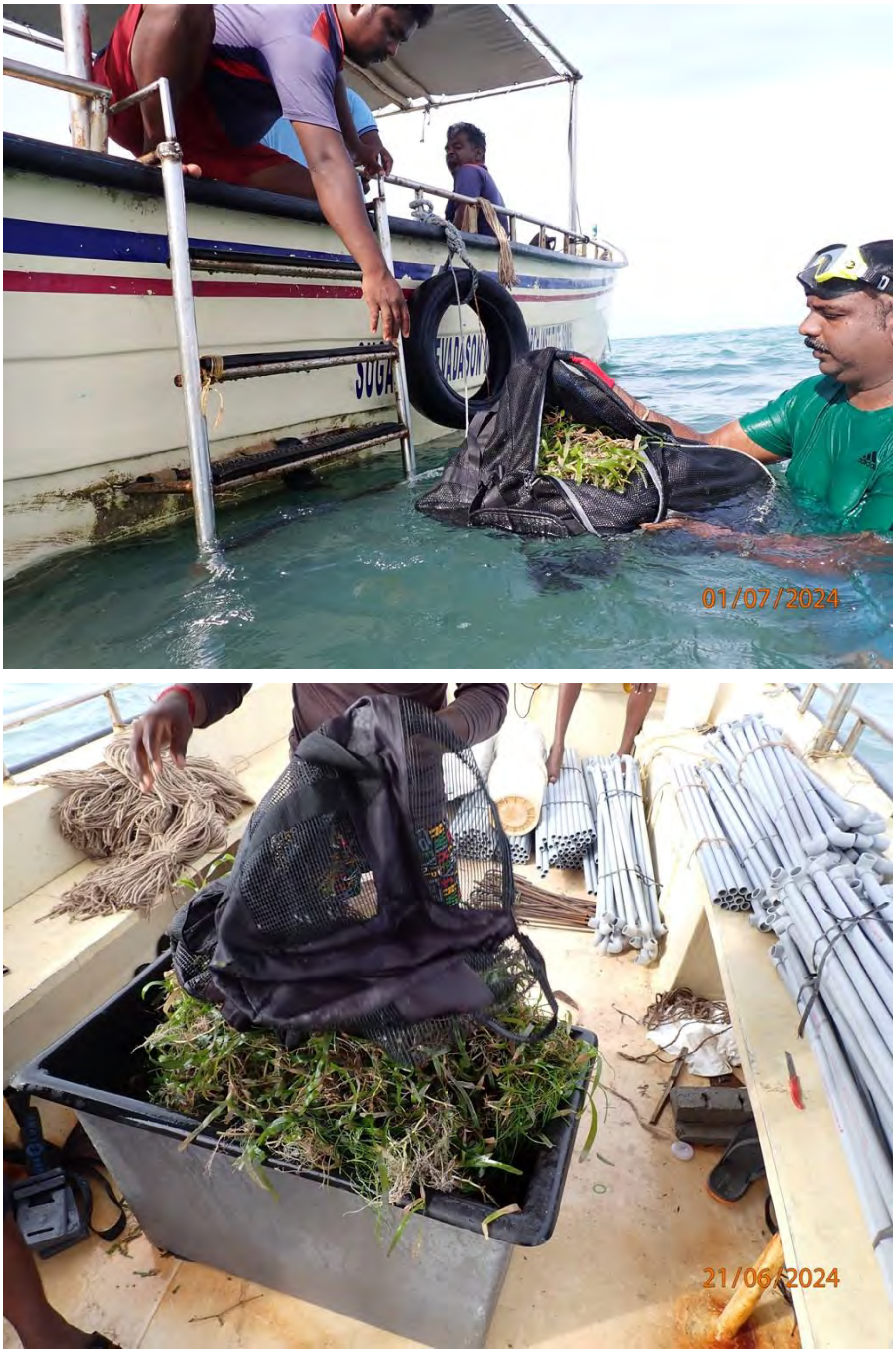


Fig.15: Seagrass shoots collected from donor site for transplantation

Fig.16: Seagrass shoots collected from donor site for transplantation

Fig.17: Seagrass shoots collected from donor site for transplantation

Fig.18: Seagrass shoots collected from donor site for transplantation

Transplantation of seagrass shoots on PVC frames

The collected seagrass shoots were sprayed with seawater and then were tied in jute rope. The jute rope tied with shoots was tied to the frames. In each frame, a minimum of six rows of jute ropes with shoots were tied. In each row, a minimum of 20 shoots were tied (Figs.19-24).

Fig.19: Jute rope used for tying seagrass shoots

Fig.20: Seagrass shoots tied in jute rope

Fig.21: Seagrass shoots tied in jute rope

Fig.22: Transplantation of seagrass shoots on PVC frames using jute rope

Fig.23: Transplantation of seagrass shoots on PVC frames using jute rope

Fig.24: Transplantation of seagrass shoots on PVC frames using jute rope

Transferring PVC frames tied with seagrass shoots to restoration site

The PVC frames tied with seagrass shoots using jute rope were taken to restoration site using boat (Figs.25-28).

Fig.25: Transferring PVC frames tied with seagrass shoots to restoration site

Fig.26: Transferring PVC frames tied with seagrass shoots to restoration site

ig.27: Transferring PVC frames tied with seagrass shoots to restoration site

Fig.28: Transferring PVC frames tied with seagrass shoots to restoration site

Fixing of transplanted frames with seagrass shoots on the sea floor

The PVC frames tied with seagrass shoots were fixed on the seafloor in seven blocks using long (1.5 ft) iron nails. Each bock consists of number of clusters varying between 4 and 8 nos. and in each cluster, the number of frames varied according to the bottom topography. The fixing was done by SCUBA divers (Tables 4 & 5; Figs.29-32).

Block 1 consists of 200 frames while blocks 2-7 consist of 300 each. Block 1 is located slightly far from Koswari Island with a distance of 3 km, whereas blocks 2 to 7 lie close to Island (within 1 km). Four native seagrass species were selected for transplantation which include *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis.* The percentage contribution of the transplanted seagrass species are 45% by *Oceana serrulata*, 20% by *Thalassia hemprichii* and 30% by *Syringodium isoetifolium* and 5% by *Halodule uninervis* (Table 6).

Table 4: Details of seven blocks with GPS coordinates depth and direction from Koswari Island

			GPS coordinates	
Koswari Island	**Direction from Koswari Island**	**Depth**	Latitude	Longitude
Block-1	North	5.0 m	8°54'12.33"N	78°12'56.27"E
Block-2	North east	3.0 m	8°52'37.96"N	78°13'23.43"E
Block-3	North east	3.0 m	8°52'37.13"N	78°13'26.31"E
Block-4	North east	3.0 m	8°52'35.37"N	78°13'27.82"E
Block-5	North east	4.5 m	8°52'33.84"N	78°13'30.19"E
Block-6	North east	4.5 m	8°52'32.07"N	78°13'32.97"E
Block-7	North east	4.5 m	8°52'30.52"N	78°13'35.39"E

Table 5: Details of clusters with no. of frames

Block No.	Cluster No.	No. of frames deployed
Block 1	Cluster 1	50
	Cluster 2	50
	Cluster 3	60
	Cluster 4	60
Block 2	Cluster 5	65
	Cluster 6	35
	Cluster 7	36
	Cluster 8	40
	Cluster 9	35
	Cluster 10	40
	Cluster 11	29
	Cluster 12	50
Block 3	Cluster 13	62
	Cluster 14	50
	Cluster 15	26
	Cluster 16	51
	Cluster 17	50
	Cluster 18	65
Block 4	Cluster 19	36
	Cluster 20	35
	Cluster 21	40
	Cluster 22	35
	Cluster 23	55
	Cluster 24	40
Block 5	Cluster 25	50
	Cluster 26	45
	Cluster 27	55
	Cluster 28	40
	Cluster 29	55
	Cluster 30	65
	Cluster 31	40
Block 6	Cluster 32	45
	Cluster 33	30
	Cluster 34	35
	Cluster 35	30
	Cluster 36	35
	Cluster 37	45
	Cluster 38	40
Block 7	Cluster 39	50
	Cluster 40	40
	Cluster 41	38

	Cluster 42	45
	Cluster 43	40
	Cluster 44	40
	Cluster 45	42
	Total =	2000

Table 6: Percentage composition of transplanted seagrass species in Koswari Island

Seagrass species	**Species % composition**
Oceana serrulata	45%
Thalassia hemprichii	20%
Syringodium isoetifolium	30%
Halodule uninervis	5%

Fig.29: Fixed transplanted PVC frames with seagrass shoots on the sea floor

Fig.30: Fixed transplanted PVC frames with seagrass shoots on the sea floor

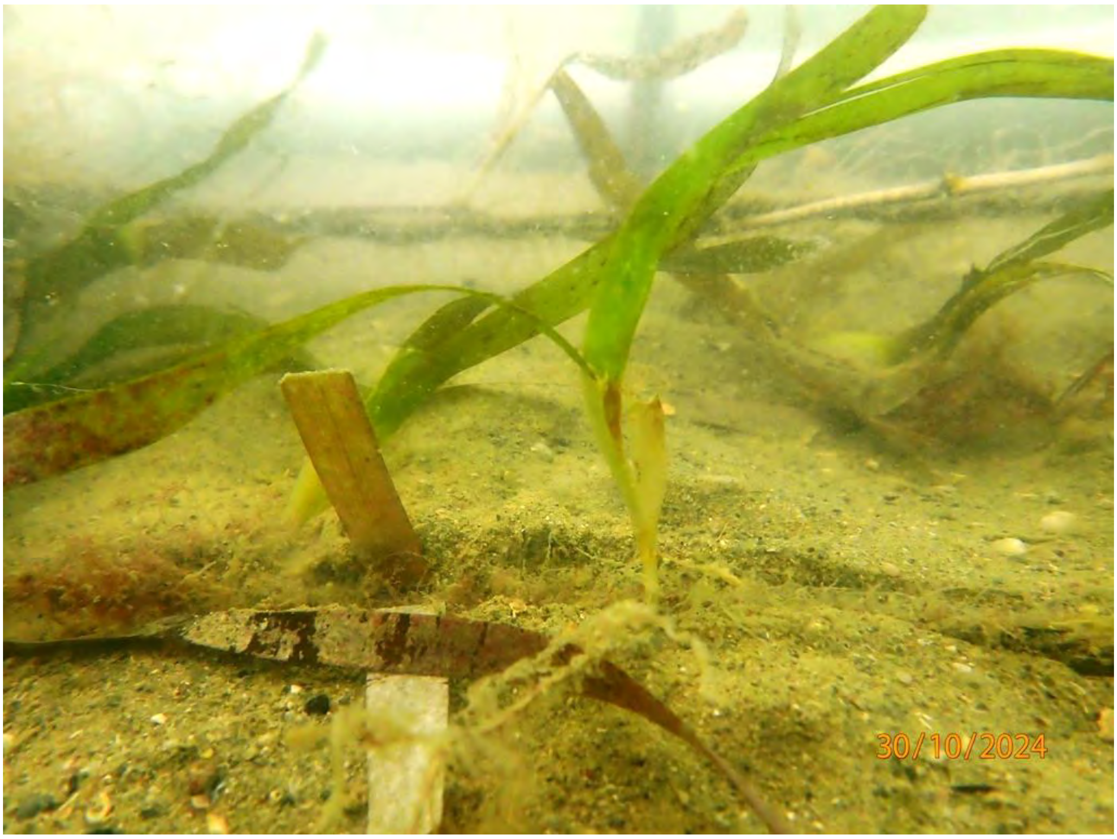


Fig.31: Fixed transplanted PVC frames with seagrass shoots on the seafloor

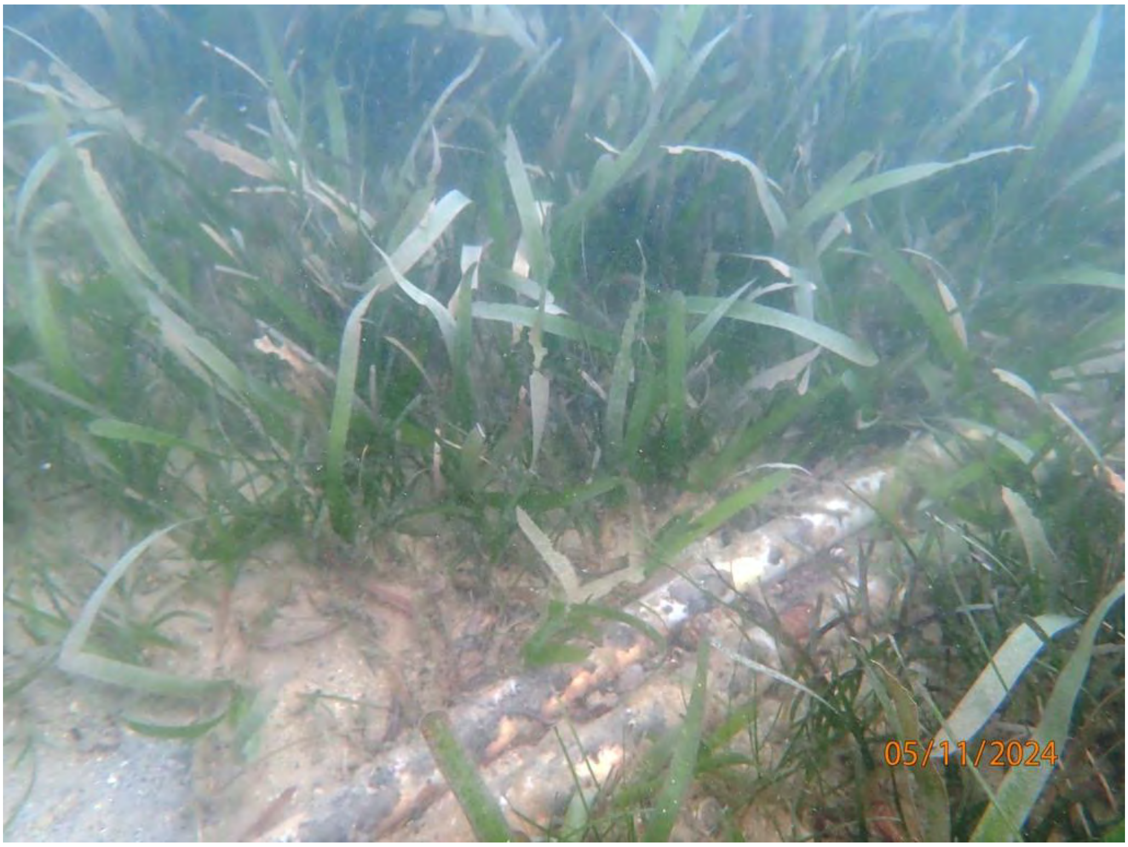


Fig.32: Well established seagrass shoots transplanted during Phase 1 period

4. Monitoring and maintenance

4.1. Fixing of monitoring stations and monitoring methods

Monitoring and maintenance was started immediately after the completion of the first phase of restoration done during July 2024 upto February 2025. Four permanent monitoring stations were fixed within the two restoration sites and marked with GPS. Stations 1 to 3 were fixed in the restoration site 2 and station 4 was fixed in restoration site 1 (Table 7; Fig. 29). Collection of data on percentage cover, shoot density, associated biodiversity and environmental parameters was carried out monthly from July 2024 to February 2025. A total of three permanent transects (100 m) were laid at each site perpendicular to the island shore. Along each transect, 10 quadrats (50 cm × 5 cm) were laid at a distance of 10 m for regular monitoring (English et al., 1997). The percentage cover of seagrasses and the percentage cover of each species and shoot density were assessed every month following Saito and Atobe (1970). To assess the increase in associated biodiversity, density of the macrofaunal categories such as echinoderms, molluscs, ascidians, sponges and sea anemones was estimated using five 1 m × 1 m quadrats. Fish density and diversity were also assessed by applying the belt transect method (English et al., 1997). The mandatory initial maintenance measure of removing the solid wastes, torn pieces of nets and seaweeds were performed. The PVC quadrats were removed once the shoots were firmly attached. In addition, PVC quadrats displaced due to disturbance caused by fishing activities were replaced as and when required during monitoring.

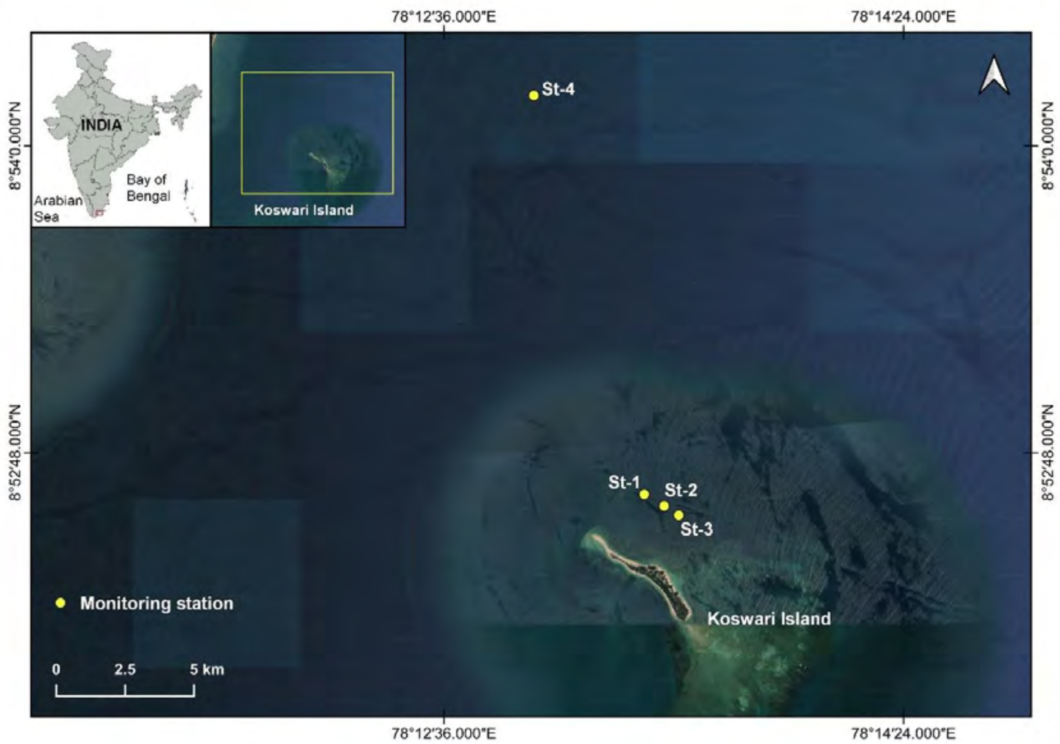


Fig. 33: Map showing the permanent monitoring stations within the restoration stations

Table 7: Details of permanent monitoring stations

Station Id	Location	Latitude	Longitude
St-1	Site 2	8°52'38.17"N	78°13'23.05"E
St-2		8°52'35.48"N	78°13'27.73"E
St-3		8°52'33.30"N	78°13'31.16"E
St-4	Site 1	8°54'11.82"N	78°12'57.12"E

4.2. Assessment of environmental parameters

Environmental parameters were assessed from restoration site 1 (representing blocks 2 to 7 and stations 1 to 3) and restoration site 2 (representing block 1 and station 4) by collecting water and sediment samples monthly from July 2024 to February 2025. Parameters assessed included seawater temperature, salinity, EC, pH, turbidity, Total Suspended Solids (TSS), dissolved Oxygen (DO), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), calcium, magnesium, nitrites, nitrates, total phosphates, silicates, chlorides, sediment pH, sedimentation, sedimentation texture, organic matter and oil & grease. In water samples, seawater temperature was measured using a standard mercury thermometer (-400 - 3000 C) according to Hagart-Alexander (2010). Salinity was determined by a Handheld Refractometer (ATAGO, 0~100‰) according to Woody et al. (2000). The electrical conductivity of sediment samples was determined using digital electrical conductivity meter (Hanna hand EC meter). The seawater pH was measured soon after collection by using pre-calibrated Hanna's pH tester (0.0 to 14.0) according to Khoo et al. (1977). Turbidity was analyzed by Turbidity meter (LUTRON TU-2016) in accordance with IS: 3025 (Part 10) - Reaffirmed 2002. The TSS was estimated by filtration method (APHA , 1998) by filtering a known volume of sample through a pre-weighed 0.45µ Whatman glass fibre filter paper (GF/C) using a Millipore filtering system. The modified Winkler's method described by Strickland and Parsons (1972) was adopted for the estimation of DO, BOD and COD. Calcium and magnesium were determined by titration with ethylene diamine tetra acetate by following Tucker and Kurtz (1961). Nitrites (NO_2) were measured by the Bendschneider and Robinson method as outlined in Grasshoff and Koroleff (1983). Nitrates (NO3) were analyzed by adopting the method of Grasshoff and Koroleff (1983). Total phosphates (PO4) were estimated by the method of Murphy and Riley as outlined in Grasshoff and Koroleff (1983). Silicates were estimated by adopting the method of Strickland and Parson (1972). Oil and grease contents in water samples were analyzed according to APHA (2012). In the sediment samples, pH was determined using pH meter as described by Jackson (1958). Organic matter in the sediment samples was analysed using Loss on Ignition method according to Heiri et al. (2001). Sediment textural analysis was performed in the laboratory using the sieving and pipetting method following Ingram (1970). The sedimentation rate was assessed using sediment traps (English et al., 1997). The collected samples were dried at 70◦ C and weighed to get sedimentation rate. Sedimentation rate was calculated as mg of sediment per cm^2 per day.

4.3. Seagrass cover and shoot density in the restored area

Seagrass cover in the restoration area kept on increasing gradually after the transplantation as the average seagrass cover increased from 20.8 in July 2024 to 33.8% in February 2025 (Fig. 34). Among the four species transplanted, the average cover of *Oceana serrulata* increased from 7.9 to 11.8%; the cover of *Thalassia hemprichii* increased from 6.2 to 9.6%; the cover of *Syringodium isoetifolium* increased from 5.9 to 10.1%; and the cover of *Halodule uninervis* increased from 0.8 to 2.4% during the study period (Fig. 35). Likewise, the average shoot density of seagrasses also increased at the restoration area gradually from 67.5 to 124.2 no.m^{-2} between July 2024 and February 2025 (Fig. 36). Among the four species, shoot density of *Oceana serrulata* increased from 23.5 to 41.7 no.m^{-2}; for *Thalassia hemprichii* it increased from 17.6 to 31.3 no.m^{-2}, for *Syringodium isoetifolium* it increased from 18.9 to 37.6 no.m^{-2} and for *Halodule uninervis* it increased from 7.5 to 13.7 no.m^{-2} (Fig. 37).

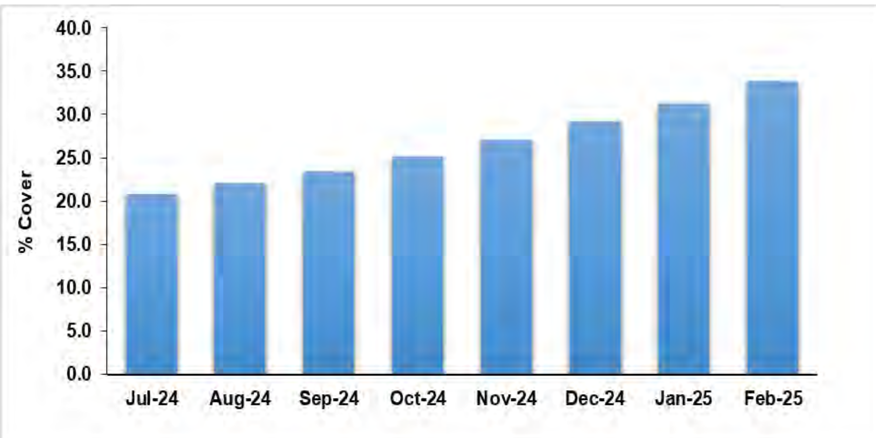


Fig. 34: Average seagrass cover in the restored area during the study period

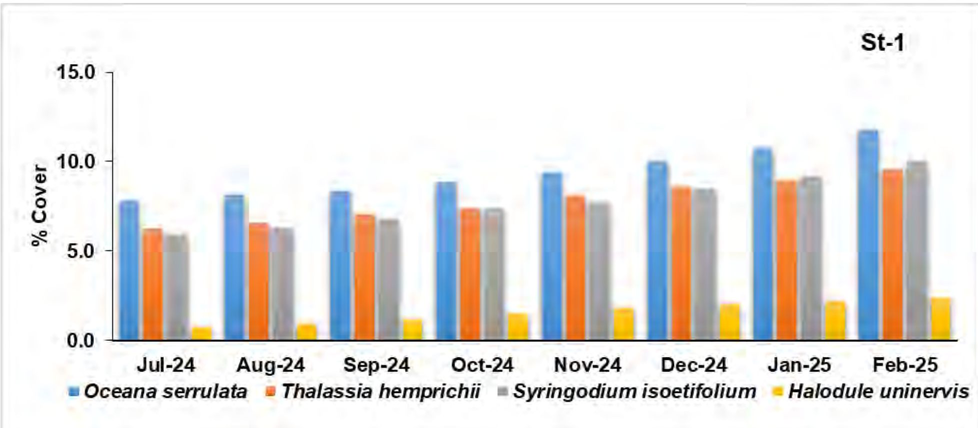


Fig. 35: Species-wise seagrass cover in the restored area during the study period

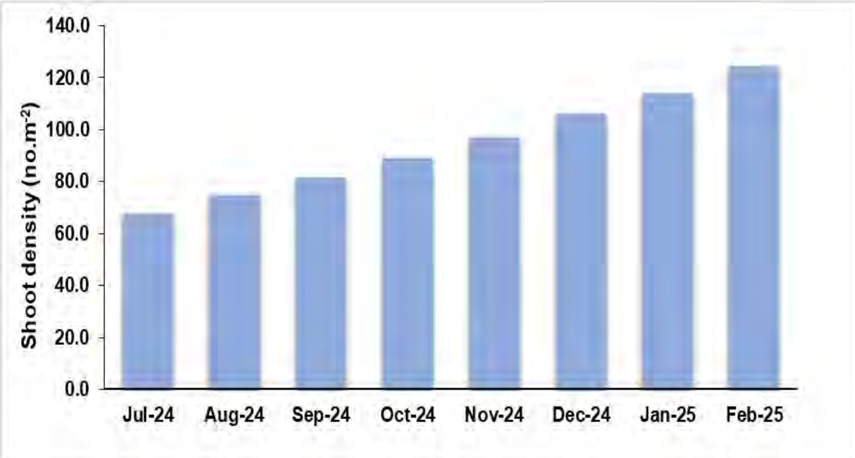


Fig. 36: Average seagrass shoot density in the restored area during the study period

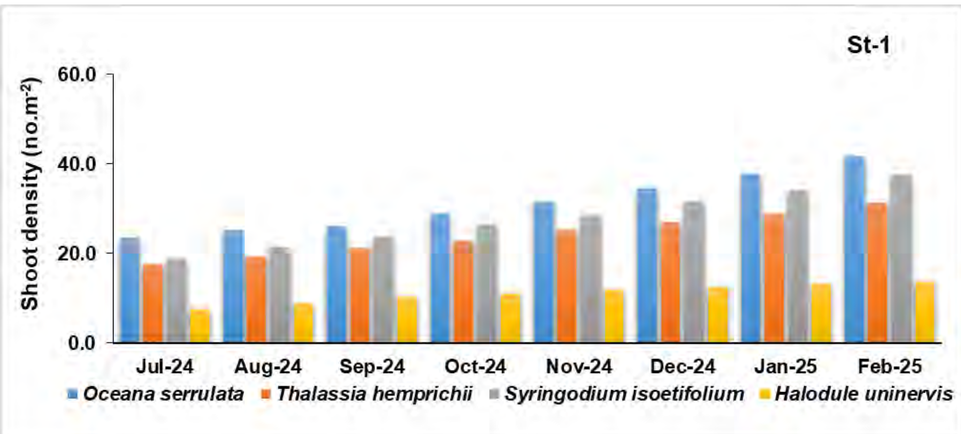


Fig. 37: Species-wise seagrass shoot density in the restored area during the study period

<u>Station 1</u>

At Station 1, the overall seagrass cover increased from 18.9 to 36.8% between July 2024 and February 2025. The cover of *Oceana serrulata* increased from 7.3 to 13.2%; the cover of *Thalassia hemprichii* increased from 5.8 to 10.5%; the cover of *Syringodium isoetifolium* increased from 4.9 to 10.8%; and the cover of *Halodule uninervis* increased from 0.9 to 2.3% during the study period (Fig. 38). The overall seagrass shoot density increased from 54.3 to 105 no.m^{-2} from July 2024 to February 2025. Shoot densities of *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis* increased from 21.8 to 39.4, 15.2 to 27.5, 17.3 to 34.2 and 8.6 to 14.2 no.m^{-2} respectively during the study period (Fig. 39).

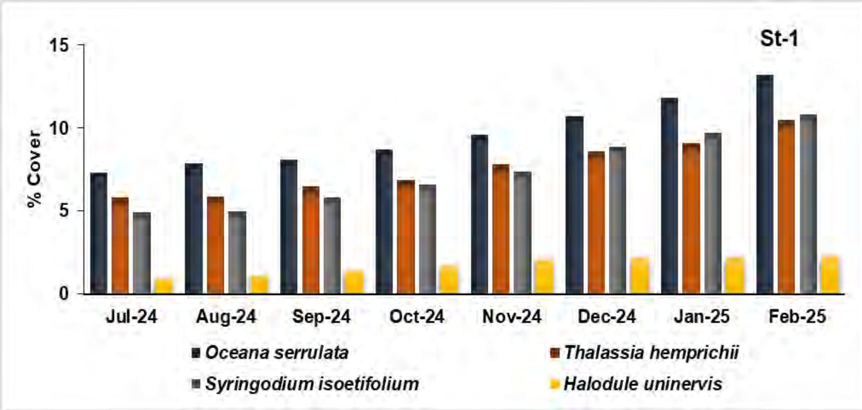


Fig. 38: Seagrass cover at station 1 during the study period

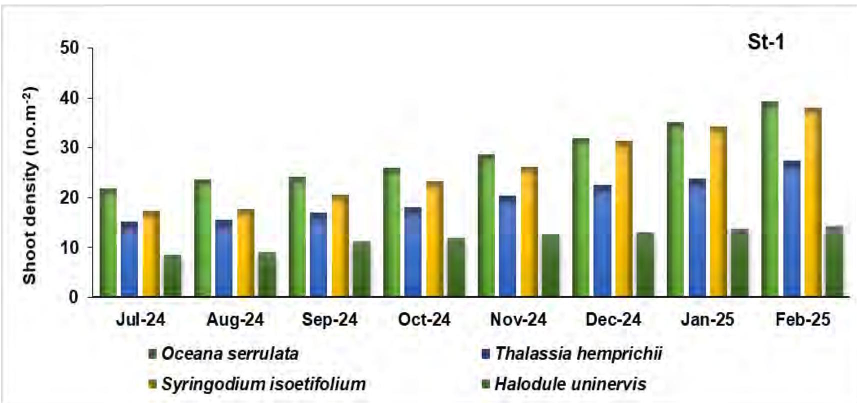


Fig. 39: Seagrass shoot density at station 1 during the study period

Station 2

At station 2, the overall seagrass cover increased from 21.4 to 32.8% between July 2024 and February 2025. The cover of *Oceana serrulata* increased from 8.6 to 11.2%; the cover of *Thalassia hemprichii* increased from 6.2 to 9.1%; the cover of *Syringodium isoetifolium* increased from 5.9 to 8.8% and the cover of *Halodule uninervis* increased from 0.7 to 2.9% during the study period (Fig. 40). The overall seagrass shoot density increased from 69 to 128.7 no.m^{-2} from July 2024 to February 2025. Shoot densities of *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis* increased from 23.7 to 41.3, 19.5 to 34.5, 18.7 to 37.8 and 7.1 to 15.1 no.m^{-2} respectively during the study period (Fig. 41).

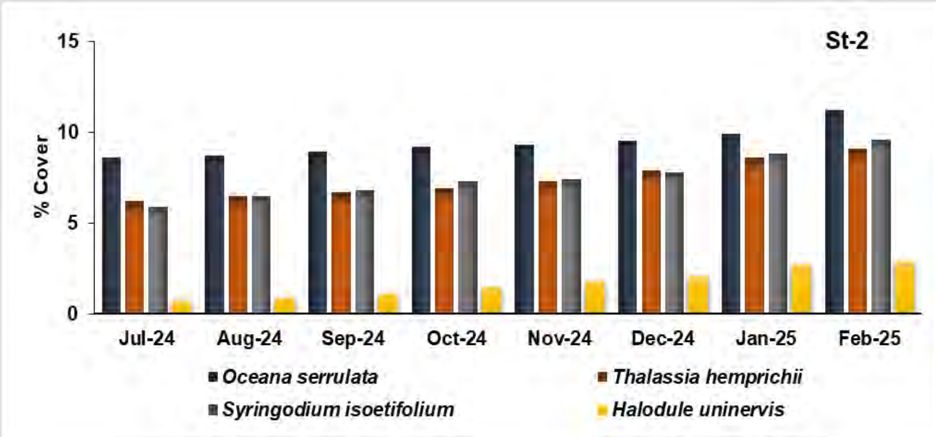


Fig. 40: Seagrass cover at station 2 during the study period

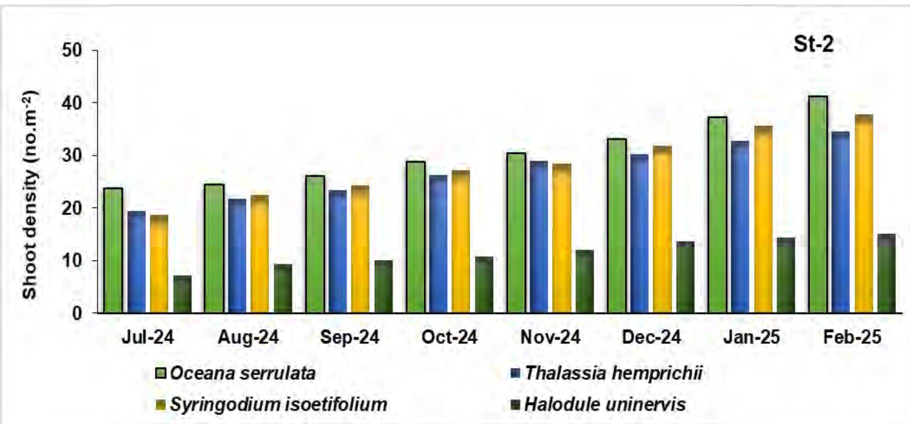


Fig. 41: Seagrass shoot density at station 2 during the study period

Station 3

At station 3, the overall seagrass cover increased from 21.5 to 31.8% between July 2024 and February 2025. The cover of *Oceana serrulata* increased from 7.6 to 11.1%; the cover of *Thalassia hemprichii* increased from 6.2 to 8.9%; the cover of *Syringodium isoetifolium* increased from 7.1 to 9.8%; and the cover of *Halodule uninervis* increased from 0.6 to 2% during the study period (Fig. 42). The overall seagrass shoot density increased from 66 to 119.1 no.m^{-2} from July 2024 to February 2025. Shoot densities of *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis* increased from 22.8 to 42.2, 17.5 to 30.6, 20.1 to 35.2and 5.6 to 11.1 no.m^{-2} respectively during the study period (Fig. 43).

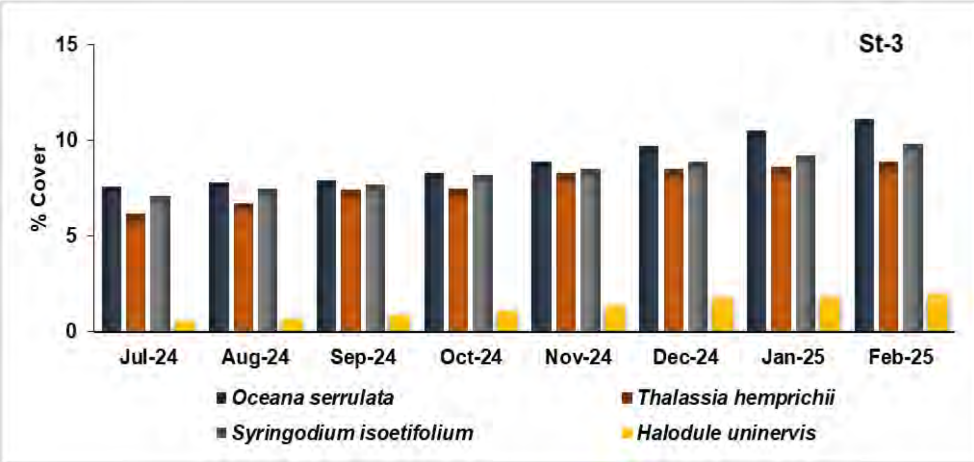


Fig. 42: Seagrass cover at station 3 during the study period

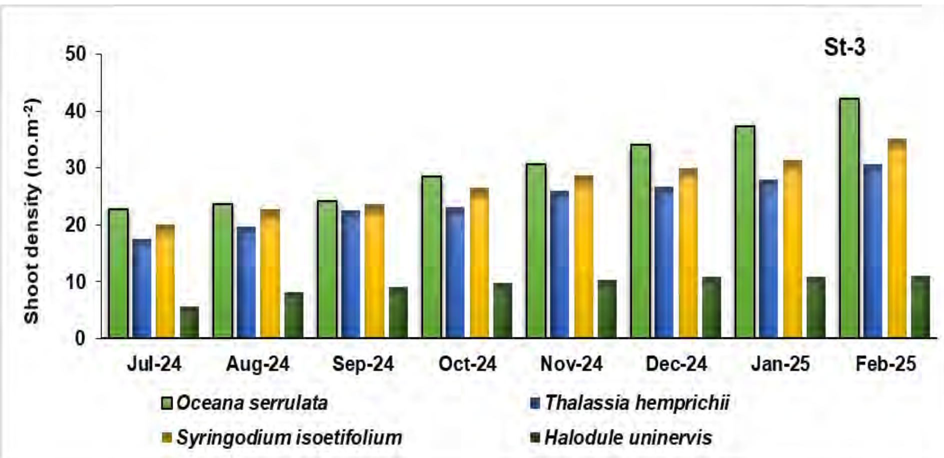


Fig. 43: Seagrass shoot density at station 3 during the study period

<u>Station 4</u>

At station 4, the overall seagrass cover increased from 21.3 to 33.8% between July 2024 and February 2025. The cover of *Oceana serrulata* increased from 7.9 to 11.6%; the cover of *Thalassia hemprichii* increased from 6.7 to 9.8%; the cover of *Syringodium isoetifolium* increased from 5.8 to 10.1%; and the cover of *Halodule uninervis* increased from 0.9 to 2.3% during the study period (Fig. 44). The overall seagrass shoot density increased from 71.9 to 129.7 no.m^{-2} from July 2024 to February 2025. Shoot densities of *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis* increased from 25.5 to 43.7, 18.3 to 32.6, 19.5 to 39.2 and 8.6 to 14.2 no.m^{-2} respectively during the study period (Fig. 45).

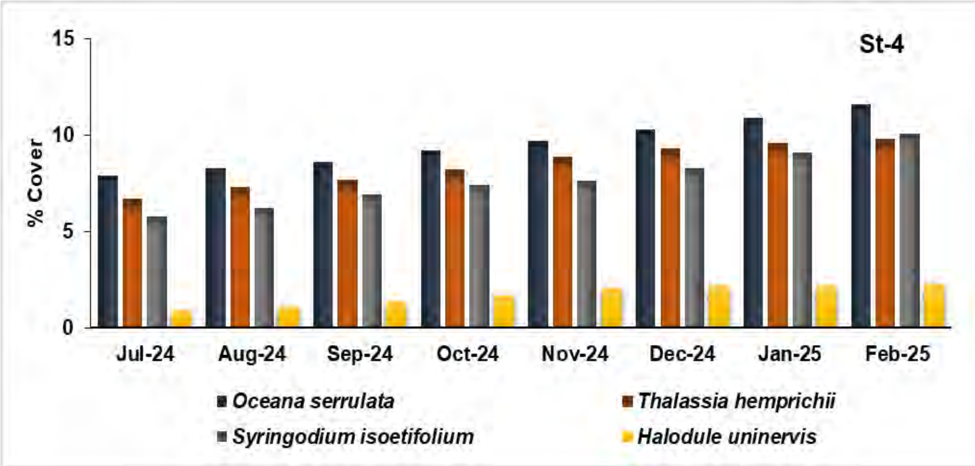


Fig. 44: Seagrass cover at station 4 during the study period

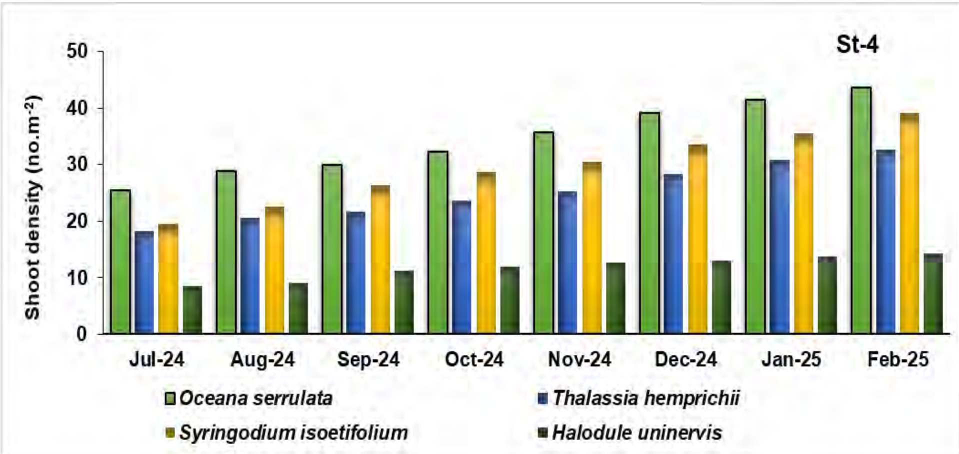


Fig. 45: Seagrass shoot density at station 4 during the study period

4.4. Seagrass-associated fish in the restored area

The density of fish in the restored area increased gradually from July 2024 to February 2025 as the seagrass cover increased. The overall density of fish increased from 10.5 to 42.4 no.250^{-1} during the study period (Fig. 46). The most common fish species in the restored area include *Eubleekeria splendens*, *Parupeneus indicus, Scarus* sp., and *Siganus canaliculatus.*

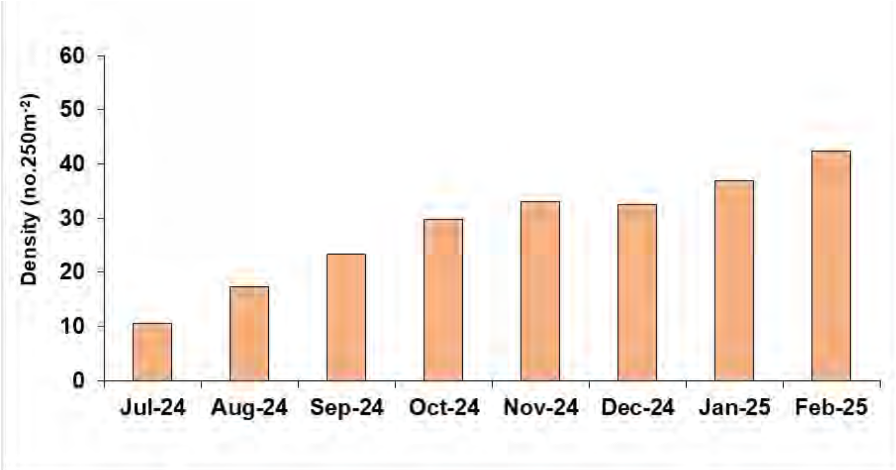


Fig. 46: Overall fish density in the restored area during the study period

Station 1

A total of 15 fish species were recorded at station 1 during the study period and the overall density of fish increased from 7.8 to 35.6 no.250^{-1} from July 2024 to February 2025 (Fig. 47; Table 8). The most common fish species include *Eubleekeria splendens*, *Parupeneus indicus, Terapon puta* and *Siganus canaliculatus*.

Fig. 47: Fish density at station 1 during the study period

Station 2

A total of 18 fish species were recorded at station 2 during the study period and the overall density of fish increased from 11.1 to 42 no.250^{-1} from July 2024 to February 2025 (Fig. 48; Table 9). The most common fish species include *Eubleekeria splendens*, *Parupeneus indicus, Siganus canaliculatus* and *Terapon puta*.

Fig. 48: Fish density at station 2 during the study period

<u>Station 3</u>

A total of 15 fish species were recorded at station 3 during the study period and the overall density of fish increased from 10.5 to 40.9 no.250^{-1} from July 2024 to February 2025 (Fig. 49; Table 10). The most common fish species include *Eubleekeria splendens*, *Parupeneus indicus, Siganus canaliculatus* and *Terapon puta*.

Fig. 49: Fish density at station 3 during the study period

<u>Station 4</u>

A total of 15 fish species were recorded at station 4 during the study period and the overall density of fish increased from 10.5 to 40.9 no.250^{-1} from July 2024 to February 2025 (Fig. 50; Table 11). The most common fish species include *Eubleekeria splendens*, *Scarus* sp., and *Siganus canaliculatus*.

Fig. 50: Fish density at station 4 during the study period

Table 8: Densities of fish species observed at station 1 during the study period (no.250^{-1})

Species	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
Sardinella sp.	0	0	0	0	3.5	2.6	2.8	0
Parupeneus indicus	2.2	1.8	2.3	2.8	2.5	2.8	3.5	5.2
Upeneus sulphurens	1.2	1.1	1.3	1.8	1.6	1.8	1.9	2.6
Halichoeres sp.	0	0	0	1.2	1.5	1.2	1.4	1.2
Lactoria cornuta	0	0	0	0	0	1.1	1.6	1.3
Lethrinus sp.	1.2	1.5	1.8	2.2	3.5	2.6	2.9	0
Lutjanus sp.	0	2.2	2.4	2.1	1.5	1.4	1.6	1.9
Plotosus lineatus	0	0	0	0	0	0	3.5	0
Mugil cephalus	0	0	0	1.2	0	1.6	1.2	2.3
Eubleekeria splendens	3.2	3.5	5.2	4.5	5.6	4.8	5.3	6.5
Scarus sp.	0	0	0	1.5	1.2	2.1	1.8	2.3
Terapon puta	0	1.5	3.2	3.6	2.6	1.5	1.8	3.5
Amphiprion sp.	0	2.3	2.3	2.5	2.3	2.1	2.5	2.5
Siganus canaliculatus	0	1.3	2.3	3.5	3.8	2.6	2.9	3.8
Siganu sjavus	0	0	1.5	1.5	1.8	1.8	1.3	2.5

Table 9: Densities of fish species observed at station 2 during the study period (no.250^{-1})

Species	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
Alepes djedaba	0	0	0	0	1.2	1.8	0	1.4
Sardinella sp.	0	0	1.8	1.4	2.9	3.1	2.4	1.6
Parupeneus indicus	2.5	2.2	2.1	2.6	2.8	2.6	3.4	4.7
Upeneus sulphurens	1.5	1.5	1.8	2.1	2.5	2.2	2.5	3.2
Halichoeres sp.	1.2	1.2	1.1	0	1.7	0	1.8	1.4
Lactoria cornuta	0	0	0	1.2	0	1.5	2.1	1.6

Lethrinus sp.	0	1.2	2.2	1.4	2.7	2.2	2.5	0
Lutjanus sp.	0	0	0	2.5	1.8	1.6	1.9	2.5
Plotosus lineatus	0	0	0	0	1.6	1.5	3.2	1.6
Mugil cephalus	0	0	0	1.4	0	1.2	1.6	1.8
Eubleekeria splendens	3.5	3.8	4.6	3.8	4.7	4.4	5.8	5.9
Scarus sp.	0	0	0	1.8	1.4	2.4	2.2	2.7
Terapon puta	1.2	1.8	2.8	3.3	2.1	1.8	2.3	3.4
Amphiprion sp.	0	1.2	1.5	1.2	1.5	1.5	1.3	1.6
Syngnathoides biaculeatus	0	0	0	0	0	1.5	0	1.8
Siganus canaliculatus	1.2	1.8	2.6	3.1	3.2	2.4	2.6	2.8
Siganus javus	0	2.3	1.7	1.8	2.3	2.2	1.8	2.3
Stongylura strongylura	0	0	0	0	0	0	0	1.7

Table 10: Densities of fish species observed at station 3 during the study period (no.250^{-1})

Species	**Jul-24**	**Aug-24**	**Sep-24**	**Oct-24**	**Nov-24**	**Dec-24**	**Jan-25**	**Feb-25**
Alepes djedaba	0	1.2	0	0	1.2	1.9	0	2.4
Sardinella sp.	0	0	0	1.9	2.9	2.2	2.2	6.3
Parupeneus indicus	2.8	1.8	2.6	1.7	2.1	3.4	3.1	4.2
Upeneus sulphurens	1.6	1.4	0	2.2	1.8	2.3	2.6	2.3
Lethrinus sp.	0	1.8	1.4	1.5	2.8	1.7	3.2	1.1
Lutjanus sp.	1.3	1.5	2.2	2.3	1.7	1.1	1.8	1.2
Plotosus lineatus	0	0	0	0	0	0	2.7	0
Mugil cephalus	0	0	0	1.5	0	1.2	1.4	1.2
Eubleekeria splendens	2.5	2.8	4.7	4.1	5.2	4.3	4.1	6.8
Scarus sp.	0	0	1.5	1.9	1.8	2.8	2.3	2.9
Terapon puta	0	1.7	3.8	3.8	3.1	1.9	2.5	2.7
Amphiprion sp.	0	1.2	1.2	1.2	1.3	1.3	1.3	1.3
Siganus canaliculatus	2.3	1.6	2.7	4.1	4.3	2.3	4.2	3.4
Siganus javus	0	0	1.8	2.2	2.6	2.6	2.9	2.9
Stongylura strongylura	0	0	0	0	0	0	0	2.2

Table 11: Densities of fish species observed at station 4 during the study period (no.250^{-1})

Alepes djedaba	0	1.5	0	1.3	1.9	2.5	0	3.2
Sardinella sp.	0	0	1.2	2.6	3.5	2.8	2.7	6.8
Parupeneus indicus	1.8	2.6	2.3	1.9	2.6	2.7	2.4	4.7

Upeneus sulphurens	2.6	1.3	0	1.7	1.4	2.9	3.2	3.2
Halichoeres sp.	2.1	1.5	1.8	2.5	2.7	2.5	2.6	2.2
Lactoria cornuta	0	0	0	0	0	2.6	2.1	1.9
Lethrinus sp.	0	2.6	1.9	1.9	1.8	2.3	3.7	1.6
Lutjanus sp.	1.2	1.8	1.7	1.4	2.7	2.8	2.5	2.3
Mugil cephalus	0	2.2	0	1.7	0	1.7	1.7	1.8
Eubleekeria splendens	1.3	0	4.2	3.5	5.9	3.4	4.6	7.6
*Scarus*sp.	2.1	3.5	2.6	2.8	2.4	3.6	2.7	3.6
Terapon puta	0	1.2	4.5	4.6	3.5	1.2	2.1	2.2
Amphiprion sp.	0	1.1	1.3	1.5	1.3	1.5	1.4	1.4
Siganus canaliculatus	1.5	1.2	3.4	4.8	4.8	2.7	4.8	2.8
Siganus javus	0	1.6	2.3	2.7	2.8	1.8	3.6	3.2
Stongylura strongylura	0	0	0	0	0	0	0	2.5

4.5. Seagrass-associated macrofauna in the restored area

The average density of benthic macrofauna in the restoration sites increased from 0.95 to 5.23 no.m^{-2} between July 2024 and February 2025 (Fig. 51). Among the five taxa assessed, molluscs were the dominant category as the average density of molluscs increased from 0.39 to 1.74 no.m^{-2} during the study period, followed by echinoderms which increased from 0.23 to 1.45 no.m^{-2}. Likewise, ascidians increased from 0.13 to 0.85 no.m^{-2}; sponges increased from 0.21 to 0.71 no.m^{-2} and sea anemones increased from 0 to 0.47 no.m^{-2} during the study period (Fig. 52).

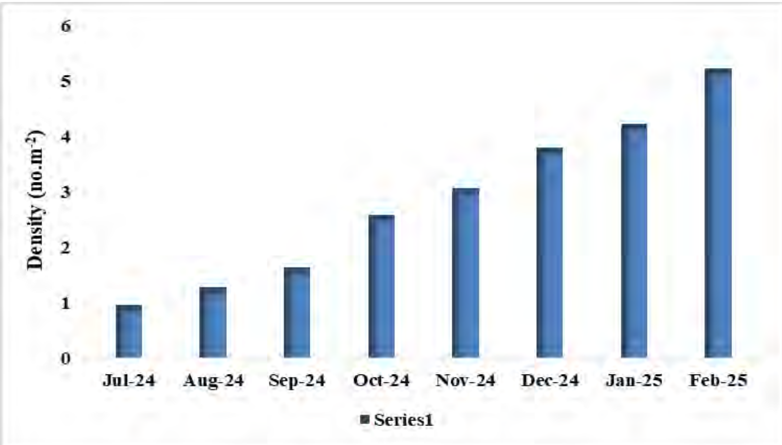


Fig. 51: Overall density of benthic macrofauna in the restored area during the study period

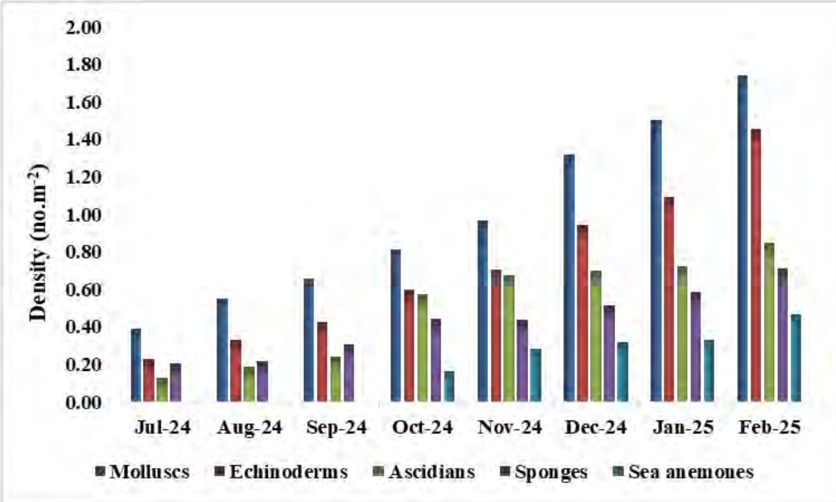


Fig. 52: Taxa-wise density of benthic macrofauna in the restored area during the study period

Station 1

The overall density of benthic macrofauna increased from 1.51 to 5.49 no.m^{-2} during the study period between July 2024 and February 2025 at station 1. Among the taxa, molluscs were the dominant category as the density of molluscs increased from 0.62 to 1.95 no.m^{-2} during the study period, followed by echinoderms which increased from 0.32 to 1.32 no.m^{-2} (Fig. 53).

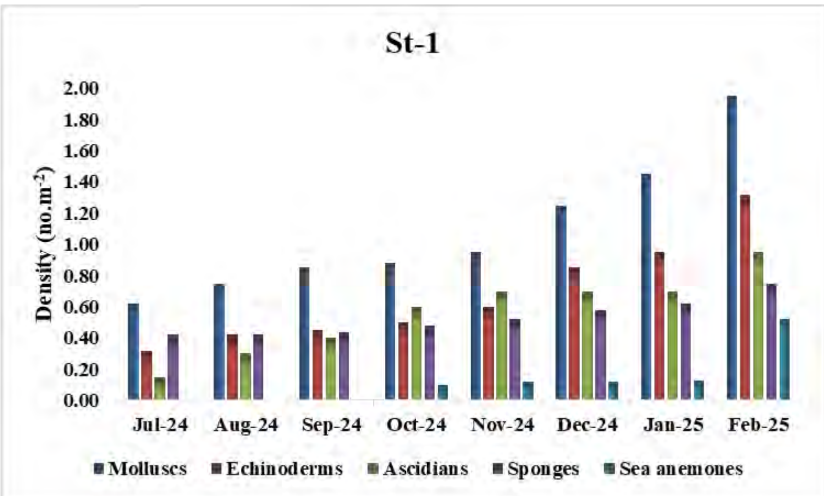


Fig. 53: Density of benthic macrofauna at station 1 during the study period

Station 2

At station 2, the overall density of benthic macrofauna increased from 0.73 to 5.57 no.m^{-2} during the study period between July 2024 and February 2025. Among the taxa, molluscs were the dominant category as the density of molluscs increased from 0.32 to 1.85 no.m^{-2} during the study period, followed by echinoderms which increased from 0.20 to 1.52 no.m^{-2} (Fig. 54).

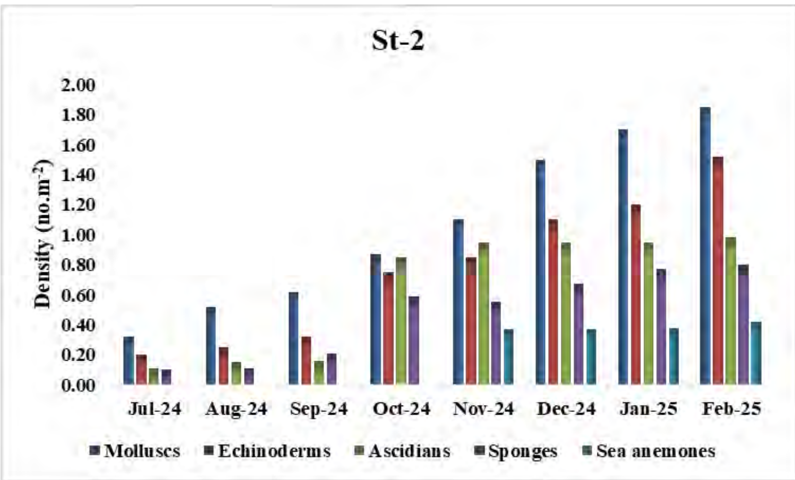


Fig. 54: Density of benthic macrofauna at station 2 during the study period

Site 3

The overall density of benthic macrofauna at station 3 increased from 0.56 to 4.83 no.m^{-2} during the study period between July 2024 and February 2025. Among the taxa, molluscs were the dominant category as the density of molluscs increased from 0.20 to 1.85 no.m^{-2} during the study period, followed by echinoderms which increased from 0.15 to 1.29 no.m^{-2} (Fig. 55).

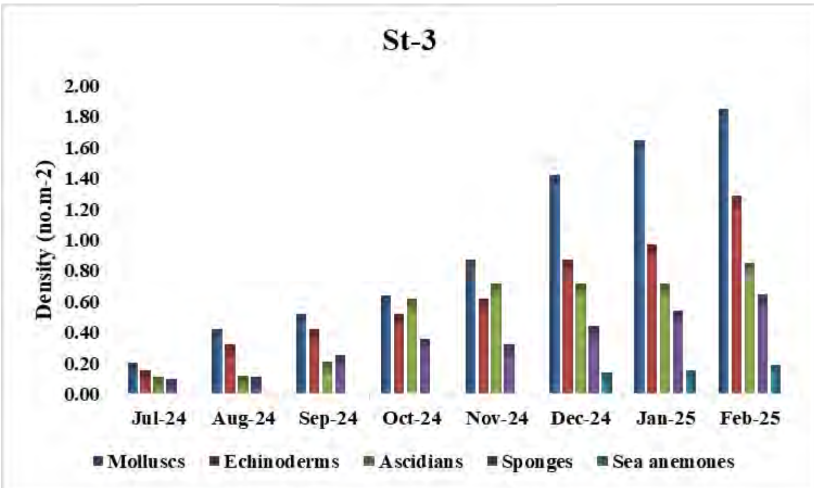


Fig. 55: Density of benthic macrofauna at station 3 during the study period

Station 4

The overall density of benthic macrofauna increased from 1.01 to 5.02 no.m^{-2} during the study period between July 2024 and February 2025 at station 4. Among the taxa, echinoderms were the dominant category as the density of echinoderms increased from 0.25 to 1.68 no.m^{-2} during the study period, followed by molluscs which increased from 0.42 to 1.32 no.m^{-2} (Fig. 56)

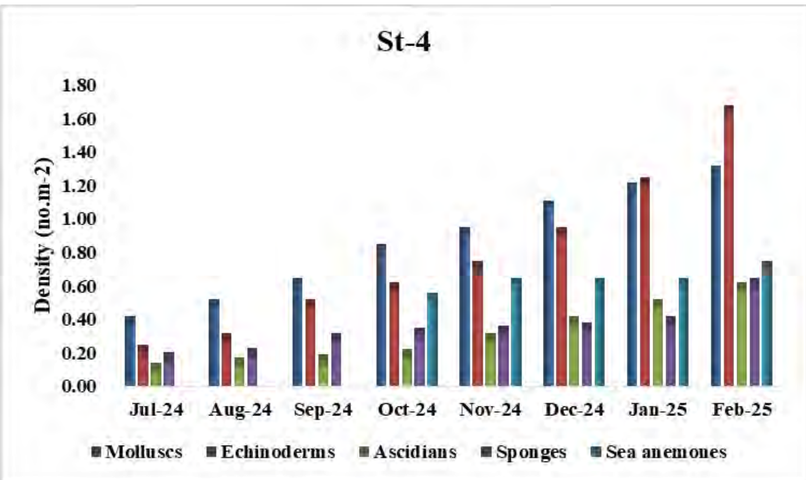


Fig. 56: Density of benthic macrofauna at station 4 during the study period

There is a significant increase in the associated biodiversity after the restoration. The checklist (Table 12) given below indicates the presence of various species in the restored site before and after restoration.

Table 12: List of species in the restoration site before and after the transplantation

S No	Species name	Before restoration	After restoration
Fishes			
1	*Alepes djedaba*	_	✓
2	*Sardinella* sp.	_	✓
3	*Parupeneus indicus*	✓	✓
4	*Upeneus sulphurens*	✓	✓
5	*Halichoeres* sp.	✓	✓
6	*Lactoria cornuta*	✓	✓
7	*Lethrinus* sp.	✓	✓
8	*Lutjanus* sp.	✓	✓
9	*Plotosus lineatus*	_	✓
10	*Mugil cephalus*	_	✓
11	*Eubleekeria splendens*	✓	✓
12	*Scarus* sp.	_	✓
13	*Terapon puta*	✓	✓
14	*Amphiprion* sp.	_	✓
15	*Syngnathoides biaculeatus*	_	✓
16	*Siganus canaliculatus*	✓	✓
17	*Siganus javus*	_	✓
18	*Strongylura strongylura*	_	✓
Molluscs			
1	*Aplysia argus*	_	✓
2	*Babylonia* sp.	_	✓

3	*Canarium* sp.	_	✓
4	*Cardium flavum*	✓	✓
5	*Cerithium punctatum*	✓	✓
6	*Cerithium rostratum*	✓	✓
7	*Clypeomorus* sp.	_	✓
8	*Colina* sp.	_	✓
9	*Conus* sp.	_	✓
10	*Cymatium* sp.	_	✓
11	*Cypraea tigris*	_	✓
12	*Euplica* sp.	_	✓
13	*Jujubinus striatus*	_	✓
14	*Lambis lambis*	_	✓
15	*Lambis* sp.	_	✓
16	*Modiolus* sp.	_	✓
17	*Pinna bicolor*	_	✓
18	*Pinna* sp.	✓	✓
19	*Tectus* sp.	✓	✓
20	*Turbinella pyrum*	_	✓
21	*Volegalea cochlidium*	_	✓
Echinoderms			
22	*Echinolampas ovata*	✓	✓
23	*Holothuria atra*	✓	✓
24	*Holothuria scabra*	_	✓
25	*Pentaceraster affinis*	_	✓
26	*Pentaceraster sp.*	_	✓
27	*Protoreaster linckii*	_	✓
28	*Salmacis bicolor*	_	✓
29	*Salmacis virgulata*	_	✓
30	*Synapta*	_	✓
Ascidians			
31	*Aplidium* sp.	_	✓
32	*Didemnum* sp.	_	✓
33	*Diplosoma* sp.	_	✓
34	*Eudistoma* sp.	_	✓
35	*Polyclinum* sp.	_	✓
36	*Trididemnum* sp.	✓	✓
Sponges			
37	*Amphimedon* sp.	_	✓
38	*Callyspongia diffusa*	✓	✓
39	*Clathria* sp.	_	✓
40	*Halichondria* sp.	✓	✓
41	*Haliclona tenuiranosa*	_	✓

42	*Rhabdastrella* sp.	_	✓
43	*Spheciospongia* sp.	_	✓
	Sea anemones		
44	*Stichodactyla haddoni*	_	✓
45	*Stichodactyla* sp.	_	✓

4.6. Physico-chemical parameters at the restoration sites

Marine water quality – Physical parameters

Temperature

In surface water, the mean temperature level was 28.6^0 C, and the level varied between 27.1^0 C and 30.1^0 C. The highest was recorded during January 2025 at station 1 and the lowest was recorded in February 2025 at station 2. In bottom water, the mean temperature was 28.5^0 C, and the level varied between 27^0 C and 30^0 C. The highest was recorded in January 2025 at station 1 and the lowest was recorded in August 2024 at station 1, and in September 2024 at station 2.

Salinity

In surface water, the mean salinity was 34.5 ppt, and the level varied between 33.6 ppt and 35.1 ppt. The highest was recorded in January 2025 at stations 1 and 2 and the lowest was recorded in November 2024 at station 2. In bottom water, the mean salinity was 34.4 ppt, and the level varied between 33.5 ppt and 35.1 ppt. The highest was recorded in January 2025 at station 2 and the lowest was recorded in November 2024 at station 2.

pH

In surface water, the mean pH was 8.1, and the level varied between 8 and 8.3. The highest was recorded in November 2024 at station 2 and the lowest was recorded in August 2024 at station 1 and in September 2024 at station 2. In bottom water, the mean pH was 8, and the level varied between 7.9 and 8.2. The highest was recorded at station 2 in November and December 2024. The lowest was recorded in August 2024 at station 1 and in September 2024 at station 2.

EC

In surface water, the mean EC was 31.8 mS/cm, and the level varied between 31.0 mS/cm and 33.4 mS/cm. The highest was recorded in January 2025 at station 2 and the lowest was recorded in November 2024 at station 2. In bottom water, the mean EC was 31.7 mS/cm, and the level varied between 30.9 mS/cm and 33.3 mS/cm. The highest was recorded in January 2025 at station 2 and the lowest was recorded in November 2024 at station 2.

Turbidity

In surface water, the mean turbidity was 5.7 NTU, and the level varied between 5.2 NTU and 6.9 NTU. The highest was recorded in November 2024 at station 1 and the lowest was recorded in October 2024 at station 2 and in December 2024 at stations 1 and 2. In bottom water, the mean turbidity was 5.8 NTU, and the level varied between 5.1 and 6.8. The highest was recorded in November 2024 at station 1 and the lowest was recorded in October 2024 at station 2 and in December 2024 at station 2.

Total suspended solids (TSS)

In surface water, the mean TSS was 97.3 mg/l, and the level varied between 85.2 mg/l and 113.6 mg/l. The highest was recorded in November 2024 at station 1 and the lowest was recorded in October 2024 at station 2. In bottom water, the mean TSS was 98 mg/l, and the level varied between 86.4 mg/l and 114.5 mg/l. The highest was recorded in November 2024 at station 1 and the lowest was recorded in October 2024 at station 2.

Marine water quality – Chemical parameters

Dissolved Oxygen (DO)

In surface water, the mean level of DO was 5.5 mg/l, and the level varied between 4.9 mg/l and 6.1 mg/l. The highest was recorded in August 2024 at station 2 and the lowest was recorded in September 2024 at station 1. In bottom water, the mean level of DO was 5.4 mg/l, and the level varied between 4.8 mg/l and 6 mg/l. The highest was recorded in August 2024 at station 2 and the lowest was recorded in September 2024 at station 1.

Biological Oxygen Demand (BOD)

In surface water, the mean BOD level was 1.8 mg/l, and the level varied between 1.4 mg/l and 2.1 mg/l. The highest was recorded in September 2024 at station 1 and the lowest was recorded in August 2024 at station 2. In bottom water, the mean BOD level was 1.8 mg/l, and the level varied between 1.5 mg/l and 2.2 mg/l. The highest was recorded in September 2024 at station 1 and the lowest was recorded in August 2024 at station 2.

Chemical Oxygen Demand (COD)

In surface water, the mean COD level was 1.3 mg/l, and the level varied between 1.1 mg/l and 1.5 mg/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded at station 2 in August, November and December 2024. In bottom water, the mean COD was 1.3 mg/l, and the level varied between 1 mg/l and 1.5 mg/l. The highest was recorded in September 2024 at station 1 and the lowest was recorded in December 2024 at station 2.

Calcium

In surface water, the mean calcium level was 392.8 mg/l, and the level varied between 375 mg/l and 410 mg/l. The highest level was recorded in October 2024 at station 1 and in February 2025 at station 1. The lowest level was recorded in September 2024 at station 2. In bottom water, the mean calcium level was 396.9 mg/l, and the level varied between 380 mg/l and 415 mg/l. The highest level was recorded in October 2024 at station 1 and in February 2025 at station 1 while the lowest was recorded in September 2024 at station 2.

Magnesium

In surface water, the mean magnesium level was 1150.8 mg/l, and the level varied between 1142 mg/l and 1162 mg/l. The highest level was recorded in February 2025 at station 1 and the lowest was recorded in July 2024 at station 1, in August 2024 at station 2, and in November 2024 at station 1. In bottom water, the mean magnesium level was 1165.3 mg/l, and the level varied between 1158 mg/l and 1175 mg/l. The highest level was recorded in July 2024 at station 2 and the lowest was recorded in November 2024 at station 1 and in February 2025 at station 2.

Nitrite

In surface water, the mean nitrite level was 0.37 µmol/l, and the level varied between 0.31 µmol/l and 0.48 µmol/l. The highest level was recorded in August 2024 at station 2 and the lowest was recorded at station 2 in January and February 2025. In bottom water, the mean nitrite level was 0.46µmol/l, and the level varied between 0.41µmol/l and 0.57 µmol/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded at stations 1 and 2 in November 2024.

Nitrate

In surface water, the mean nitrate level was 1.2 µmol/l, and the level varied between 0.9 µmol/l and 1.5µmol/l. The highest level was recorded in August 2024 at stations 1 and 2 while the lowest was recorded in November 2024 at station 2. In bottom water, the mean nitrate level was 1.3µmol/l, and the level varied between 1.1µmol/l and 1.6 µmol/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded in November2024 at station 2 and in February 2025 at station 2.

Total Phosphate

In surface water, the mean total phosphate level was 1.0 µmol/l, and the level varied between 0.8 µmol/l and 1.3µmol/l. The highest level was recorded in January 2025 at station 2 and the lowest was recorded in July 2024 at station 1. In bottom water, the mean total phosphate level was 1.1µmol/l, and the level varied between 0.9µmol/l and 1.4 µmol/l. The highest level was recorded in January 2025 at station 1 and the lowest was recorded in August 2024 at station 2.

Silicate
In surface water, the mean silicate level was 17.6 µmol/l, and the level varied between 16.5 µmol/l and 18.6µmol/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded in January 2025 at station 2. In bottom water, the mean silicate level was 18.0 µmol/l, and the level varied between 17.1µmol/l and 18.9 µmol/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded in August 2024 at station 1 and in January 2025 at station 2.

Chloride
In surface water, the mean chloride level was 16.7 g/l, and the level varied between 16.4 g/l and 17.0 g/l. The highest level was recorded in December 2024 at station 1 and the lowest was recorded in September at station 2. In bottom water, the mean chloride level was 16.8g/l, and the level varied between 16.3 g/l and 17.2 g/l. The highest level was recorded in September 2024 at station 1 and the lowest was recorded in September 2024 at station 2.

Oil and Grease
In surface water the mean oil and grease level was 0.14 mg/l, and the level varied between 0.12 mg/l and 0.17 mg/l. The highest level was recorded in October 2024 at station 1 and the lowest was recorded in July 2024 at station 1 and in January 2025 at stations 1 and 2. In bottom water, the mean oil and grease level was 0.17 mg/l, and the level varied between 0.13 mg/l and 0.2 mg/l. The highest level was recorded in August 2024 at station 1 and the lowest was recorded in January 2025 at station 2.

Marine sediment quality parameters

pH
The mean pH in the sediment was 8.2, and the level varied between 7.9 and 8.4 during the monitoring period. The highest was recorded in January and February 2025 at station 1 and the lowest was recorded in August 2024 at station 2.

Sediment texture
In sediment samples, sand fraction was found to play a dominant role, followed by silt and clay, and the mean values were 94.1%, 5.4%, and 2.5%, respectively. The sand fraction percentage varied between 89.5% and 97.4%; the silt fraction percentage varied between 2.5% and 10.0%; and the clay fraction percentage varied between 0.1% and 1.6%. Among the monitoring periods, the highest sand fraction was recorded in November 2024 at station 2 and the lowest was recorded in October 2024 at station 1; the highest silt fraction was recorded in October 2024 at station 1 and the lowest was recorded in November 2024 at station 2; the highest clay fraction was recorded in February 2025 at station 2.

Organic matter

The mean organic matter in the sediment samples was 2.0%, and the level varied between 1.3% and 2.2% during the study period. The highest level was recorded in July 2024 at station 1, in November 2024 at station 2 and in February 2025 at station 2. The lowest level was recorded in October 2024 at station 2.

Sedimentation rate

The mean sedimentation rate was 30.7 $mg/cm^2/day$ during the study period, and the level varied between 28.1 $mg/cm^2/day$ and 34.7 $mg/cm^2/day$. The highest was recorded in December 2024 at station 1 and the lowest was recorded in July 2024 at station 1.

Tables 12 to 14 provide the details of environmental parameters of water and sediment from the restoration sites. Plates 1to 10 show the stages of restored area during the monitoring period.

Table 13: Marine water quality parameters at site 1

Marine water quality		Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
Physical parameters									
Temperature (^oC)	Surface	30.1	28.6	28.8	28.4	28.9	29.4	28.3	27.4
	Bottom	30.0	28.5	28.7	28.3	28.8	29.4	28.2	27.3
Salinity(ppt)	Surface	34.5	34.6	34.8	34.5	33.8	34.6	35.1	34.8
	Bottom	34.4	34.5	34.7	34.5	33.7	34.5	35.0	34.7
pH	Surface	8.1	8.0	8.1	8.2	8.1	8.2	8.1	8.2
	Bottom	8.1	7.9	8.0	8.1	8.0	8.1	8.0	8.1
EC (mS/cm)	Surface	31.2	31.3	31.8	31.3	31.1	31.8	33.3	32.6
	Bottom	31.1	31.1	31.7	31.2	31.0	31.7	33.2	32.5
Turbidity(NTU)	Surface	6.4	5.8	5.5	5.3	6.9	5.2	5.6	5.9
	Bottom	6.5	5.7	5.6	5.4	6.8	5.3	5.7	6.1
Total Suspended Solids (mg/l)	Surface	107.6	98.3	93.1	86.4	113.6	93.2	89.7	107.3
	Bottom	108.8	97.3	91.8	88.2	114.5	93.2	90.2	108.9
Chemical parameters									
Dissolved oxygen (mg/l)	Surface	5.5	5.9	4.9	5.4	5.5	5.6	5.4	5.2
	Bottom	5.4	5.8	4.8	5.3	5.4	5.5	5.3	5.1
BOD (mg/l)	Surface	2.0	1.7	2.1	1.8	1.8	1.9	1.9	1.7
	Bottom	2.1	1.8	2.2	1.9	1.9	1.8	1.8	1.8
COD (mg/l)	Bottom	1.4	1.2	1.5	1.3	1.2	1.2	1.4	1.3
	Surface	1.4	1.3	1.5	1.4	1.3	1.3	1.3	1.3
Calcium (mg/l)	Surface	395	400	400	410	385.0	390	400	410

	Bottom	400	405	395	415	390.0	395	405	415
Magnesium (mg/l)	Surface	1142	1153	1149	1153	1142	1146	1153	1145
	Bottom	1165	1164	1173	1164	1158	1159	1167	1161
Nitrite (µmol/l)	Surface	0.33	0.35	0.32	0.39	0.41	0.35	0.37	0.32
	Bottom	0.45	0.45	0.48	0.44	0.43	0.46	0.42	0.44
Nitrate (µmol/l)	Surface	1.2	1.2	1.5	1.2	0.9	1.2	1.2	1.2
	Bottom	1.3	1.4	1.6	1.4	1.2	1.4	1.3	1.4
Total phosphate µmol/l	Surface	0.8	1.1	1.1	0.9	0.9	1.0	1.2	1.0
	Bottom	1.1	1.2	1.2	1.2	1.3	1.1	1.4	1.2
Silicate (µmol/l)	Surface	17.2	18.4	18.6	17.4	17.4	17.8	16.6	17.2
	Bottom	17.4	18.6	18.9	18.5	18.2	18.4	17.5	18.2
Chloride (g/l)	Surface	16.8	16.9	16.8	16.7	16.8	17.0	16.8	16.9
	Bottom	16.8	17.0	17.2	16.8	16.9	16.8	16.9	17.1
Oil and Grease (mg/l)	Surface	0.12	0.15	0.16	0.17	0.16	0.14	0.12	0.14
	Bottom	0.18	0.20	0.19	0.18	0.20	0.15	0.13	0.16

Table 14: Marine water quality parameters at site 2

Marine water quality		Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
Physical parameters									
Temperature (°C)	Surface	29.6	28.3	28.6	28.2	28.6	29.3	27.9	27.1
	Bottom	29.4	28.2	28.5	28.0	28.5	29.2	27.8	27.0
Salinity(ppt)	Surface	34.1	34.3	34.6	34.2	33.6	34.8	35.1	34.9
	Bottom	34.1	34.2	34.5	34.1	33.5	34.7	35.1	34.8
pH	Surface	8.1	8.1	8.0	8.1	8.3	8.2	8.2	8.2
	Bottom	8.0	8.0	7.9	8.0	8.2	8.2	8.1	8.0
EC (mS/cm)	Surface	31.1	31.2	31.6	31.2	31.0	32.2	33.4	32.7
	Bottom	31.0	31.1	31.5	31.1	30.9	32.1	33.3	32.6
Turbidity(NTU)	Surface	6.4	5.6	5.3	5.2	6.5	5.2	5.4	5.7
	Bottom	6.3	5.7	5.2	5.1	6.4	5.2	5.3	5.8
Total Suspended Solids (mg/l)	Surface	106.3	93.8	89.4	85.2	109.4	91.0	87.2	105.9
	Bottom	104.5	95.3	90.1	86.4	109.8	92.6	89.1	107.6
Chemical parameters									
Dissolved oxygen (mg/l)	Surface	5.8	6.1	5.1	5.6	5.8	5.7	5.5	5.5
	Bottom	5.7	6.0	4.9	5.5	5.7	5.5	5.4	5.4
BOD (mg/l)	Surface	1.8	1.4	1.8	1.6	1.6	1.7	1.7	1.6
	Bottom	1.9	1.5	1.9	1.7	1.7	1.8	1.7	1.7
COD (mg/l)	Bottom	1.3	1.1	1.3	1.2	1.1	1.1	1.3	1.2

	Surface	1.3	1.2	1.4	1.2	1.2	1.0	1.2	1.1
Calcium (mg/l)	Surface	380	385	375	400	385	380	395	395
	Bottom	385	390	380	405	385	385	400	400
Magnesium (mg/l)	Surface	1148	1142	1159	1151	1159	1150	1159	1162
	Bottom	1175	1168	1167	1162	1172	1164	1167	1158
Nitrite (µmol/l)	Surface	0.39	0.48	0.47	0.37	0.40	0.38	0.31	0.31
	Bottom	0.41	0.52	0.57	0.42	0.48	0.47	0.43	0.44
Nitrate (µmol/l)	Surface	1.2	1.5	1.3	1.4	0.9	1.1	1.2	1.0
	Bottom	1.4	1.3	1.4	1.3	1.1	1.2	1.2	1.1
Total phosphate µmol/l	Surface	1.0	0.8	1.0	0.8	0.9	0.9	1.3	0.8
	Bottom	1.1	0.9	1.1	1.1	1.0	1.0	1.3	1.0
Silicate (µmol/l)	Surface	17.3	17.9	17.8	17.0	17.8	17.9	16.5	18.1
	Bottom	17.2	18.0	18.1	18.2	17.9	18.2	17.1	18.0
Chloride (g/l)	Surface	16.6	16.5	16.4	16.5	16.6	16.5	16.6	16.7
	Bottom	16.7	16.6	16.3	16.6	16.9	16.8	16.8	16.9
Oil and Grease (mg/l)	Surface	0.13	0.14	0.12	0.16	0.15	0.16	0.15	0.13
	Bottom	0.15	0.14	0.15	0.17	0.18	0.18	0.13	0.18

Table 15: Marine sediment quality parameters at site 1

Marine sediment quality	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
pH	8.2	8.1	8.2	8.2	8.2	8.3	8.4	8.4
Sand (%)	92.5	91.5	94.9	89.5	96.2	95.0	91.9	93.5
Silt (%)	6.9	7.9	4.3	10.0	2.8	4.3	7.6	5.8
Clay (%)	0.7	0.6	0.8	0.5	1.0	0.7	0.5	0.7
Organic Matter (%)	2.2	2.0	2.1	1.9	2.1	2.1	1.9	2.0
Sedimentation rate (mg/cm^2/day)	28.12	29.65	30.26	28.65	31.65	34.65	28.97	29.44

Table 16: Marine sediment quality parameters at site 2

Marine sediment quality	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Jan-25	Feb-25
pH	8.0	7.9	8.1	8.2	8.3	8.3	8.2	8.1
Sand (%)	94.1	93.0	96.0	92.4	97.4	95.4	94.5	94.2
Silt (%)	5.6	6.0	3.1	7.4	2.5	4.0	5.1	4.2
Clay (%)	0.3	1.0	0.9	0.2	0.1	0.6	0.4	1.6
Organic Matter (%)	2.1	1.8	1.9	1.3	2.2	2.1	1.8	2.2
Sedimentation rate (mg/cm^2/day)	30.47	31.65	32.65	30.65	29.65	32.65	30.65	31.27

5. Comparison with a nearby degraded site

There was no reference degraded site fixed for the present project. However, we have been monitoring a nearby degraded site (control site) in Koswari Island for some other studies. Hence, we have now compared the physico-chemical and biological parameters of this degraded site with the restoration site. As anticipated, densities of fish and macrofaunal communities were increasing in the restoration site significantly while there was no/little fluctuation at the degraded site (Figs. 57-58). As the cover of seagrasses increases in the restoration site, more associated fauna will find shelter and food for them to thrive in the area. Apart from enhanced nutrient content and dissolved oxygen level in the restoration site, physico-chemical parameters did not show big differences between these sites (Tables 17-18). Levels of turbidity and total suspended solids in the restoration site decreased slightly while the levels of dissolved oxygen, nitrites, nitrates and phosphates increased slightly. The graphs and table given below show the differences in the parameters between degraded and restored sites.

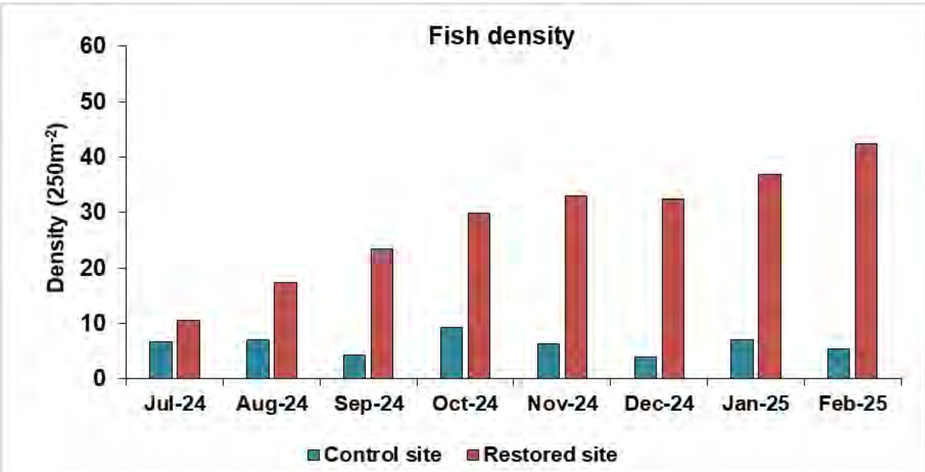


Fig. 57: showing the differences in fish density between restored and control site

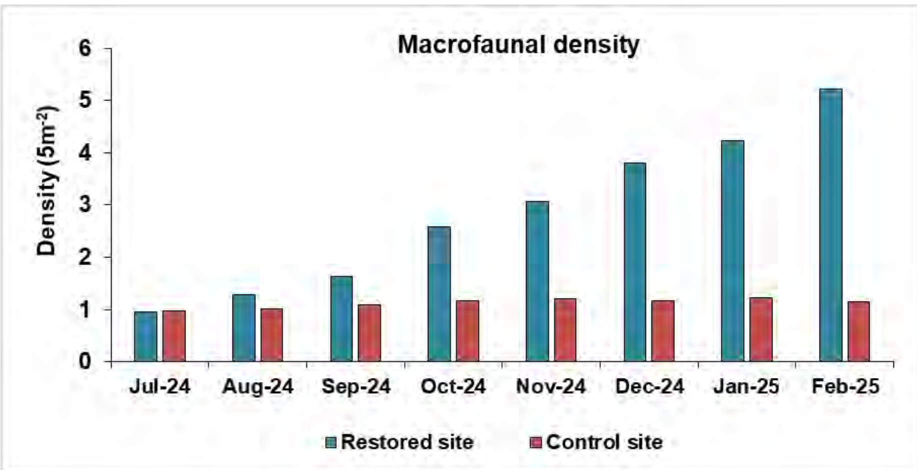


Fig. 58: Figure showing the differences in macrofaunal density between restored and control site

Table 17: Physico-chemical characters of surface (S) and bottom (B) waters in the restored and control sites

Marine water quality		Jul-24		Aug-24		Sep-24		Oct-24		Nov-24		Dec-24		Jan-25		Feb-25	
Physical parameters		**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**	**Restored**	**Control**
Temperature (°C)	S	29.9	29.9	28.5	28.8	28.7	28.9	28.3	28.6	28.8	28.6	29.4	29.6	28.1	28.5	27.3	27.7
	B	29.7	29.8	28.4	28.4	28.6	28.7	28.2	28.4	28.7	28.4	29.3	29.4	28.0	28.3	27.2	27.4
Salinity (ppt)	S	34.3	34.4	34.5	34.5	34.7	35.0	34.4	34.6	33.7	33.5	34.7	34.9	35.1	35.3	34.9	34.9
	B	34.3	34.3	34.4	34.3	34.6	34.9	34.3	34.2	33.6	33.4	34.6	34.7	35.1	35.2	34.8	34.7
pH	S	8.1	8.1	8.1	8.2	8.1	8.1	8.2	8.2	8.2	8.3	8.2	8.2	8.2	8.2	8.2	8.2
	B	8.1	8.1	8.0	8.0	8.0	8.0	8.1	8.1	8.1	8.2	8.2	8.1	8.1	8.1	8.1	8.2
EC (mS/cm)	S	31.2	31.1	31.3	31.4	31.7	31.9	31.3	31.5	31.1	31.2	32.0	32.4	33.4	33.6	32.7	32.8
	B	31.1	31.1	31.1	31.2	31.6	31.8	31.2	31.3	31.0	31.0	31.9	32.0	33.3	33.3	32.6	32.6
Turbidity (NTU)	S	6.4	6.4	5.7	5.8	5.4	5.7	5.3	5.5	6.7	7.1	5.2	5.4	5.5	5.6	5.8	6.2
	B	6.4	6.5	5.7	5.9	5.4	6.0	5.3	5.5	6.6	7.1	5.3	5.5	5.5	5.8	6.0	6.4
Total Suspended Solids (mg/l)	S	107.0	106.8	96.1	99.5	91.3	95.6	85.8	87.2	111.5	116.8	92.1	98.5	88.5	93.6	106.6	116.4
	B	106.7	107.4	96.3	97.8	91.0	95.4	87.3	88.8	112.2	120.4	92.9	103.4	89.7	98.7	108.3	120.8
Chemical parameters																	
Dissolved oxygen (mg/l)	S	5.7	5.5	6.0	5.6	5.0	4.7	5.5	5.2	5.7	5.3	5.7	5.4	5.5	5.2	5.4	5.1
	B	5.6	5.3	5.9	5.4	4.9	4.6	5.4	5.0	5.6	5.1	5.5	5.2	5.4	5.1	5.3	5.0
BOD (mg/l)	S	1.9	1.8	1.6	1.8	2.0	2.2	1.7	1.8	1.7	1.9	1.8	2.1	1.8	2.1	1.7	1.9
	B	2.0	2.0	1.7	1.9	2.1	2.3	1.8	2.0	1.8	2.1	1.8	2.0	1.8	2.2	1.8	2.0
COD (mg/l)	S	1.4	1.3	1.2	1.4	1.4	1.6	1.3	1.4	1.2	1.3	1.2	1.3	1.4	1.6	1.3	1.5
	B	1.4	1.4	1.3	1.5	1.5	1.7	1.3	1.5	1.3	1.5	1.2	1.6	1.3	1.7	1.2	1.7
Calcium (mg/l)	S	388	390	393	390	388	405	405	415	385	390	385	390	398	410	403	410
	B	393	410	398	410	388	390	410	420	388	405	390	400	403	415	408	415
Magnesium	S	1145	1155	1148	1155	1154	1150	1152	1158	1151	1150	1148	1155	1156	1162	1154	1165

(mg/l)	B	1170	1170	1166	1165	1170	1158	1163	1168	1165	1165	1162	1167	1167	1168	1160	1170
Nitrites (µmol/l)	S	0.36	0.32	0.42	0.32	0.40	0.28	0.38	0.36	0.41	0.37	0.37	0.32	0.34	0.28	0.32	0.27
	B	0.43	0.40	0.49	0.36	0.53	0.40	0.43	0.40	0.46	0.41	0.47	0.41	0.43	0.36	0.44	0.32
Nitrates (µmol/l)	S	1.2	1.0	1.4	1.0	1.4	1.1	1.3	1.1	0.9	0.7	1.2	0.8	1.2	0.9	1.1	0.8
	B	1.4	1.2	1.4	1.3	1.5	1.3	1.4	1.2	1.2	1.0	1.3	1.0	1.3	1.1	1.3	1.0
Total phosphates µmol/l	S	0.9	0.7	1.0	0.7	1.1	0.9	0.9	0.7	0.9	0.7	1.0	0.8	1.3	1.1	0.9	0.7
	B	1.1	1.0	1.1	0.9	1.2	1.0	1.2	0.9	1.2	0.9	1.1	0.9	1.4	1.1	1.1	0.9
Silicates (µmol/l)	S	17.3	17.2	18.2	18.5	18.2	18.7	17.2	17.8	17.6	18.1	17.9	18.3	16.6	16.9	17.7	18.1
	B	17.3	17.5	18.3	18.8	18.5	19.0	18.4	18.7	18.1	18.5	18.3	18.6	17.3	17.5	18.1	18.3
Chlorides (g/l)	S	16.7	16.7	16.7	16.7	16.6	16.6	16.6	16.7	16.7	16.8	16.8	17.2	16.7	16.9	16.8	17.1
	B	16.8	16.8	16.8	17.0	16.8	17.2	16.7	16.9	16.9	17.1	16.8	17.4	16.9	17.3	17.0	17.2
Oil and Grease (mg/l)	S	0.13	0.14	0.15	0.13	0.14	0.18	0.17	0.18	0.16	0.17	0.15	0.16	0.14	0.16	0.14	0.14
	B	0.17	0.18	0.17	0.18	0.17	0.20	0.18	0.20	0.19	0.21	0.17	0.19	0.13	0.17	0.17	0.18

Table 18: Physico-chemical parameters of marine sediment in the restored and control sites

Marine sediment quality	Jul-24		Aug-24		Sep-24		Oct-24		Nov-24		Dec-24		Jan-25		Feb-25	
	Restored	Control	Restored	Control	Restored	Control	Restored	Control	Restored	Control	Restored	Control	Restored	Control	Restored	Control
pH	8.1	8.2	8	8.2	8.15	8.2	8.2	8.3	8.25	8.3	8.3	8.3	8.3	8.4	8.25	8.4
Sand (%)	93.3	95.3	92.3	94.8	95.5	95.3	91.0	93.9	96.8	96.3	95.2	95.6	93.2	94.8	93.9	94.6
Silt (%)	6.25	4.3	6.95	4.6	3.7	4.3	8.7	5.5	2.65	3.2	4.15	3.9	6.35	4.6	5	4.9
Clay (%)	0.5	0.4	0.8	0.6	0.85	0.4	0.35	0.6	0.55	0.5	0.65	0.5	0.45	0.6	1.15	0.5
Organic Matter (%)	2.15	1.6	1.9	1.6	2	1.5	1.6	1.4	2.15	1.7	2.1	1.8	1.85	1.5	2.1	1.7
Sedimentation rate (mg/cm^2/day)	29.295	31.64	30.65	32.08	31.455	32.8	29.65	26.7	30.65	33.6	33.65	36.4	29.81	33.8	30.355	33.6

6. Removal of PVC pipes

After the establishment of seagrass shoots, PVC pipes were removed from the sea bottom in February 2025.

Fig. 59: Removal of PVC pipes after the establishment of transplanted seagrasses

7. Comparison with Alternative Methodologies

As per published reports and track records, manual transplantation of sprigs has been proven to be the best choice for seagrass restoration in the Gulf of Mannar and Palk Bay (Edward et al. 2019; Balaji et al. 2020). This method was developed by SDMRI after initial experimentations with several techniques such as plug method, staple method and manual transplantation of sprigs method (Edward et al, 2008). Sprigs method has several variants with different success rates. This method, generally using PVC frames of 1 X 1 m and jute twines, has been proven to be highly successful (Edward et al. 2019). Bamboo frames (or sticks of any other plant) of 1 X 1 m and frames made of coir ropes have also been used to carry out manual transplantation of seagrass sprigs (Balaji et al. 2020; SDMRI unpubl.). The method involving bamboo frames exhibits significant compromises on the survival of transplanted seagrasses (SDMRI unpubl.). Straight wooden sticks in large numbers are required for large-scale restoration and it is difficult to get them in plenty for wide-scale restoration. Quadrats made by tying these sticks are unstable at the bottom, whereas PVC frames are sturdy and stable. Moreover, PVC frames are negatively buoyant as one of the corners is open to take in seawater, but this is not possible with wooden sticks. Hence, keeping the shoots in touch with sea bottom is very difficult with wooden frames. Due to this, the survival rate of transplants decreases by about 30% with wooden frames (SDMRI unpubl.). The manpower requirement is also comparatively very high for the stick method as it requires manual tying. As PVC quadrats are removed after three months of transplantation, the restoration activity does not allow any debris to pile up underwater.

Instead of PVC frames, eco-friendly coir ropes can also be used for seagrass restoration with a bigger frame area (for instance 5 X 5 m). Coir rope method does not affect the survival of the transplants unlike wooden frame method (SDMRI unpubl.). The problem with the coir rope method is it requires more underwater time and hence requires more professional scientific scuba divers. Thus it increases the cost of skilled manpower. The cost for the use of PVC frames is higher than that of using coir ropes, but comparatively the overall costing goes little higher in the case of coir ropes due to the increased underwater dive manpower cost.

Seagrass restoration in the Gulf of Mannar is generally carried out in subtidal waters at depths between 1 and 6 m. It is very important to note here that seagrass restoration cannot be carried out by skin diving as it requires more time underwater. Skin divers with a maximum time of one minute underwater cannot perform the work properly. Hence, using community members for transplantation will only result in poor survival rate. Instead, community members can be used in tying the sprigs with jute twines and skin divers from the community can be used to transport the frames from the boat to the divers underwater.

8. Conclusion and Remarks

Using the standardized low-tech and low-cost seagrass restoration method called manual transplantation of seagrass sprigs, restoration has been carried out in 1 acre of degraded seagrass area near Koswari Island in Tuticorin Wildlife Range of Gulf of Mannar Marine National Park. A total of 2,000 PVC frames (1 X 1 m) were used for restoration of 2,000 sq.m of degraded area, which involved scuba diving. Four common seagrass species were transplanted namely *Oceana serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis*. The entire process of seagrass restoration was carried out successfully in degraded reef areas and the transplants have rooted in the degraded sites and started growing well. Monthly monitoring of restored seagrass area shows promising results as parameters like seagrass cover, shoot density, associated fish and associated macrofauna have gradually increased during the monitoring period between July 2024 and February 2025.

An increase in average seagrass cover from 20.8 to 33.8% and seagrass shoot density from 67.5 to 124.2 no.m^{-2} within eight months indicates that the restored seagrass areas are in the process of becoming similar to that of a natural seagrass bed. The increase in the seagrass shoot density during the monitoring period is relatively 84% and this relative increase was for 1 acre and it can be extrapolated for one sq.km as well. To complement the evaluation of success, the densities of associated fishes and benthic macrofauna in the restoration sites have also increased along with the increasing seagrass biomass. It is thus clear that restored seagrass areas have started to provide ecological services they are known to offer. However, it is still early stages to evaluate the complete success of seagrass restoration. Monthly monitoring is being continued to assess the trend in seagrass biomass and associated biota in the restored areas. It is anticipated that the restored seagrass areas would fully act like a natural seagrass bed within two years.

"Assessment of seagrass biomass, carbon storage in the soil, and carbon sequestration capacity of the restored seagrass area was not conducted in the current project, as it was not included in the study components. However, an approximate value was estimated based on secondary literature -

1. ***Blue Carbon stored in the above & below ground biomass* -** Ganguly et al. (2018) reported from Palk Bay in Tamil Nadu and Chilika Lake in Odisha that the carbon storage in the above-ground biomass ranged from 0.20 to 0.96 Mg C/ha, while the range was 0.30 to 2.9 Mg C/ha for the below-ground biomass. In addition, a recent estimate (Asir et al. 2025, in press) of the above-ground and below-ground biomass for a seagrass cover of 31% in Palk Bay finds a storage of 0.89 Mg C/ha. **Based on these estimates for the seagrass cover in the restored sites (33.8%) in the current**

project, an approximate storage of 0.36 Mg C/acre may be expected to be attained. As seagrass cover keeps increasing at the restoration sites, carbon storage will also be increasing.

2. ***Blue Carbon stored in the existing soil of the restored site* -** Similarly, previous studies on the carbon storage in soil in the restored seagrass area of the nearby Vaan Island in Gulf of Mannar observed 79.61 Mg C/ha while the carbon storage in a degraded seagrass areas in the Gulf of Mannar was found to be 60.12 Mg C/ha (ECCFD 2025, in press). The present seagrass restoration area (Koswari Island) is nearer to Vaan Island. **Hence, similar results are expected, and accordingly, the approximate soil carbon stored in the existing soil of the restoration site could be 24.34 Mg C/acre (as the restoration is performed in the degraded site).**

3. ***Blue Carbon sequestration rate of the restored site* -** As far as the carbon sequestration capacity of restored seagrass is concerned, Greiner et al. (2013) reported that 10-year old restored seagrass meadows facilitated an accumulation of 36.68 g C m^{-2} yr^{-1}, which falls slightly below the range for carbon burial in natural seagrass meadows (40-190 g C m^{-2} yr^{-1}) estimated by Mcleod et al. (2011). **Hence, taking these values into account, it can be assumed that the present seagrass restoration activity can enable an accumulation of 0.1485 Mg C $Acre^{-1}$ yr^{-1}.**

Therefore, the total blue carbon stored (or expected blue carbon storage) through the current seagrass restoration project in terms of the combined values of above-ground and below-ground biomass and Soil Organic Carbon would be approximately 24.7 Mg C/acre. Furthermore, the present seagrass restoration activity in one acre is also expected to enable an addition of 1.485 Mg C in the soil carbon stock in 10 years, which, of course, depends on various biotic and abiotic factors”.

9. References

1. Anthony, J. D., & Perrow, M. R. (2002). *Handbook of ecological restoration* (Vol. 2). Cambridge University Press.
2. American Public Health Association (APHA), American Water Works Association (AWWA), & Water Environment Federation (WEF). (1998). *Standard methods for the examination of water and wastewater* (19th ed.). American Public Health Association.
3. American Public Health Association (APHA), American Water Works Association (AWWA), & Water Environment Federation (WEF). (2012). *Standard methods for the examination of water & wastewater* (22nd ed.). American Public Health Association.
4. Balaji, V. (2018) Acoustic survey of seagrass beds in northern Palk Bay, India. *Indian Journal of Geo Maine Sciences, 47(8),* 1607-1615.
5. Balaji, V., Sekar, V., & Murugesan, G. (2020). Comparison of seagrass restoration methods adopted in Palk Bay, India. Journal of the Marine Biological Association of India, 62(1), 96.
6. Balaji, S., Patterson Edward, J. K., & Samuel, D. V. (2012). *Coastal and marine biodiversity of Gulf of Mannar, southeastern India – A comprehensive updated species list* (Publication No. 22). Gulf of Mannar Biosphere Reserve Trust.
7. Balaji, V., Sekar, V., & Murugesan, G. (2020). Comparison of seagrass restoration methods adopted in Palk Bay, India. *Journal of the Marine Biological Association of India, 62*(1), 96.
8. Barry, S. C., Hyman, A. C., Jacoby, C. A., Reynolds, L. K., Kowalewski, M., & Frazer, T. K. (2021). Variation in seagrass-associated macroinvertebrate communities along the Gulf Coast of peninsular Florida: An exploration of patterns and ecological consequences. *Frontiers in Marine Science, 8*, 596966.
9. Bensam, P., & Udhayashankar, T. R. (1990). Colonization and growth of the seagrasses *Halodule uninervis* (Forsskål) Aschers. and *Halophila ovalis* (R. Br.) Hooker

f. in marine culture ponds at Mandapam. *The Second Indian Fisheries Forum, Abstracts* (No. 91).

10. Bilgi, D. S., Mathews, G., Diraviya Raj, K., Laju, R. L., Arasamuthu, A., & Edward, J. K. P. (2022). Underwater surveys in the Gulf of Mannar, Tamil Nadu, southern India, unveil new seagrass beds. *Journal of Aquatic Biology & Fisheries, 10*(1), 103–108.
11. Cerbian, J. (1999). Patterns in the fate of production in plant communities. *The American Naturalist, 154*, 449–468.
12. Duarte, C. M., Middelburg, J. J., & Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences, 2*(1), 1–8.
13. Dunic, J. C., Brown, C. J., Connolly, R. M., Turschwell, M. P., & Côté, I. M. (2021). Long-term declines and recovery of meadow area across the world's seagrass bioregions. *Global Change Biology, 27*(17), 4096–4109.
14. Duarte, C. M., Kennedy, H., Marbà, N., & Hendriks, I. (2011). Assessing the capacity of seagrass meadows for carbon burial: Current limitations and future strategies. *Ocean & Coastal Management, 83*, 32–38.
15. ECCFD (2025) Blue Carbon Wealth of Tamil Nadu, India - the role of coastal ecosystems as carbon sinks, Environment, Climate Change and Forests Department, Government of Tamil Nadu, Chennai, India in partnership with Suganthi Devadason Marine Research Institute, Tuticorin, India, 127pp. In press.
16. Edward, J. K. P., Patterson, J. & Wilhelmson, D. (2008). Conservation of coral reefs and seagrasses of the Gulf of Mannar and Palk Bay, Southeastern India: significant contributions from SDMRI during 2000-2008. SDMRI Special Research Publication No. 13.
17. Edward, J. K. P., Diraviya Raj, K., Mathews, G., Kumar, P.D., Arasamuthu, A., D'Souza, N. and Bilgi, D.S., (2019) Seagrass restoration in Gulf of Mannar, Tamil Nadu, southeast India: a viable management tool. Environmental Monitoring and Assessment,doi.org/10.1007/s10661-019-7546-5.

18. English, S., Wilkinson, C., & Baker, V. (1997). Line intercept transect. In S. English, C. Wilkinson, & V. Baker (Eds.), *Survey manual for tropical marine resources* (pp. 34–51). Australian Institute of Marine Science.
19. Fonseca, M. S. (1992). Restoring seagrass systems in the United States. In G. W. Thayer (Ed.), *Restoring the nation's marine environment*. Maryland Sea Grant College.
20. Förderer, M., Rödder, D., & Langer, M. R. (2018). Patterns of species richness and the center of diversity in modern Indo-Pacific larger foraminifera. *Scientific Reports, 8*(1), 8189.
21. Ganguly, D., Singh, G., Purvaja, R., Bhatta, R., Selvam, A. P., Banerjee, K., & Ramesh, R. (2018). Valuing the carbon sequestration regulation service by seagrass ecosystems of Palk Bay and Chilika, India. Ocean & Coastal Management, 159, 26-33.
22. Geevarghese, G. A., Akhil, B., Magesh, G., Krishnan, P., Purvaja, R., & Ramesh, R. (2018). A comprehensive geospatial assessment of seagrass distribution in India. *Ocean & Coastal Management, 159*, 16–25.
23. Green, A. E., Unsworth, R. K., Chadwick, M. A., & Jones, P. J. (2021). Historical analysis exposes catastrophic seagrass loss for the United Kingdom. *Frontiers in Plant Science, 12*, 629962.
24. Greiner, J.T., McGlathery, K.J., Gunnell, J., McKee, B.A. (2013). Seagrass Restoration Enhances "Blue Carbon" Sequestration in Coastal Waters. PLoS ONE 8 (8):e72469.doi:10.1371/journal.pone.0072469
25. Hagart-Alexander, C. (2010). *Temperature measurement*. Instrumentation reference book.
26. Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology, 25*, 101–110.
27. Heise, R. J., & Bortone, S. A. (1999). Estuarine artificial reefs to enhance seagrass planting and provide fish habitat. *Gulf of Mexico Science, 17*(2), 1.
28. Hendriks, I. E., Sintes, T., Bouma, T. J., & Duarte, C. M. (2008). Experimental assessment and modeling evaluation of the effects of the seagrass *Posidonia*

oceanica on flow and particle trapping. *Marine Ecology Progress Series, 356*, 163–173.

29. Horinouchi, M., Mizuno, N., Jo, Y., Fujita, M., Sano, M., & Suzuki, Y. (2009). Seagrass habitat complexity does not always decrease foraging efficiencies of piscivorous fishes. *Marine Ecology Progress Series, 377*, 43–49.
30. Jackson, M. L. (1958). The pH was determined in 1:2 soil water suspensions using a digital pH meter. *Soil Chemical Analysis.* Prentice Hall.
31. Jagtap, T. G. (1991). Distribution of seagrasses along the Indian coast. *Aquatic Botany, 40*(4), 379–386.
32. Jagtap, T. G., Komarpant, D. S., & Rodrigues, R. S. (2003). Status of a seagrass ecosystem: An ecologically sensitive wetland habitat from India. *Wetlands, 23*(1), 161–170.
33. Jänes, H., Macreadie, P. I., Zu Ermgassen, P. S., Gair, J. R., Treby, S., Reeves, S., & Carnell, P. (2020). Quantifying fisheries enhancement from coastal vegetated ecosystems. *Ecosystem Services, 43*, 101105.
34. Jiang, Z., Cui, L., Liu, S., Zhao, C., Wu, Y., Chen, Q., & Huang, X. (2020). Historical changes in seagrass beds in a rapidly urbanizing area of Guangdong Province: Implications for conservation and management. *Global Ecology and Conservation, 22*, e01035.
35. Kerr, J. (2017). *Introduction to energy and climate: Developing a sustainable environment.* CRC Press.
36. Khoo, K. H., Ramette, R. W., Culberson, C. H., & Bates, R. G. (1977). Determination of hydrogen ion concentrations in seawater from 5 to 40°C: Standard potentials at salinities from 20 to 45%. *Analytical Chemistry, 49*(1), 29–34.
37. Koroleff, F. (1983). Determination of total phosphorus. In K. Grasshoff, M. Erhardt, & K. Kremling (Eds.), *Methods for seawater analysis* (2nd ed., pp. 167–173). Verlag Chemie.
38. Kurniawan, F., Arkham, M. N., Rustam, A., Rahayu, Y. P., Adi, N. S., Adrianto, L., & Damar, A. (2020). An ecosystem services perspective for the economic value of

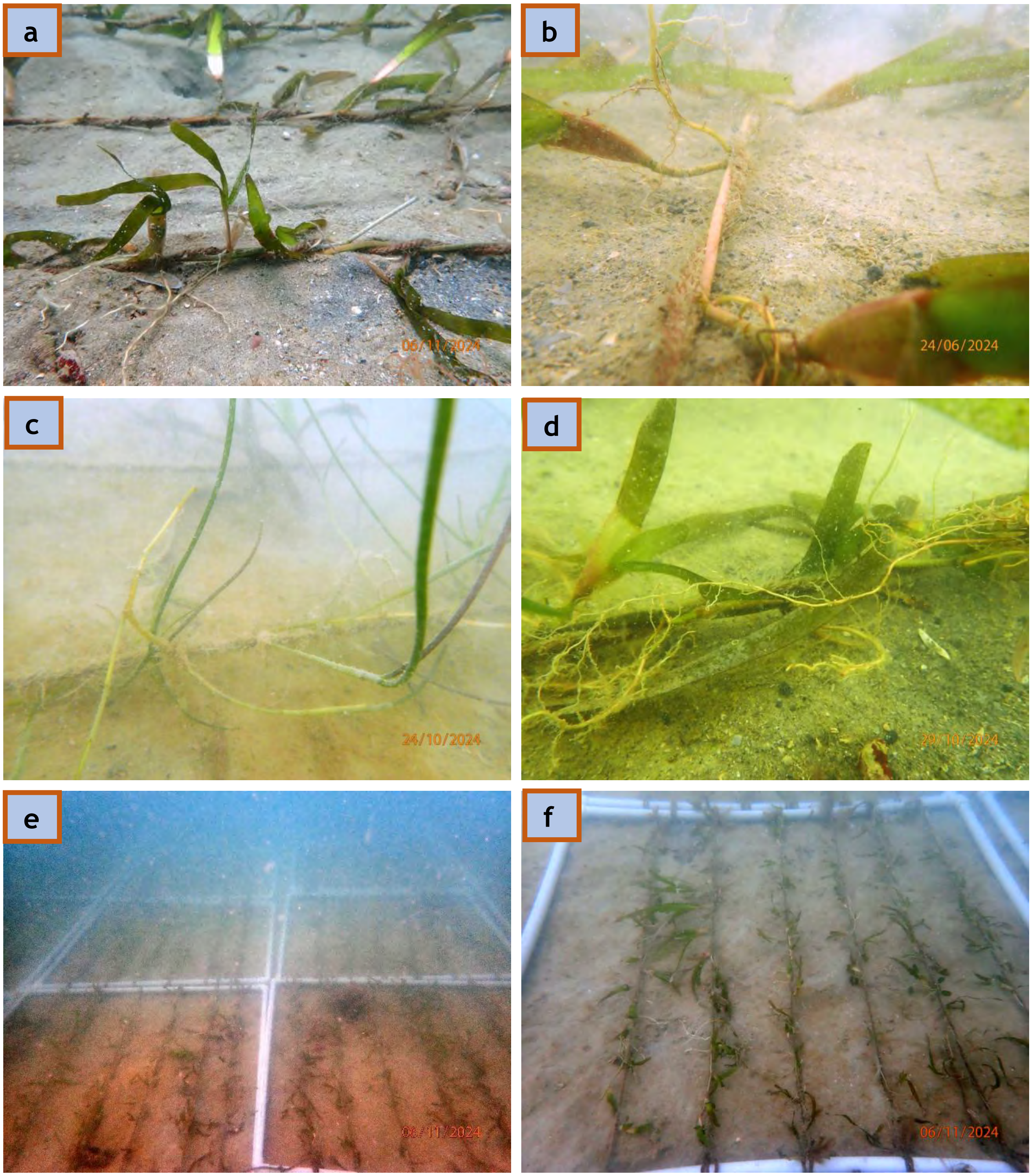
seafood production supported by seagrass ecosystems: An exercise in Derawan Island, Indonesia. *IOP Conference Series: Earth and Environmental Science, 414*(1), 012008.

39. Mathews, G., Raj, K. D., Thinesh, T., Patterson, J., Edward, J. P., & Wilhelmsson, D. (2010). Status of seagrass diversity, distribution, and abundance in Gulf of Mannar Marine National Park and Palk Bay (Pamban to Thondi), southeastern India. *South Indian Coastal and Marine Bulletin, 2*(2), 1–21.
40. McArthur, L. C., & Boland, J. W. (2006). The economic contribution of seagrass to secondary production in South Australia. *Ecological Modelling, 196*(1–2), 163–172.
41. McKenzie, L. J., Yaakub, S.M., & Yoshida, R.L. (2003). Seagrass-watch: Guideline for team grass Singapore participants. Proceedings of a training workshop, National Park Board, Biodiversity Centre Singapore, 24th-25th March. 32.
42. McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment, 9*(10), 552–560.
43. Nakamura, Y. (2009). Status of seagrass ecosystems in the Kuroshio region: Seagrass decline and challenges for future conservation. *Kuroshio Science, 3*(1), 39–44.
44. Nellemann, C., & Corcoran, E. (2009) Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment, UNEP/Earthprint.
45. Nurdianto, D. A., & Resosudarmo, B. P. (2016). The economy-wide impact of a uniform carbon tax in ASEAN. *Journal of Southeast Asian Economies, 33*, 1–22.
46. Ogden, J. C., & Gladfelter, E. H. (Eds.). (1983). *Coral reefs, seagrass beds and mangroves: Their interaction in the coastal zones of the Caribbean: Report of a workshop.* UNESCO.
47. Paling, E. I., Fonseca, M., van Katwijk, M. M., & Keulen, M. V. (2009). Seagrass restoration. In *Coastal wetlands* (pp. 687–713). Elsevier.

48. Pandelaki, L., Rompas, R. M., Rembet, U. N., Wantasen, A. S., Gerung, G. S., & Ngangi, E. L. (2020). Economic value of seagrass ecosystem in Nain Island, South Minahasa Regency, North Sulawesi, Indonesia.
49. Parthasarathy, N., Ravikumar, K., Ganesan, R., & Ramamurthy, K. (1991). Distribution of seagrasses along the coast of Tamil Nadu, Southern India. *Aquatic Botany, 40*, 145–153.
50. Raj, K. D., Mathews, G., Obura, D. O., Laju, R. L., Bharath, M. S., Kumar, P. D., ... & Edward, J. P. (2020). Low oxygen levels caused by *Noctiluca scintillans* bloom kills corals in Gulf of Mannar, India. *Scientific Reports, 10*(1), 22133.
51. Saito, Y., & Atobe, S. (1970). Phytosociological study of intertidal marine algae. I. Usujiri Benten-Jima, Hokkaido. *Bulletin of the Faculty of Fisheries, 21*, 37–69.
52. Serrano, O., Gómez-López, D. I., Sánchez-Valencia, L., Acosta-Chaparro, A., Navas-Camacho, R., González-Corredor, J., ... & Marbà, N. (2021). Seagrass blue carbon stocks and sequestration rates in the Colombian Caribbean. *Scientific Reports, 11*(1), 1–12.
53. Serrano, O., Mateo, M. A., Renom, P., & Julià, R. (2012). Characterization of soils beneath a *Posidonia oceanica* meadow. *Geoderma, 185–186*, 26–36.
54. Short, F., Carruthers, T., Dennison, W., & Waycott, M. (2007). Global seagrass distribution and diversity: A bioregional model. *Journal of Experimental Marine Biology and Ecology, 350*(1–2), 3–20.
55. Short, F., Short, C., & Novak, A. (2016). Seagrasses. In *Encyclopedia of Estuaries* (pp. 1–10). Springer.
56. Strickland, J. D. H., & Parsons, T. R. (1972). *A practical handbook of seawater analysis*.
57. Tan, Y. M., Dalby, O., Kendrick, G. A., Statton, J., Sinclair, E. A., Fraser, M. W., ... & Sherman, C. D. (2020). Seagrass restoration is possible: Insights and lessons from Australia and New Zealand. *Frontiers in Marine Science, 7*, 617.
58. Thangaradjou, T. (2000). *Eco-biology, culture and experimental transplantation of seagrasses of the Gulf of Mannar Biosphere Reserve* (Doctoral dissertation, Annamalai University, India). *Aquatic Biology & Fisheries, 10*(1), 103–108.

59. Thangaradjou, T., & Kannan, L. (2008). Survival and growth of transplants of laboratory-raised axenic seedlings of *Enhalus acoroides* (Lf) Royle and field-collected plants of *Syringodium isoetifolium* (Aschers.) Dandy, *Thalassia hemprichii* (Ehrenb.) Aschers., and *Halodule pinifolia* (Miki) den Hartog. *Journal of Coastal Conservation, 12*, 135–143.
60. Thangaradjou, T., Kannan, L., & Ravichandran, S. (1998). Seagrasses of the Gulf of Mannar. In Kannan, L. & Kannan, R. (Eds.), *Living on the edges* (pp. 76–83). ENVI Publication Series 3/98, Annamalai University.
61. Touchette, B. W. (2007). Seagrass-salinity interactions: Physiological mechanisms used by submersed marine angiosperms for a life at sea. *Journal of Experimental Marine Biology and Ecology, 350*, 194–215.
62. Tucker, B. B., & Kurtz, L. T. (1961). Calcium and magnesium determinations by EDTA titrations. *Soil Science Society of America Journal, 25*(1), 27–29.
63. Unsworth, R. K., McKenzie, L. J., Collier, C. J., Cullen-Unsworth, L. C., Duarte, C. M., Eklöf, J. S., ... & Nordlund, L. M. (2019). Global challenges for seagrass conservation. *Ambio, 48*, 801–815.
64. Waycott, M., Duarte, C. M., Carruthers, T. J., Orth, R. J., Dennison, W. C., Olyarnik, S. & Williams, S. L. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences, 106*(30), 12377–12381.
65. Woody, C., Shih, E., Miller, J., & Royer, T. (2000). Measurement of salinity in the coastal ocean: A review of requirements and technologies. *Marine Technology Society Journal, 34*(2), 26–34.

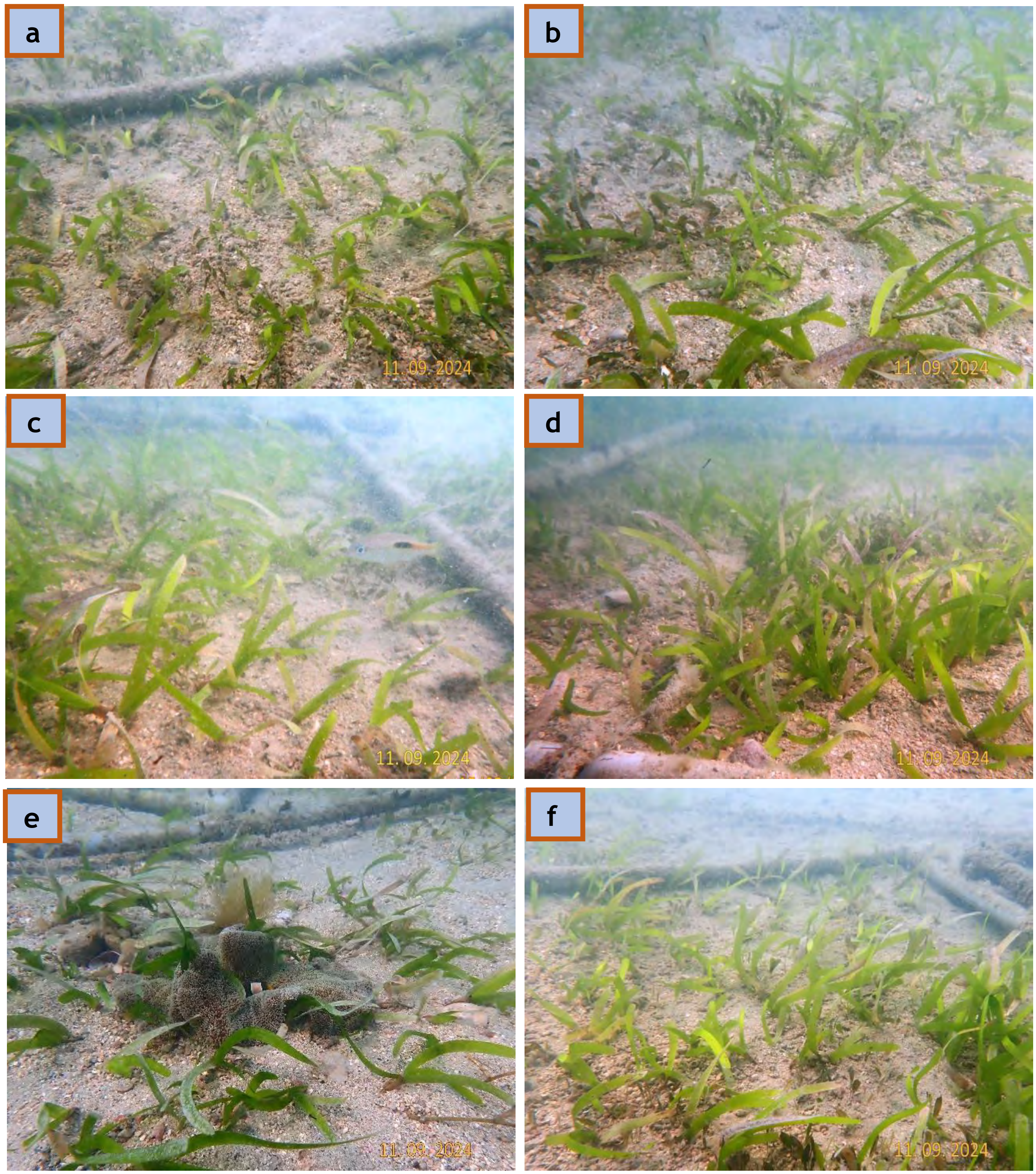
Plates 1 & 2: Underwater photos of seagrass restoration site during the first day of transplantation



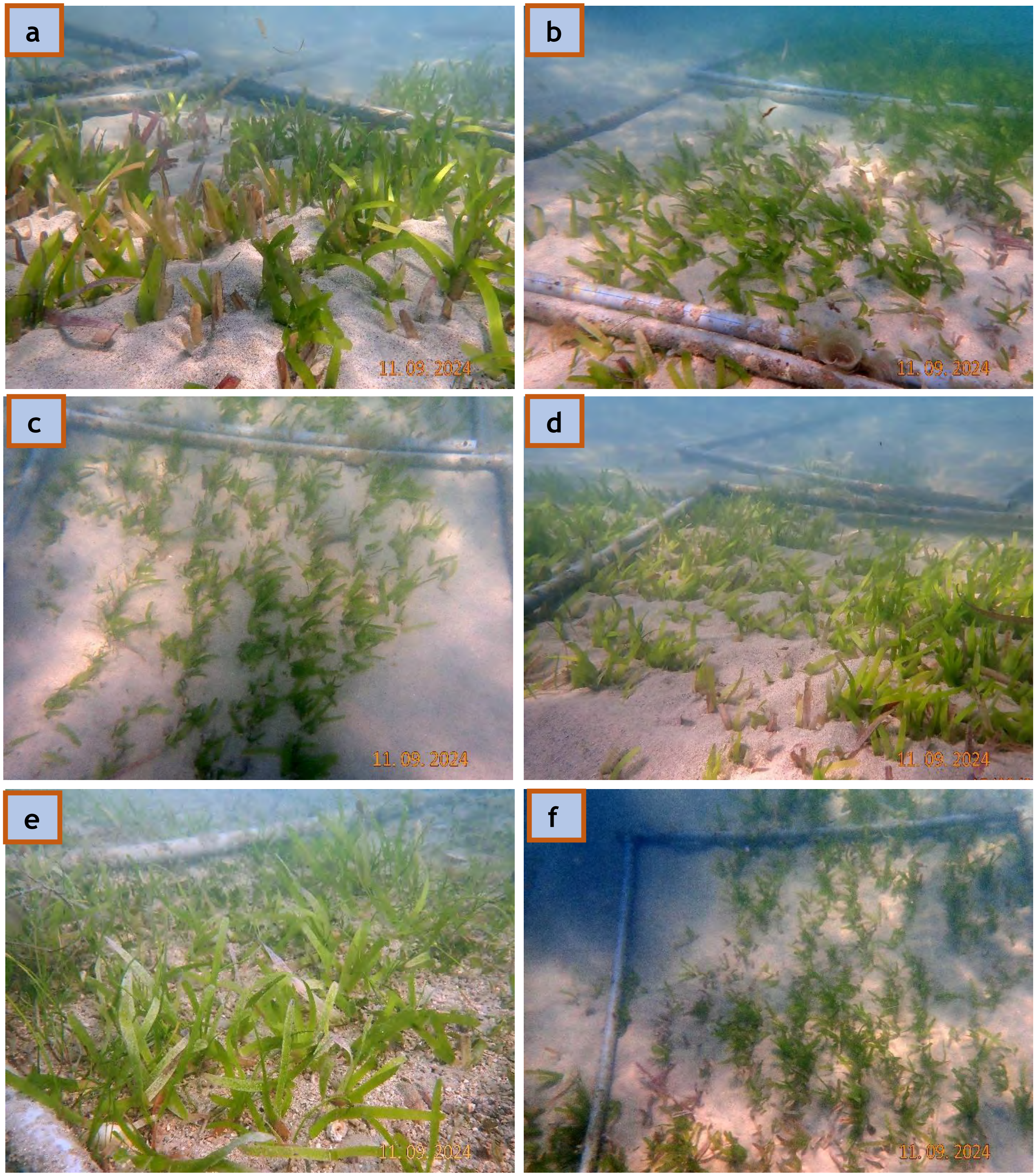
(a) & (b) *Oceana serrulata* (c) *Syringodium isoetifolium* (d) *Thalassia hemprichii* (e) & (f) *restored seagrass species*
(b)

(a) & (b) *Oceana serrulata* (c) *restored seagrass species* (d) *Thalassia hemprichii* (e) & (f) *Oceana serrulata*

Plates 3 & 4: Underwater photos of seagrass restoration site after four months



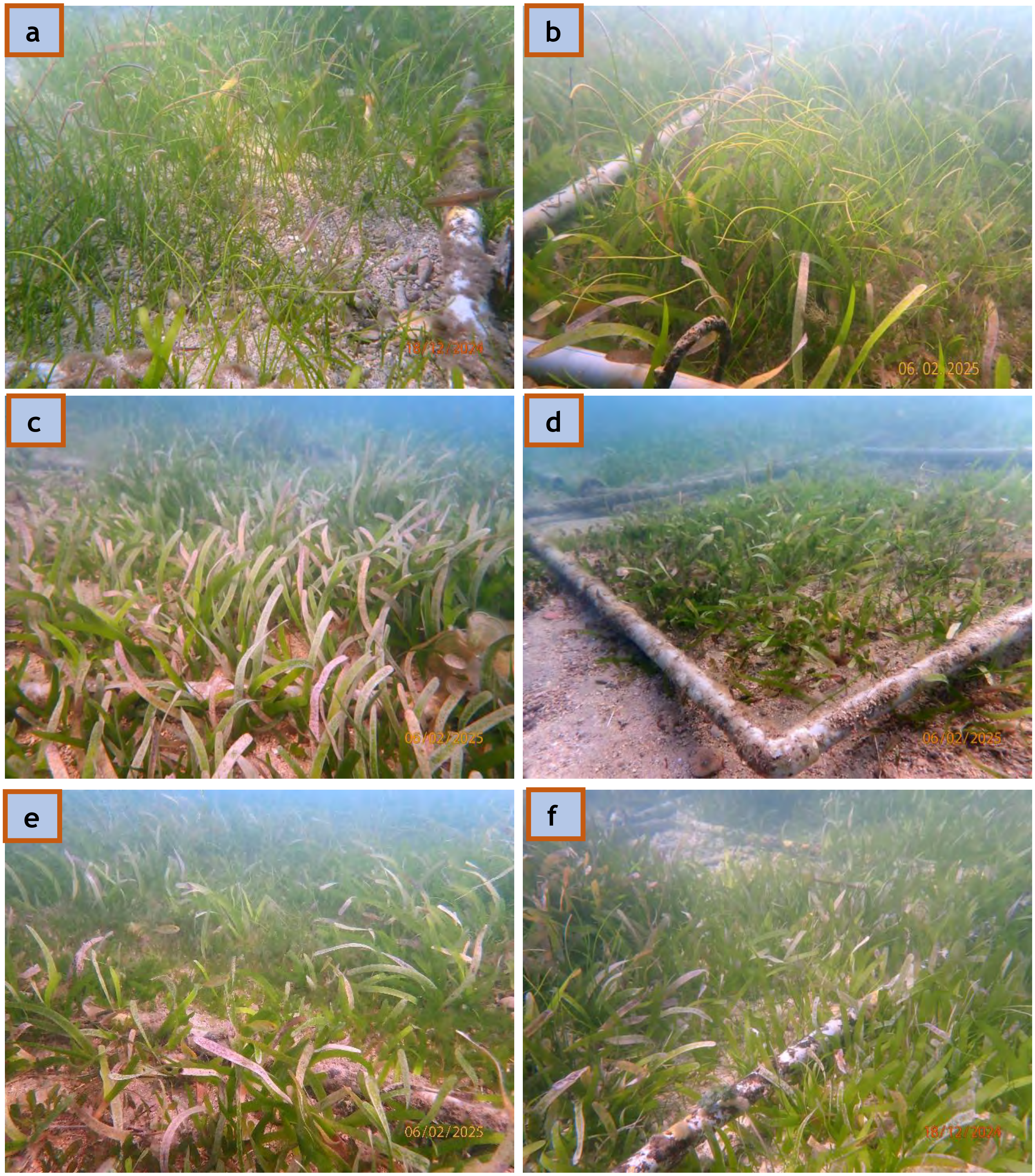
(a),(b), (c),(d) *Oceana serrulata (*e) *Thalassia hemprichii* (f) *Oceana serrulata*



(a),(b), (c),(d) *Oceana serrulata (*e) *Thalassia hemprichii* (f) *Oceana serrulata*

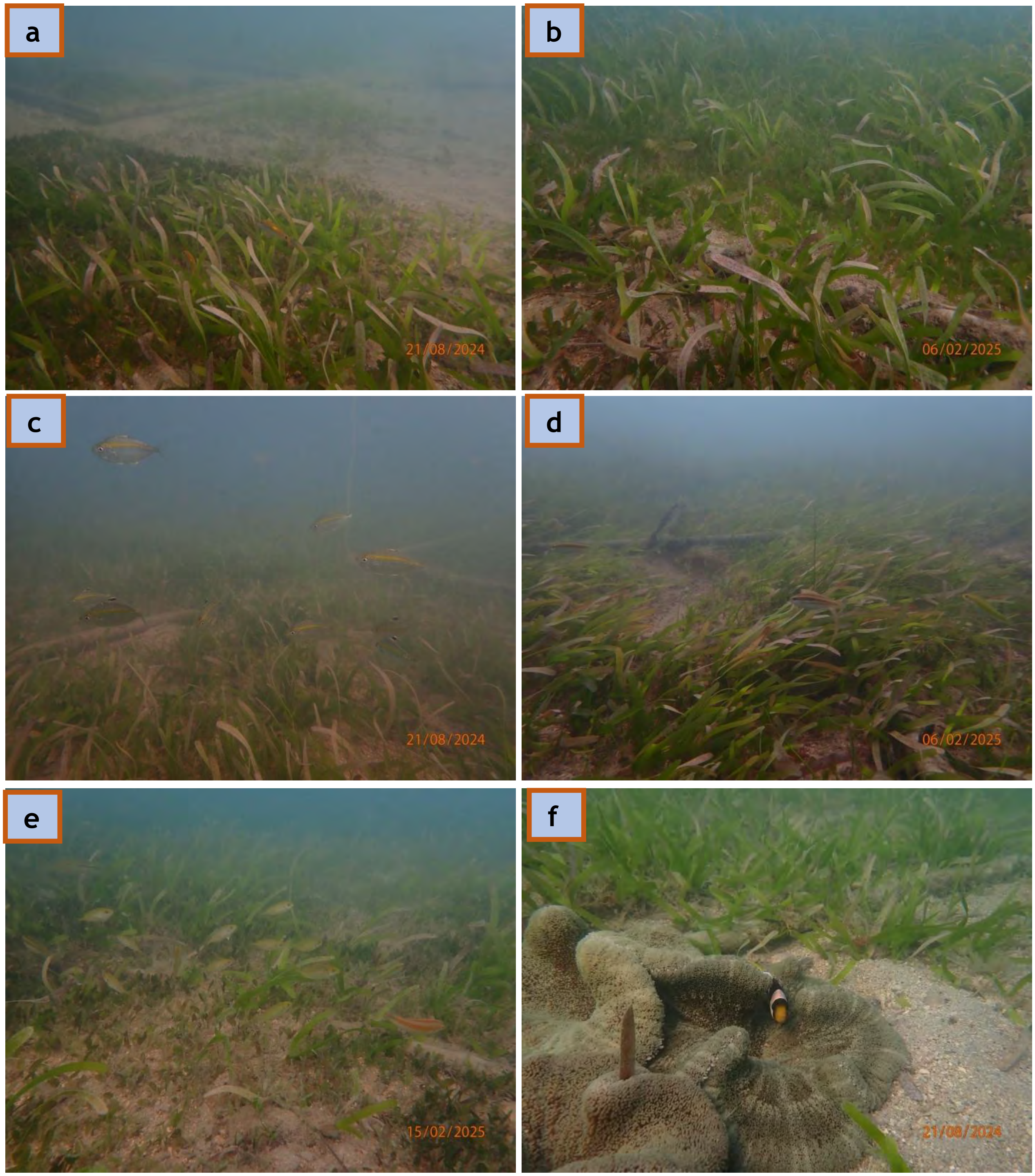
Plates 5 & 6: Underwater photos of seagrass restoration site after eight months

(a),(b), (c),(d), (e) and (f) *Oceana serrulata*



(a) & (b) *Oceana serrulata* and *Syringodium isoetifolium* (c), (d), (e) and (f) *Oceana serrulata*

Plate 7: Observed associated fish species in seagrass restoration sites of Koswari Island



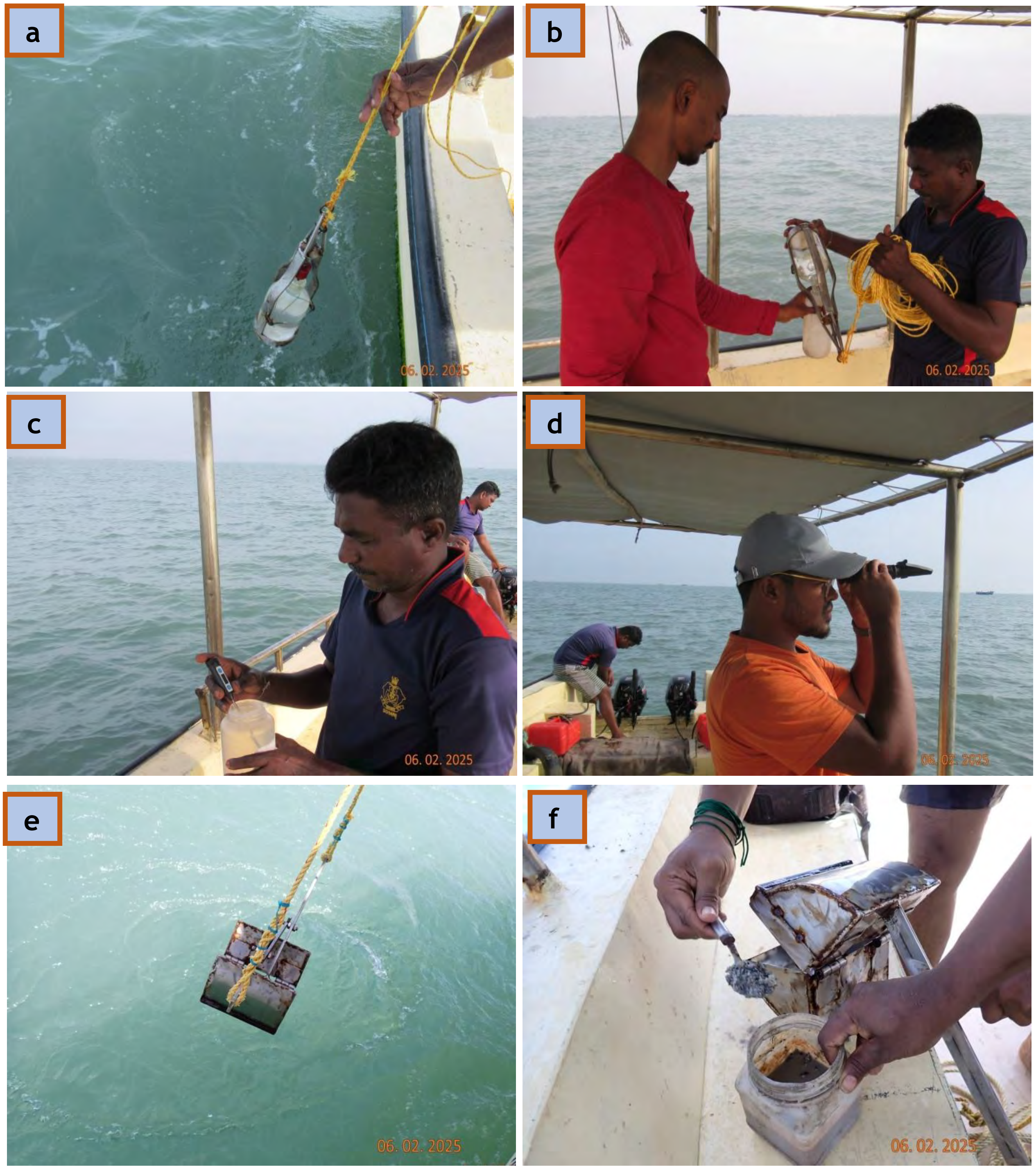
(a) *Parupeneus indicus* (b) *Siganus canaliculatus* (c) *Eubleekeria splendens* (d) *Terapon puta* (e) *Siganus* sp. (f) *Amphiprion* sp.

Plate 8 & 9: Observed associated benthic macrofauna in seagrass restoration sites in Koswari Island

(a) *Salmacis virgulata* (b) *Oceana serrulata* (c) *Pinna* sp. (d) *Harpulina lapponica* (e) *Lambis lambis* (f) *Stichodactyla* sp.

(a) *Didemnum* sp. (b) *Padina* sp. (c) *Stichodactyla* sp. (d) *Holothuria scabra* (e) *Lambis lambis* (f) *Holothuria atra*

Plate 10: Physio-chemical sample collection at seagrass restoration site



(a) & (b) water sampling using Meyer's water sampler (c) water temperature analysis (d) water salinity analysis using refractometer (e) & (f) Sediment collection using Petersen grab