

Seasonal dynamics of macroalgal dominance and its ecological impacts on coral reefs in Mangadu, Palk Bay, India

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ABSTRACT

This study investigates the seasonal patterns of macroalgal dominance and biomass accumulation on coral reefs in Mangadu, located along the southeast coast of India, and evaluates their ecological implications for reef health. Field surveys revealed extensive proliferation of green (Chlorophyta), brown (Phaeophyta), and red (Rhodophyta) algae, frequently overgrowing live corals and reef substrates. Such overgrowth reduced light availability, created hypoxic microenvironments, and intensified competition through shading and direct contact, particularly by *Sargassum* spp. and *Halimeda* spp. Distinct seasonal variations were observed, with Chlorophyta dominating during the monsoon, while Phaeophyta prevailed during summer and pre-monsoon periods. Rhodophyta contributed minimally throughout the study period. Among the taxa, *Caulerpa sedoides* and *Sargassum wightii* were consistently dominant. Biomass peaked during the post-monsoon season, suggesting enhanced growth under nutrient-enriched conditions. The results indicate that macroalgal dominance is strongly influenced by seasonal environmental variability and anthropogenic pressures, posing a significant threat to coral reef resilience in the Mangadu region. These findings highlight the urgent need for effective management strategies to mitigate macroalgal overgrowth and protect reef ecosystems.

Keywords: Algal accumulation, Anthropogenic impact, Coral reef, Macro algae dominance, Mangadu, Palk Bay.

INTRODUCTION

Marine macroalgae (seaweeds) are integral components of coastal ecosystems and provide vital habitats and food sources for a diverse array of marine organisms¹ (Chaturvedi et al., 2022; Erniati et al., 2023). These photosynthetic organisms play a critical role in ocean health by absorbing dissolved carbon dioxide and releasing oxygen, thereby contributing significantly to the planet's atmospheric balance across various ocean depths (Bhuyan et al., 2021; Fong & Paul, 2010). Morphologically and biochemically diverse seaweeds are broadly categorized into three primary phyla, based on their pigmentation: Chlorophyta (green algae), Phaeophyta (brown algae), and Rhodophyta (red algae) (Hegazi, 2002; Pathak et al., 2020). Beyond their structural contributions, seaweeds function as natural biofilters, efficiently absorbing excess nutrients like nitrogen and phosphorus from the water column. This nutrient sequestration helps mitigate eutrophication, improves water quality, and serves as an important indicator of marine environmental well-being (Adharini et al., 2021; Widyartini et al., 2023).

Seaweeds exhibit varied reproductive strategies, encompassing both sexual reproduction via gamete release and asexual propagation through fragmentation, where detached portions develop into new individuals (Liu et al., 2017). Their ability to anchor firmly to diverse substrates such as rocks, coral reefs, shells, and submerged wood is facilitated by specialized structures known as holdfasts (Carling, 2014; Preskitt et al., 2004). Globally, over 10,000 distinct species of marine algae have been identified, with India recording 844 species, including 191 Phaeophyta species. In particular, the state of Tamil Nadu has the highest diversity within India, accounting for approximately 302 recorded seaweed species (Remya & Rajasree, 2015; Pathak et al., 2020).

The Mangadu coast, located in Palk Bay on the southeast coast of India, is recognized for its rich marine biodiversity encompassing diverse seaweed populations and extensive coral reef ecosystems (Costa Jr et al., 2002; Marimuthu et al., 2022). The rapid growth rates of many seaweed species, often surpassing those of terrestrial plants, have led to their significant economic utilization by local fishermen in Mangadu through harvesting and

cultivation. Specifically, the commercial cultivation of *Kappaphycus alvarezii* is actively promoted to support livelihoods, given its capacity to double in biomass within a single week (Zhu & Lee, 1997). However, despite the inherent value of these seaweed communities, the Mangadu coast has recently experienced substantial accumulation and overgrowth of seaweeds on nearshore coral reefs.

This phenomenon has been exacerbated by various anthropogenic factors. Activities such as dropping anchors and boat movements in shallow waters cause sediment resuspension, which can smother corals and reduce light penetration (Ramos et al., 2010). Moreover, overfishing contributes to the decline of herbivorous and predatory fish, disrupting natural food web dynamics and reducing crucial top-down control of algal populations (Hay, 1997; Pal & Bhattacharyya, 2020). This imbalance frequently precipitates algal blooms and allows seaweeds to grow unchecked, directly competing with corals for space and light (Rasher & Hay, 2010; Fong & Paul, 2010). As seaweeds proliferate, they can rapidly overgrow coral colonies, impede photosynthesis, and ultimately lead to coral stress, disease, and bleaching (Gomez-Lemos & Diaz-Pulido, 2017; Smith et al., 2023). Critically, damaged and bleached reef structures provide new, stable surfaces for seaweed attachment and further expansion, creating a detrimental feedback loop that threatens the long-term health and resilience of Mangadu reefs (Costa Jr et al., 2002; Marimuthu et al., 2022). The study aims to quantify the spatial extent and ecological impacts of this accumulation and to support conservation and management efforts along the Mangadu coast of Palk Bay.

MATERIALS AND METHODS

Field survey

A pilot study was conducted at 9°19'30.02"N and 79°19'26.75"E to identify and document seaweed accumulation in the nearshore reef area (Figure 1). The distribution and percentage cover of macroalgae were assessed using a combination of the belt transect and quadrat methods (Ramos et al., 2010; Marimuthu et al., 2022; English et al., 1997). A seasonal survey was carried out from June 2024 to May 2025 to capture temporal variations in seaweed abundance. A 30-meter transect tape was laid perpendicular to the shoreline at 15 randomly selected locations across the study area. Along each transect, 25 quadrats (1 m²) were systematically placed and examined during each season. This sampling design enabled the collection of detailed information on the spatial patterns, species diversity, and relative abundance of macroalgae within defined survey zones (Preskitt et al., 2004; English et al., 1997).

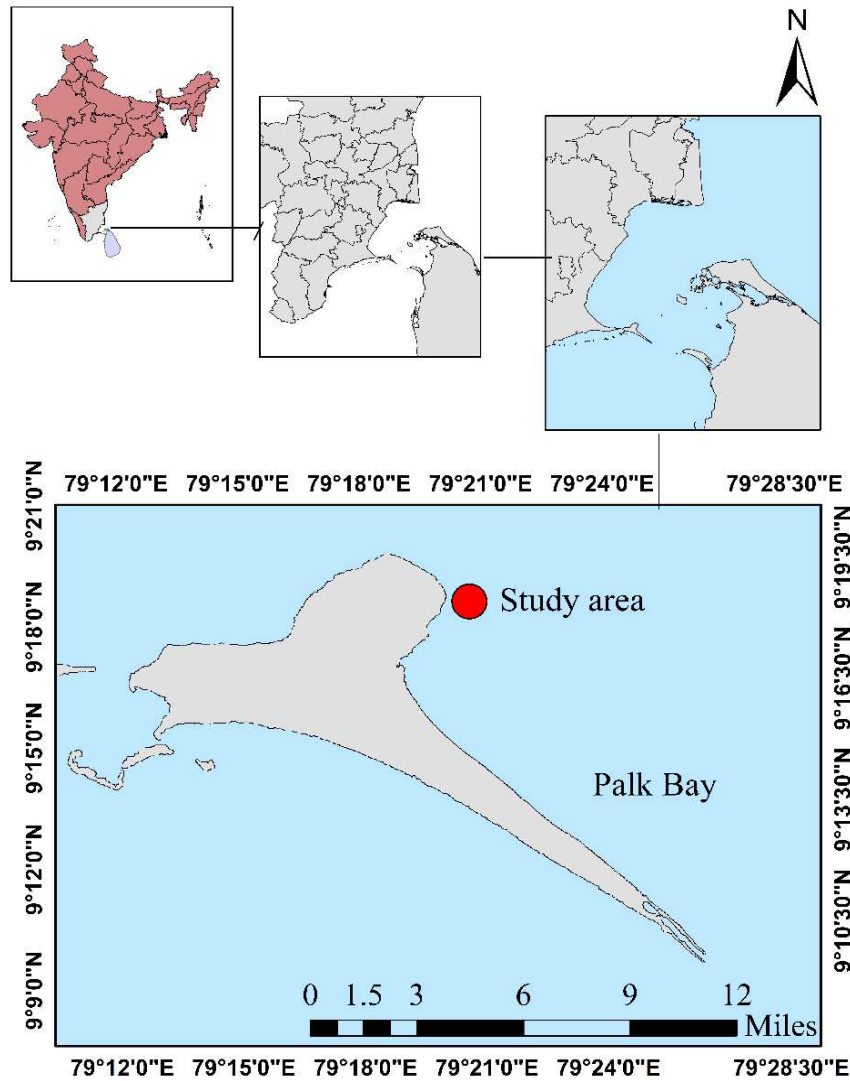


Figure 1. The study area map showing coastal site located at 9°19'30.02"N and 79°19'26.75"E along the Mangadu shoreline.

Biomass analysis

Seaweed biomass was quantified by quadrat sampling in the Mangadu reef area. A total of 5 (1 m²) quadrats were selectively collected for destructive sampling during each seasonal sampling period. All macroalgae within the selected quadrats were collected carefully. In the laboratory, the samples were thoroughly cleaned to remove sediment and epiphytes, and their wet weight was immediately measured. To determine dry weight, the samples were then oven-dried at 60°C for 48 hours until a constant weight was achieved. These wet and dry weight measurements were used to estimate the total macroalgal biomass per square metre within the study area (Zhu & Lee, 1997).

Sample collection

Seaweed samples were carefully removed using a knife and stored in polyethylene bags, while an underwater camera was used to document macroalgal cover and reef conditions in situ. All collected specimens were preserved in 4% formaldehyde solution for subsequent taxonomic identification in the laboratory.

Seasonal water samples were collected from the study area using 500 mL sterile polythene bottles during sampling. The samples were immediately transported to the laboratory under controlled conditions and analysed for key physicochemical parameters following standard APHA (1998) protocols.

Statistical analysis

The seasonal data: summer, pre-monsoon, monsoon and post-monsoon, and the results are shown by season. Both environmental and biological data were statistically analyzed using univariate, graphical/distributional, and multivariate methods available in the statistical software PRIMER (Ver. 7.0; Clarke *et al.* 2016). The benthic community structure was described using species numbers and abundance data, the diversity index (H') (Shannon and Wiener, 1949), Margalef's richness index (d) (Margalef, 1958), and evenness (J') (Pielou, 1966). Dendrogram and ordination plots were drawn to illustrate the similarities between the zones, samples, and stations (Shepard, 1962; Legendre & Legendre 2012).

Principal Component Analysis (PCA) was used to visualize the correlation between physicochemical parameters and seasons in the study area. Similarly, Canonical Correspondence Analysis (CCA) was employed to relate the abundance of seaweed taxa with linear representations of environmental variables across seasons. Multidimensional Scaling (MDS) was further applied to assess similarities and dissimilarities in species abundance patterns among seasons, providing a robust ordination of community structure. In addition, hierarchical cluster analysis (HCA) was performed to classify the seasonal assemblages of seaweeds based on their abundance data, thereby grouping seasons with similar community compositions.

RESULT

Seaweed accumulation

A field survey conducted on the reefs of Mangadu revealed significant dominance and accumulation of macroalgae, particularly from the Chlorophyta, Phaeophyta, and Rhodophyta algal groups. These algae have been observed grow extensively over live coral colonies, dead coral skeletons, and various reef substrates. High algal biomass was found to directly smother coral colonies, especially branching corals, such as *Acropora*. Algal mats reduce light penetration and create hypoxic microzones around coral tissues, particularly at night. Physical contact and shading by species such as *Sargassum* and *Halimeda* led to tissue recession in the coral colonies (figure 2 & figure 13). The assessment of macroalgal accumulation indicated varying dominance among algal groups across different seasons: during the Monsoon Season, Chlorophyta constituted approximately 66% of the total algal cover, Phaeophyta accounted for 32%, and Rhodophyta represented 2%; in the Post-Monsoon Season, Chlorophyta represented 44%, Phaeophyta 50%, and Rhodophyta 6% of the accumulation; the Summer Season showed Phaeophyta dominating with 61% accumulation, followed by Chlorophyta at 39%, while Rhodophyta exhibited 0% accumulation; and during the Pre-Monsoon Season, Phaeophyta accounted for 52% of accumulation, Chlorophyta 43%, and Rhodophyta 5% (figure 3). The green algal assemblage, primarily composed of *Caulerpa*, *Ulva*, and *Halimeda* spp., exhibits extensive overgrowth on live coral surfaces and reef substrates, often forming dense mats that impede light penetration and water circulation. Brown algae, notably *Sargassum* and *Turbinaria* spp., contribute to additional shading and spatial competition with coral colonies. Despite their minimal overall presence, accumulation of red algae was occasionally observed in low-energy microhabitats.

Distribution and Percentage Cover

Belt transect and quadrat assessments of macroalgal communities on Mangadu coral reefs revealed seasonal variations in species dominance and diversity. *Caulerpa sedoides* emerged as the most consistently dominant macroalga across all seasons, peaking at 39% cover during the monsoon and maintaining high representation during the pre-monsoon (27.3%) and summer (20.6%) seasons. This Chlorophyte frequently forms dense mats across reef flats and lagoon zones, often outcompeting other algae for space and light. *Sargassum wightii*, a robust brown alga, showed seasonal peaks in summer (36.5%) and post-monsoon (29.4%), indicating its preference for higher water temperatures and energy-rich reef crest zones. Its upright, leathery thalli allow it to thrive under intense wave action. Another brown alga, *Turbinaria ornata*, consistently contributed to the assemblage with 14-16.4% cover, especially during the pre-monsoon and monsoon, reflecting its resilience in high-energy environments. Among the calcareous green algae, *Halimeda opuntia* was notably abundant during the monsoon (21%) and pre-monsoon (16.1%) seasons. Its ecological role in sediment formation and reef framework development is evident from its widespread presence across the fore-reef and back reef zones. Other macroalgal species showed lower but seasonally variable coverage. *Caulerpa taxifolia* contributed modestly during all seasons, especially in post-monsoon (6.9%) and monsoon (6%), often occupying shaded microhabitats. *Padina pavonica*, a small brown alga, showed an increase in cover during pre-monsoon (8.9%) and summer (6.9%), while remaining low during the monsoon (1%) (figure 4). The red alga *Dichotomaria obtusata* was present across multiple seasons but never exceeded 6%, typically occupying low-light, sediment-rich microhabitats. *Codium adhaerens* and *Stoechospermum marginatum*, although rare, were seasonally detected in the post-monsoon and summer seasons, respectively, reflecting localized and niche-specific occurrences within the reef ecosystem.

Seaweed Diversity

Quadrat assessment in the Mangadu reef area revealed a diverse macroalgal community comprising nine distinct species, as shown in the data provided. Among the recorded taxa, *Caulerpa sedoides* was the most abundant, with 860 individuals, dominating the algal composition across all seasons. This was followed by *Sargassum wightii* with 853 individuals, a prominent brown macroalga, and *Turbinaria ornata* with 572 individuals. *Halimeda opuntia* also significantly contributed to the calcareous algal cover of the reef with 565 individuals. In contrast, *Caulerpa taxifolia* was encountered less frequently with 218 individuals. *Padina pavonica* was present with 342 individuals, while *Dichotomaria obtusata* had 92 individuals. *Codium adhaerens* and *Stoechospermum marginatum* were the least abundant, with 28 and 26 individuals, respectively, and were not observed in any seasons. The overall diversity of the algal community, considering the provided data, reflected a significant total of 3556 individuals across all recorded species and seasons (figure 5). The seasonal distribution shows fluctuations in abundance for various species, with some thriving in specific periods, such as *Sargassum wightii* during the post-monsoon season (338 individuals) and *Caulerpa sedoides* also showing high numbers in the post-monsoon season (289 individuals).

Table 1. Diversity indexes

Season	Shannon-Wiener diversity index (H')	Simpson's Index of Diversity (D)	Species richness (S)	Evenness (E)
Monsoon	1.53	0.7409	7	0.785
Post Monsoon	1.88	0.83	8	0.90
Summer	1.79	0.82	7	0.92
Pre Monsoon	1.69	0.80	6	0.95

The Post Monsoon season showed the highest species diversity, with the maximum values for the Shannon-Wiener Diversity index (1.88), Simpson's Index of Diversity (0.83), and species richness (8). Conversely, the Monsoon season has the lowest species diversity, with the minimum values for Shannon-Wiener Diversity Index (1.53), Simpson's Index of Diversity (0.7409), and Evenness (0.785). The Pre Monsoon season shows the highest Evenness value (0.95), while having the lowest Species richness (6). Summer had intermediate values across all the season (Table1).

Density

The quadrat-based density assessment, conducted across a total area of 100 m² in the Mangadu reef, revealed a distinct distribution of macroalgal species. *Caulerpa sedoides* emerged as the most dominant species, exhibiting a high density of 8.6 individuals per m², indicative of its widespread presence throughout the reef system. Closely following in dominance was *Sargassum wightii* with a density of 8.53 individuals per m². Other significant contributors included *Turbinaria ornata* and *Halimeda opuntia*, which recorded densities of 5.72 and 5.65 individuals per m², respectively, and the latter particularly highlighted its contribution to the reef's calcareous structure. Conversely, species such as *Padina pavonica* (3.42 individuals per m²), *Caulerpa taxifolia* (2.18 individuals per m²), and *Dichotomaria obtusata* (0.92 individuals per m²) exhibited comparatively lower densities, suggesting a more restricted distribution within the study area. The lowest observed densities were for *Codium adhaerens* (0.28 individuals per m²) and *Stoechospermum marginatum* (0.26 individuals per m²) (figure 6). Collectively, these findings provide crucial baseline data on the spatial distribution and ecological dominance patterns of macroalgal species within the Mangadu reef system.

Seaweed Biomass

Seasonally, the post-monsoon period generally supported the highest individual counts for several species, with *Sargassum wightii* peaking at 338 individuals and *Caulerpa sedoides* at 289 individuals. The summer season also showed considerable abundance of species such as *Sargassum wightii* (254 individuals) and *Halimeda opuntia* (181 individuals). Conversely, some species, like *Caulerpa taxifolia*, *Dichotomaria obtusata*, *Codium adhaerens*, and *Stoechospermum marginatum*, showed periods of absence or very low counts in specific seasons, particularly during the monsoon and pre-monsoon. Total seaweed biomass exhibited clear seasonal fluctuations, with the highest values observed during the post-monsoon season. The wet weight biomass peaked at 7.82 kg in

the post-monsoon, followed by the summer (5.19 kg), pre-monsoon (4.87 kg), and monsoon (4.55 kg) seasons. Similarly, the dry weight biomass was highest during the post-monsoon at 1.98 kg, with lower values recorded in summer (1.12 kg), pre-monsoon (1.08 kg), and monsoon (0.81 kg) (figure 7). This indicates that the post-monsoon period is crucial for macroalgal growth and accumulation in the Mangadu Reef.

Benthic accumulation

Benthic accumulation data revealed seasonal shifts in the dominant life forms on the reef. Seaweed cover was consistently the highest component, peaking during the summer season at 62%, followed by post-monsoon (59%), pre-monsoon (49%), and monsoon (41%). This aligns with the higher macroalgal abundance and biomass observed in the post-monsoon and summer periods. Live coral cover showed the highest percentage in the monsoon at 39.31%, maintaining relatively stable levels in the pre-monsoon (34.17%) and summer (34.00%), periods but slightly decreased in the post-monsoon period (31.77%). Conversely, bleached coral percentages were highest during the monsoon (19.69%) and pre-monsoon (16.83%), suggesting potential environmental stressors during these periods. The lowest bleached coral presence was observed in summer (3.49%) and post-monsoon (9.55%), indicating periods of recovery or reduced stress for corals (figure 8). These integrated findings underscore the dynamic and seasonally influenced nature of the Mangadu reef ecosystem, highlighting the interplay between macroalgal proliferation, biomass accumulation, and the health of the coral communities.

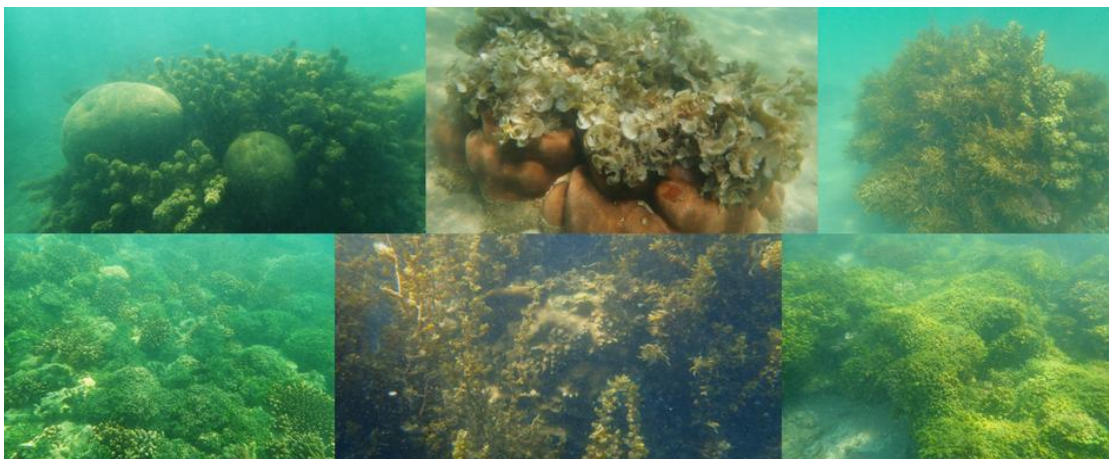
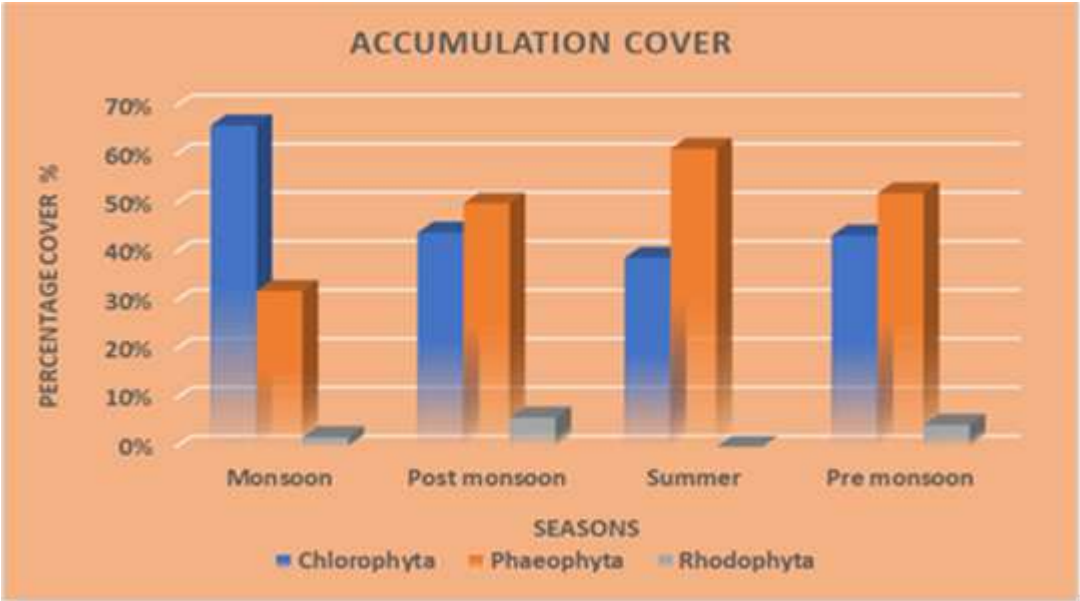
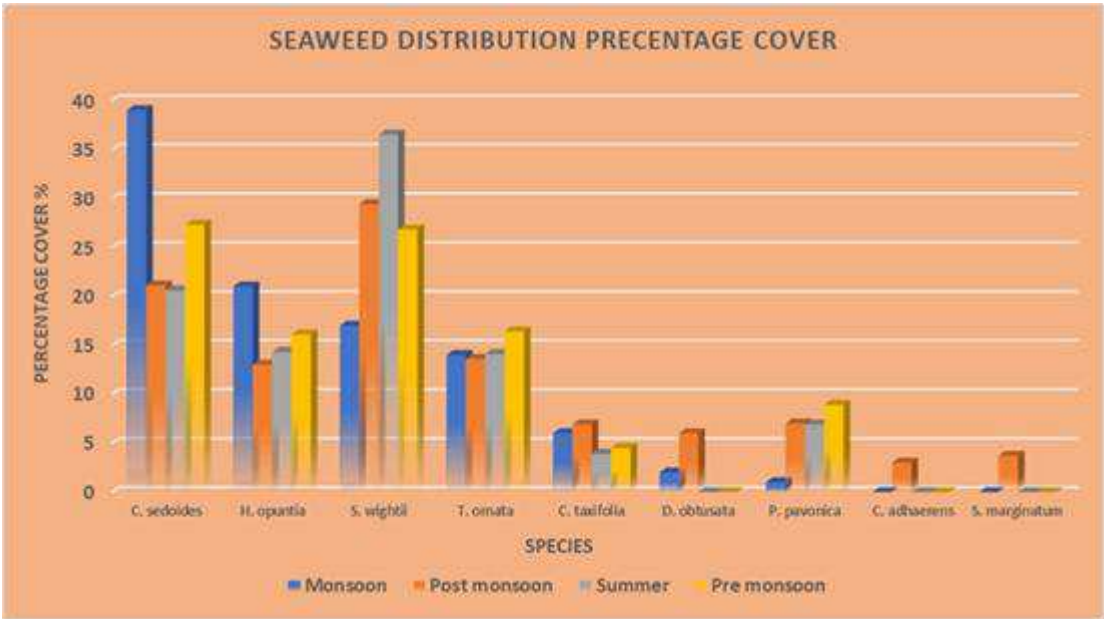


Figure 2. Seaweed dominance and accumulation on the Mangadu reef indicate significant overgrowth and habitat alteration



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Figure 3. Seasonal percentage cover of accumulated seaweeds, illustrating distinct temporal shifts in macroalgal distribution and abundance across the study area.



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Figure 4. Percentage cover of seaweed species distribution, illustrating variation in the relative abundance of dominant macroalgal taxa across the study area.

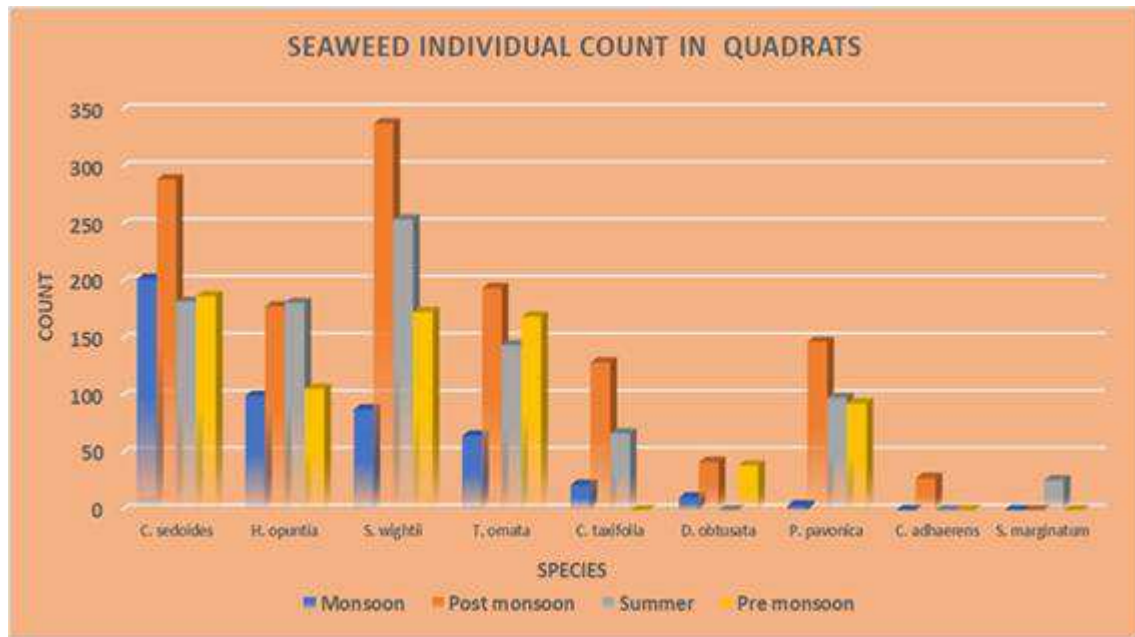


Figure 5. Quadrat-level enumeration of seaweed species, illustrating variations in species-level abundance and composition across the sampling area.

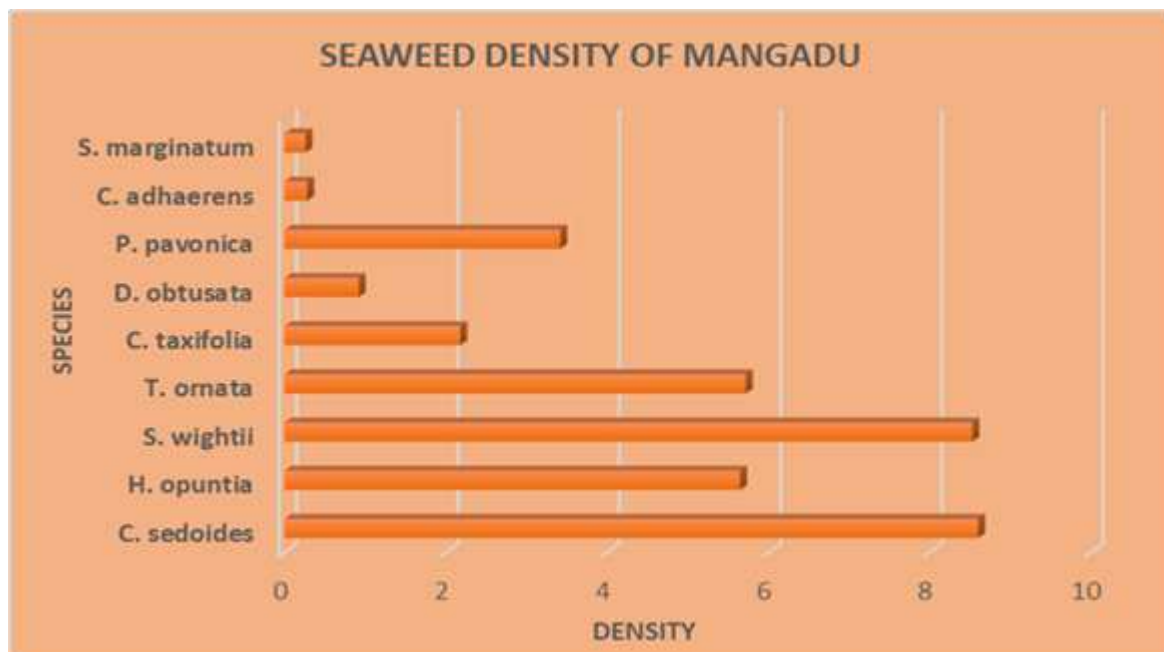


Figure 6. Distribution of seaweed species densities across quadrats, highlighting variability in community structure within the survey area.

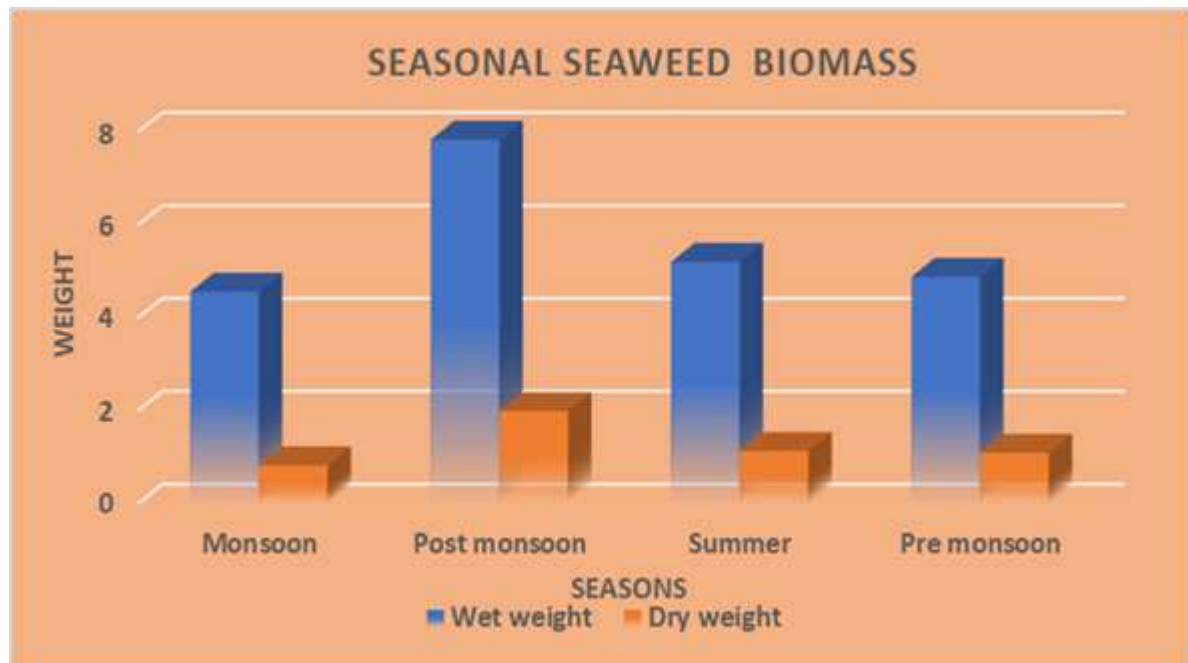


Figure 7. Biomass of seaweeds in the Mangadu reef area, depicting spatial variation in macroalgal accumulation across the study site.

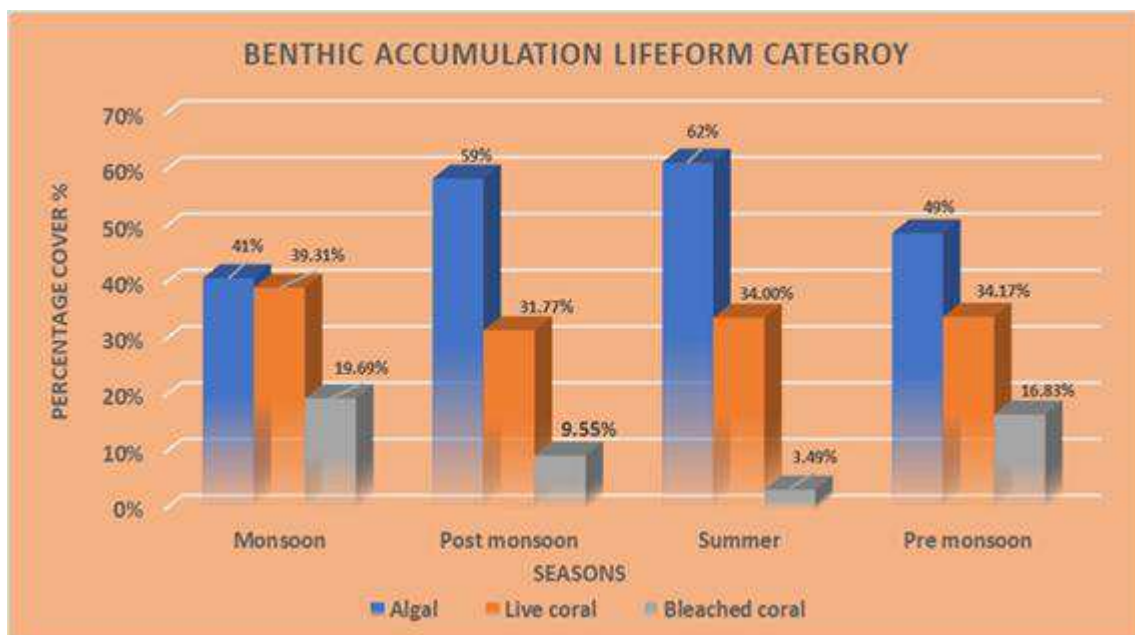


Figure 8. Percentage cover of benthic accumulation by life-form categories, illustrating the relative dominance of different benthic groups across the study area.

Principal Component Analysis (PCA-Biplot)

Principal Component Analysis (PCA) highlighted strong seasonal shifts in water quality that were directly relate to seaweed dominance and accumulation in the study area. Pre-monsoon conditions, influenced by elevated salinity and nutrient enrichment (TN, NH₃, NO₂, PO₄, TA), created a eutrophic environment favourable for rapid macroalgal spread. During the monsoon, higher dissolved oxygen and stable pH indicated improved water quality and flushing, temporarily reducing the stress of algal accumulation. In contrast, the post-monsoon period was linked with higher BOD, nitrate, silicate, and residual organic matter, which further sustained algal biomass buildup. Summer was distinct, with temperature-driven changes and concentrated salts influencing seaweed stress responses but also promoting opportunistic growth of tolerant species. These seasonal nutrient dynamics explain the pulses of seaweed overgrowth, with nutrient enrichment during the pre- and post-monsoon phases, which act as major drivers of dominance and accumulation on the reef (table 2 & figure 9).

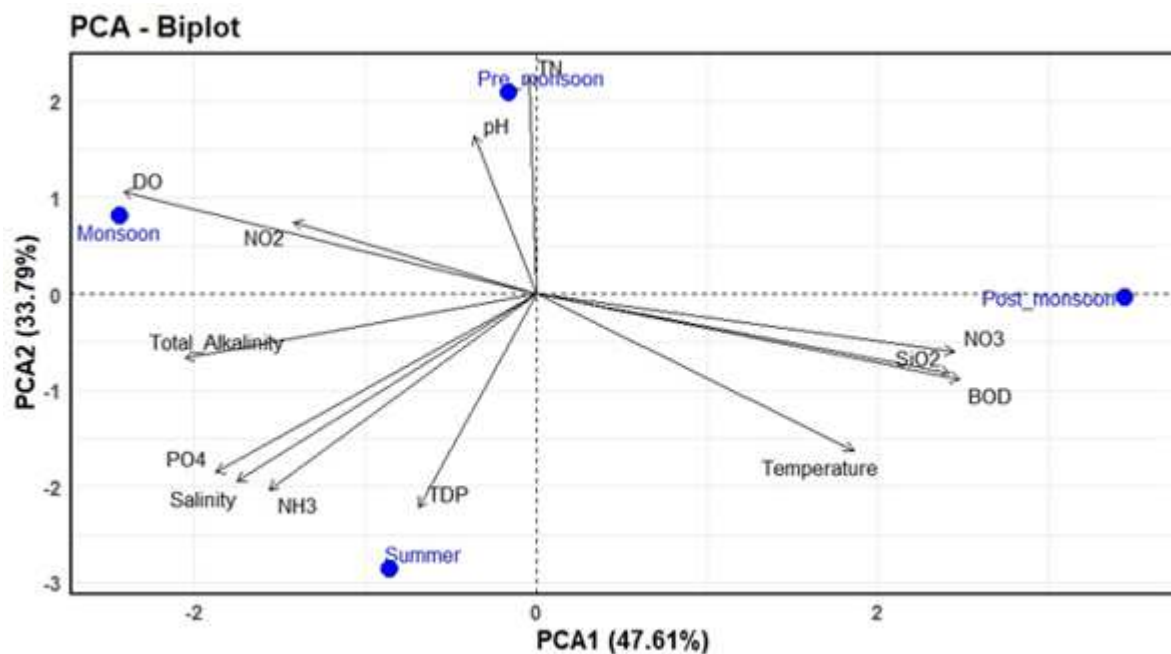


Figure 9. A Principal Component Analysis (PCA) plot showing the correlation between seasonal water quality parameters in Mangadu, indicated that variations in water chemistry strongly influence seaweed growth and accumulation.

Table 2. Seasonal variation in water quality parameters recorded in Mangadu during the study period.

Parameter	Monsoon	Post- monsoon	Summer	Pre- monsoon
Temperature	27	29	29	28
Salinity	33	31	34	31
pH	8.1	8.1	8.1	8.1
DO	5.3	4.6	4.9	5.1
BOD	2.88	3.32	3.08	2.97
TA	121	99	134	127
PO ₄	0.92	0.68	1.06	0.74
NO ₃	1.54	2.57	2.16	2.12
NO ₂	0.36	0.29	0.39	0.46
SiO ₂	10.76	13.57	12.54	12.17
NH ₃	0.327	0.298	0.367	0.312
TN	36.58	34.89	27.65	58.32
TDP	2.03	1.89	2.18	1.54

Canonical Correspondence Analysis (CCA- Plot)

The CCA ordination plot demonstrated clear relationships between seaweed species dominance and environmental parameters across seasons in Mangadu. *Caulerpa sedoides*, *Halimeda opuntia*, *Sargassum wightii*, *Turbinaria ornata*, and *Caulerpa taxifolia* were strongly associated with higher dissolved oxygen (DO) and pH, particularly during the monsoon and post-monsoon seasons. In contrast, *Dichotomaria obtusata*, *Padina pavonica*, and *Codium adhaerens* were more influenced by elevated nutrient concentrations such as nitrates (NO₃), nitrites (NO₂), and total nitrogen (TN), which were dominant in the pre-monsoon period. *Stoechospermum marginatum* was closely associated with summer conditions, where salinity, phosphate (PO₄), ammonia (NH₃), and total dissolved phosphorus (TDP) were relatively high. The total variance explained for species environment relationships was 0.304, with eigenvalues of 0.286 and 0.245 for axis 1 and 2, respectively, while axis 3 accounted for 0.198 (figure 10). These findings indicate that species dominance and algal accumulation are tightly linked to seasonal variations in water quality, with nutrient enrichment and hydrological shifts playing key roles in driving seaweed overgrowth.

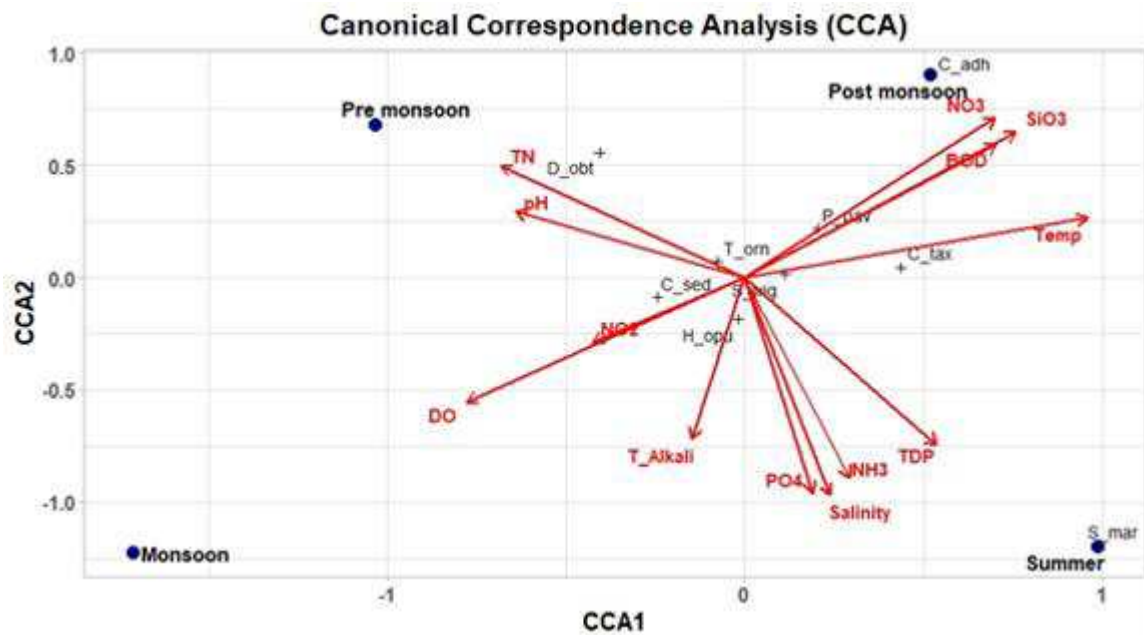


Figure 10. Canonical Correspondence Analysis (CCA) ordination showing the relationship between seaweed species and environmental parameters across seasons in Mangadu.

Hierarchical cluster analysis

The cluster dendrogram of seasonal seaweed abundance showed two major groupings, reflecting the similarities in community composition across seasons. The monsoon and pre-monsoon are closely clustered, indicating that these two periods share a similar seaweed assemblage structure, likely influenced by comparable hydrological and nutrient conditions. In contrast, post-monsoon and summer formed a separate cluster, suggesting a shift in species dominance under drier conditions and reduced freshwater input. The separation between the two seasonal clusters at a higher similarity distance highlights distinct ecological responses of seaweed communities to seasonal changes in the Mangadu reef environment (figure 11).

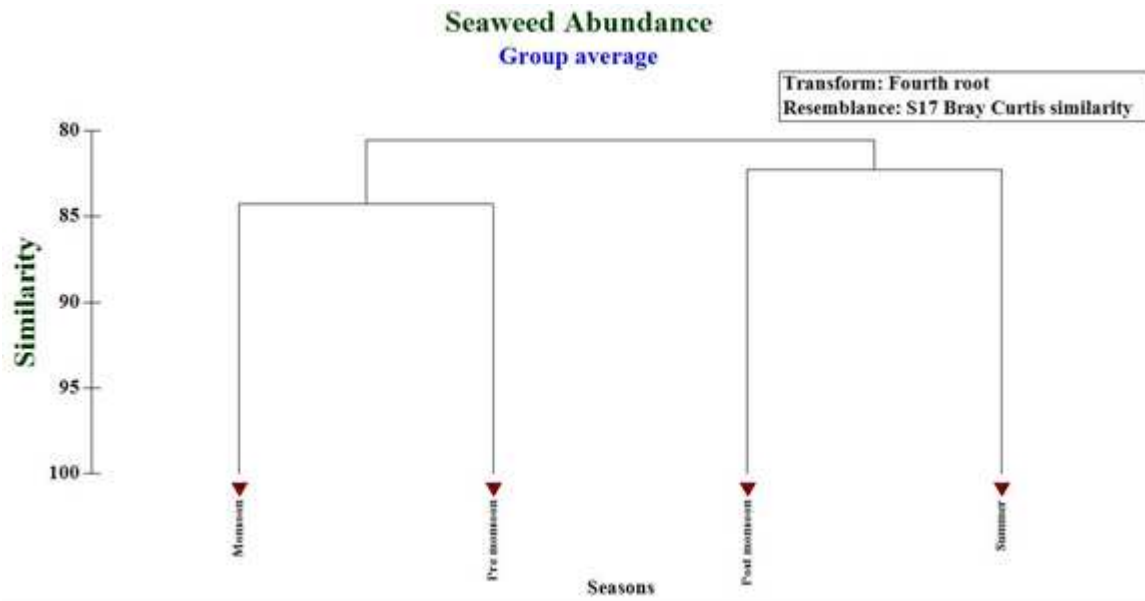


Figure 11. Dendrogram of seasonal seaweed abundance data from Mangadu during the study period.

Multidimensional Scaling (MDS- Plot)

The MDS ordination illustrates clear seasonal patterns in seaweed abundance, with all four seasons clustering within overlapping similarity contours, indicating broadly comparable community composition. Monsoon and pre-monsoon samples exhibit the greatest similarity, suggesting stable assemblages under moderate environmental conditions, whereas the summer season is positioned distinctly apart, reflecting shifts in abundance likely driven by increased temperature and light availability. Post-monsoon samples occupy an intermediate position, representing a transitional community structure following monsoonal disturbance (figure 12). The 2D stress value of 0 confirms an excellent fit of the ordination, demonstrating that the spatial arrangement accurately captures the seasonal variation in macroalgal abundance across the Mangadu reef system.

Seaweed Abundance

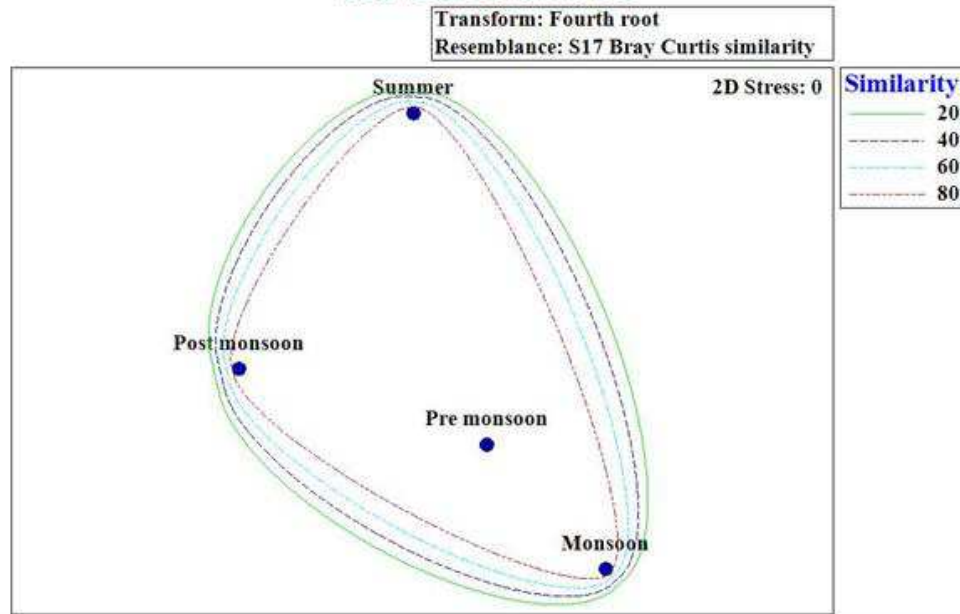


Figure 12. Multidimensional Scaling (MSD) was used to determine the Seaweed abundance in various seasons of Mangadu.

DISCUSSION

The Mangadu reef system demonstrates a pronounced trend toward macroalgal dominance, a condition widely recognized as a hallmark of declining reef health (Fong & Paul, 2010; Hay, 1997). The substantial representation of Chlorophyta and Phaeophyta, along with the persistent prevalence of *Caulerpa sedoides* and *Sargassum wightii*, indicates a shift from coral-dominated to algal-dominated benthic communities' patterns consistent with observations in other tropical reef regions (Costa Jr et al., 2002; Erniati et al., 2023; Remya & Rajasree, 2015). Seasonal variation further shaped community structure, with opportunistic green algae flourishing during monsoonal periods, while structurally robust brown algae such as *Sargassum wightii* and *Turbinaria ornata* increased under warm, high-energy conditions typical of the post-monsoon and summer seasons (Liu et al., 2017; Widyartini et al., 2023).

The ecological implications of such macroalgal expansion are substantial. Extensive algal mats reduce light availability and create localized hypoxic conditions, thereby altering microhabitats essential for coral survival (Fong & Paul, 2010; Pal & Bhattacharyya, 2020). Upright macroalgae can physically and chemically interfere with coral growth, recruitment, and recovery, with some species producing allelopathic compounds that damage coral tissues (Rasher & Hay, 2010; Gomez-Lemos & Diaz-Pulido, 2017). These impacts were evident in the seasonal benthic cover patterns observed, where macroalgal coverage reached up to 62% in summer, coinciding with a decline in live coral cover to approximately 34%. Similar declines in coral settlement and survivorship under high macroalgal cover have been reported elsewhere, emphasizing the role of algae as effective competitors for space and resources (Gomez-Lemos & Diaz-Pulido, 2017; Smith et al., 2023).

Anthropogenic activities appear to intensify this ecological imbalance. Seaweed farming particularly of the cultivated red alga *Kappaphycus alvarezii* has been associated with habitat alteration, competition with native species, and accidental introduction into nearby reef ecosystems (Adharini et al., 2021; Pal & Bhattacharyya, 2020). Additionally, mechanical disturbances such as anchoring, boat movement, and sediment resuspension

create open or weakened substrates that accelerate macroalgal colonization (Wilson, 2010; Fong & Paul, 2010; Ramos et al., 2010). Similar disturbance-driven shifts in benthic composition have been documented in other tropical reef systems undergoing stress (Marimuthu et al., 2022; Preskitt et al., 2004).

Together, these natural and anthropogenic drivers explain the pronounced seasonal algal dominance observed at Mangadu and underscore the vulnerability of reef ecosystems to sustained macroalgal pressure. The findings highlight an urgent need for integrated management strategies such as regulating nearshore activities, controlling invasive or farmed macroalgae, and enhancing herbivore populations to mitigate macroalgal overgrowth and promote long-term coral resilience (Smith et al., 2023; Hay, 1997).

CONCLUSION

The macroalgal assessment of the Mangadu nearshore reef reveals substantial overgrowth dominated by green and brown algae, signalling a critical decline in reef health. This spread is closely linked to anthropogenic drivers such as nutrient inputs from *Kappaphycus alvarezii* cultivation, physical disturbances from anchoring and harvesting activities, and diminished grazing pressure due to overfishing. Moreover, the wild collection of seaweeds has declined following the introduction of *Kappaphycus*, which has led to an increase in wild algal cover. Consequently, the proportion of natural coral reefs has reduced due to the expansion of algal assemblages. It is the need of the hour to promote sustainable wild algal collection practices in order to safeguard the health of coral reef ecosystems. The resulting negative feedback loop where coral degradation and bleaching create additional substrate for algal colonization further accelerates the shift toward an algal-dominated system. These findings underscore the urgent need for coordinated management interventions, including stricter regulation of seaweed aquaculture, mitigation of mechanical reef disturbances, conservation of herbivorous fish communities, and implementation of robust long-term monitoring programs. Collectively, these measures are essential to halt ongoing degradation and to enhance the ecological resilience. As a conservation strategy for local farmers to promote seaweed cultivation away from coral reef zones, encouragement of local fishers to harvest native macroalgal species for sustainable commercialization, control of macroalgae spread of the Mangadu reef ecosystem.

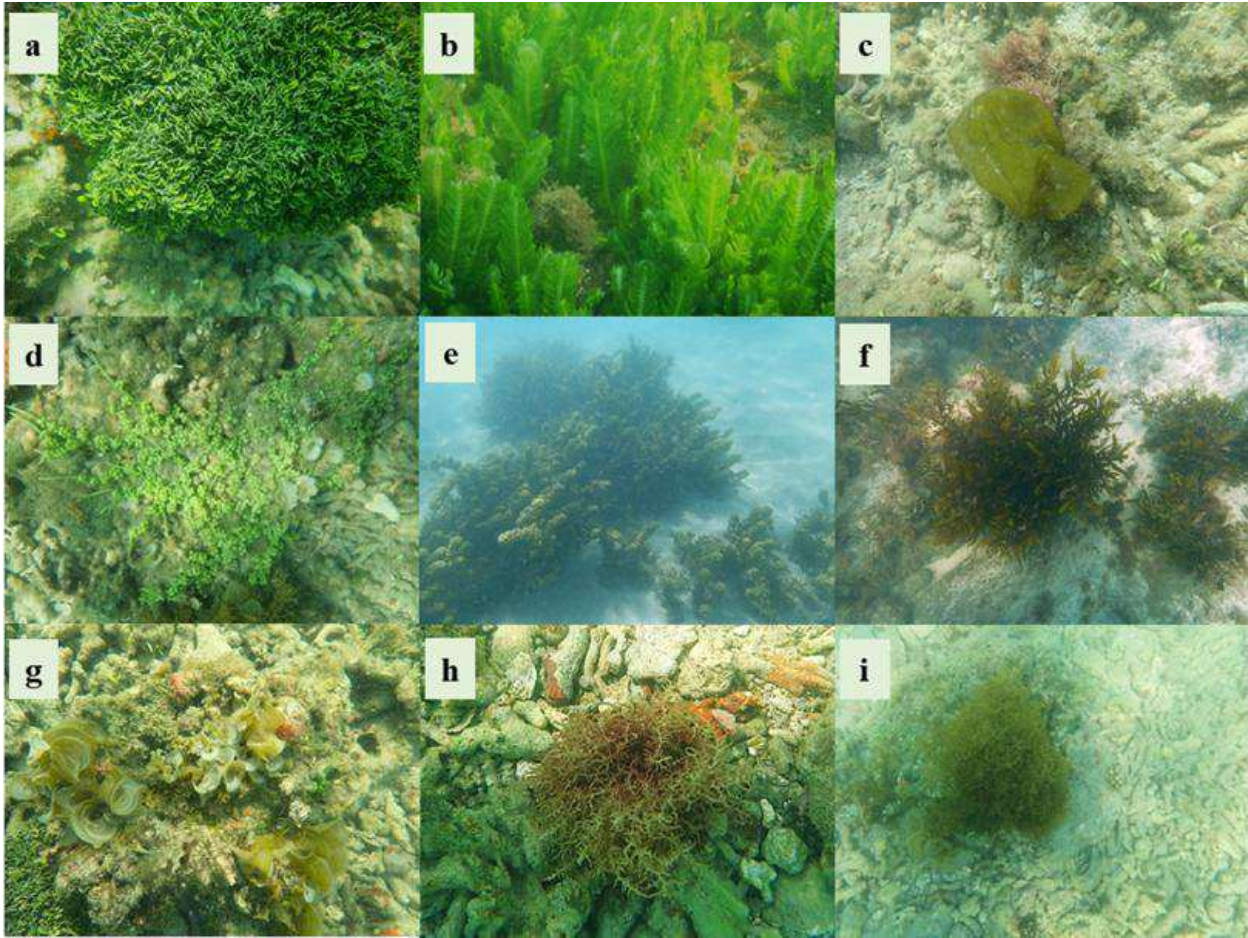


Figure 13. Identified macro algae species in Mangadu (a) *Halimeda opuntia*, (b) *Caulerpa taxifolia*, (c) *Codium adhaerens*, (d) *Caulerpa sedoides*, (e) *Turbinaria ornata*, (f) *Sargassum wightii*, (g) *Padina pavonica*, (h) *Dichotomaria obtusata*, and (i) *Stoechospermum marginatum*.

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