

CLIMATE CHANGE INDUCED CHANGES ALONG THE KARACHI COAST OF PAKISTAN AND A PHASE SHIFT FROM SARGASSUM FORESTS TO SARGASSUM BEDS: FUTURE CONSEQUENCES AND MITIGATION STRATEGIES

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Abstract

Underwater habitats along the Karachi coast are dominated by monospecific strands of *Sargassum*. Macroalgal growth in these habitats mostly starts at the end of November during the post-monsoon period due to calm water conditions. However, stunted growth of *Sargassum* was observed after the NILOFAR cyclone. The current study was undertaken to highlight the impacts of climate change on *Sargassum* forests and overall community structure. Underwater observations were made from January to March from 2022 to 2024. NOAA online monthly mean sea surface temperature data were used for October and November 2014 to 2024. To detect any changes in community structure, the data was compared with previous studies. Stunted growth of *Sargassum* followed by mixed community structure was observed at 4 dive sites (HB 1, HB 2, Bu 1, and Bu 2). However, no *Sargassum* species was recorded at FB. The monthly mean sea surface temperature data for November remained close to 26.5°C. Comparing data with previous studies, it appeared that many species were not found in the current study. The possible causes of stunted growth might be due to rising sea surface temperatures that increase the frequency of cyclone formation and altered local wind patterns. Regardless of other factors, such as humidity, low-pressure, a sea surface temperature above 26.5°C is necessary for cyclone formation. Sea surface temperature and wind speed are positively correlated with each other. As a result of cyclones and particularly an increase in wind speed, the propagules could not settle at the right time due to strong wave action. Stunted growth also reduced canopy cover. Reduction in canopy cover increased the growth of the perennial species due to the availability of sunlight. *Sargassum* has many benefits; however, its major roles are absorption of carbon dioxide and utilization of nutrients. As a considerable reduction in *Sargassum* biomass has occurred, it is possible that the concentration of carbon dioxide and phytoplankton growth will increase in the future, resulting in an increase in warming and eutrophication. Sindh coast is highly vulnerable to climate change mainly due to shallow depth and weak upwelling (upwelling mostly occurs below 50 meters). Global warming also interacts with local stressors (urbanization, urban heat islands) and exerts negative impacts on marine communities. Karachi is the largest city of Pakistan. The severity of the urban heat island phenomenon in Karachi is progressively escalating. Future conservation efforts should prioritize close collaboration with government agencies and academia, while simultaneously enhancing climate change awareness and capacity building in the field of marine biology. Additionally, minimizing local warming effects require constructing eco-friendly residential sectors, controlling vehicular volatile organic compounds emissions, and properly managing future infrastructure development.

Key words: Global warming; Upwelling; Arabian Sea; Karachi coast; NILOFAR Cyclone; Postmonsoon

Introduction

Climate change is basically the degradation of the environment or changes in the weather patterns of an area and is one of the major environmental issues of today's world (Drake, 2014; Raizada *et al.*, 2022; Ullah *et al.*, 2025). Different factors (e.g., variations in solar radiation, impact of human activities, changes in earth orbit, variations in galactic cosmic rays intensity, geological events, and geophysical processes) are responsible for changing the climate system of the Earth. (Crowley, 1983; Kirkby, 2007; Nikolov & Petrov, 2014). Among these factors, rising temperature is a basic cause of climate change. Rising temperature or global warming is caused by anthropogenic activities and natural forces (e.g., variation in thermal circulation and volcanic eruptions) (Jian-Bin *et al.*, 2012; Ring *et al.*, 2012). Global warming

synergistically interacts with local drivers (e.g., urbanization, urban heat, and diseases) and negatively impacts the growth, existence, and post-settlement of seaweeds (Casado-Amezúa *et al.*, 2019; Gissi *et al.*, 2021). Currently, increasing anthropogenic activities such as the production of methane, chlorofluoro carbons, and nitrous oxide are a major cause of warming. Global warming is a major threat to aquatic and land ecosystems across the world (Parmesan & Yohe, 2003; Prowse *et al.*, 2009; Dijkstra *et al.*, 2011). A shift has occurred in the habitat-forming organisms across a range of aquatic and terrestrial ecosystems, mainly due to mutual impacts of anthropogenic activities and climate change (Scheffer *et al.*, 2001; Ullah *et al.*, 2024). Such types of changes are enhanced by a severe disturbance when the community is already surviving under the influence of one or more stressors (Sousa, 1984; Ebeling *et al.*, 1985).

Sargassum is a genus of the order Fucales and is divided into four subgenera (e.g., *Sargassum*, *Arthrophyucus*, *Phyllotrichia*, and *Bactrophyucus*) (Mattio & Payri, 2011). *Sargassum* species are major canopy-forming macroalgae and play a crucial ecological role in marine ecosystems (Löffler & Hoey, 2018; Yip *et al.*, 2018). There are about 500 species of *Sargassum*, widely distributed in tropical, subtropical, and temperate habitats (e.g., ocean basins of the Indian, Pacific, and Atlantic Oceans) (Yoshida, 1989; Yip *et al.*, 2020). The impacts of climate change and anthropogenic activities mostly appeared on brown seaweed, especially canopy-forming. Global warming changed their composition and ecosystem functions (Leclerc *et al.*, 2015; Casado-Amezúa *et al.*, 2019). Due to climate change and ocean pollution, a considerable decline has occurred in the biomass of canopy-forming macroalgae, resulting in a considerable impact on biodiversity and ecosystem functioning (Grabal-Landry *et al.*, 2020; Peres *et al.*, 2023). Climate change is mainly responsible for shifting seaweeds' distribution and structural patterns (Müller, 2009; Gao *et al.*, 2021). Globally, there are evidence of the losses of *Sargassum* species due to urbanization, pollution, habitat loss, and global warming (Phillips & Blackshaw, 2011; Gorman *et al.*, 2020; Peres *et al.*, 2023). Rising temperature is considered as an important factor that not only controls the distribution patterns of *Sargassum* but also affects on sexual maturity, metabolism, development, and growth stages (Wu *et al.*, 2022; Korabik *et al.*, 2024).

Pakistan is highly vulnerable to climate change due to its geographic location, high dependence on agriculture and water resources, low adaptive capacity of the people, and weak system of emergency preparedness (Malik *et al.*, 2012; Ullah & Takaaki, 2016; Fahad & Wang, 2020). Adjacent to the northern side of the Arabian Sea, Pakistan possesses a coastline of about 1050 km, divided between Sindh and Balochistan provinces (Saifullah, 1999). The coastal waters of Pakistan have rich algal biomass and diversity due to high nutrient supplementation and a warm climate (Wiggert *et al.*, 2000). Numerous studies were conducted on ecology and taxonomy (Nizamuddin, 1964; Saifullah *et al.*, 1984; Shameel & Tanaka, 1992; Shaikh, & Shameel, 1995; Shameel *et al.*, 1996; Hameed & Muzammil, 1999) of seaweeds along the Karachi but these studies were mostly limited to intertidal areas or based on drift samples. However, Ali *et al.*, (2017, 2019) first time explored the underwater rocky habitats along the Karachi coast and reported huge algal patches (spread over hectares) dominated by monospecific strands of *Sargassum* in terms of biomass. The growth of *Sargassum* in underwater habitats along the Karachi coast mostly starts during post-monsoon (approximately at the end of November) due to calm water conditions (Ali *et al.*, 2017, 2019). However, stunted growth of *Sargassum* species was observed after the NILOFAR Cyclone, occurred in the Arabian Sea in November 2014, following a change in community structure (e.g., from monospecific strands to mixed community (Ali *et al.*, 2017). Global warming is increasing in the Arabian Sea region (Sun *et al.*, 2019), the present study is conducted to record climate change impacts on the size of *Sargassum* thalli and overall changes in community structure.

Materials and Methods

Study sites: The study sites for the current work were based on the previous studies (Ali *et al.*, 2017, 2019), conducted along the Karachi coast of Pakistan. The coastal area of the Karachi is a part of Sindh coast with a length of approximately 100 km (Anon., 1991). Rocky cum sandy beaches, tidal flats, shallow lagoons and creeks are the major features of the coast line. The coast is mostly under the influence of geological changes including coastal erosion and sea level rise (Khan *et al.*, 2020; Naseer *et al.*, 2021; Kanwal *et al.*, 2022).

Methods: SCUBA diving was conducted at 5 dive sites (2 at Hawks Bay, 1 at French Beach and 2 at Buleji (Fig. 1). Surveys were conducted from January to March, 2022 to 2024. Relative species abundance at each dive site was determined using a 1 m² quadrat. The quadrats were deployed randomly. Overall, 50 quadrats were laid (10 at each dive site of Hawks Bay, French Beach and Buleji). The quadrat was suitably weighted to avoid floating. Species within each quadrat were uprooted using a scalpel and stored in polythene bags. The species were counted in the field and scaled using a 1-6 numerical scale (1= up to 5 individuals; 2= up to 15 individuals; 3= up to 30 individuals; 4= up to 50 individuals; 5= up to 100 individuals and 6= up to 200 individuals). Underwater observations at each dive site were also recorded including habitat features, respective depths and GPS coordinates (Table 1). In situ images were also taken using a digital camera (Fujifilm Fine Pix F550 EXR) in an underwater housing. Visual estimation was also made to determine the algal cover to the nearest percent. The samples were also brought to the laboratory, pressed on herbarium sheets, and stored at the Center of Excellence in Marine Biology, University of Karachi, for future reference. Identification was made following the literature Shameel & Tanaka (1992), Shaikh, & Shameel (1995), Aliya & Shameel (1996) Nizamuddin & Aisha (1996), Carpenter & Niem (1998) and available herbaria at the Center of Excellence in Marine Biology, University of Karachi.

To find any changes in the community structure at the selected dive sites, the data were compared with Ali *et al.*, (2017, 2019). To determine the climate change impacts at each site, the height of the *Sargassum* thalli was measured. Approximately, the height of 15 *Sargassum* species was measured at each dive site, and impacts were categorized as 0= species not found; 1= Partial: measured height of thalli up to 3 m; 2= moderate: measured height of thalli up to 1 m; 3= severe impacts: measured height of thalli less than 1 m.

Monthly mean sea surface temperature data: Monthly mean sea surface temperature data for the months of October and November were used. The sea surface temperature data was obtained from the NOAA online website (https://www.coralreefwatch.noaa.gov/product/vs/timeseries/south_asia.php#%20gulf_of_kutch) with 5 km resolution. The sea surface temperature data of Gulf of Kutch was used mainly due to its closeness to study sites and prevailing similar geomorphological and hydrological conditions (Banse, 1968; White, 1984; Faruque & Ramachandran, 2014). The monthly mean sea surface temperature data was used from 2014 to 2024 because warming in the Arabian Sea increased from 2014 and 2015 (Kumari *et al.*, 2021).



Fig. 1. Map of Sind coast. Inset showing the study sites.

Table 1. Observations recorded at each dive site. Abbreviations used as HB 1–HB 2: Hawks Bay dive sites 1–2; FB: French Beach; Bu 1–Bu 2; Buleji dive sites 1–2.

Dive site	Depth	GPS coordinates	General observations
HB 1	4	24°51'.113"N, 66°49'.955"E	The site was located about 400 m from shoreline. The habitat was mostly rocky with occasionally distributed small sandy patches. Although, <i>Sargassum</i> dominated the site but a considerable reduction thalli height was noted following the formation of mixed community structure. The genus <i>Sargassum</i> dominated the site following occasional distribution of <i>Padina pavonica</i> , <i>Codium fragile</i> , <i>Colpomenia sinuosa</i> , <i>Meristotheca papulosa</i> , <i>Iyengaria stellate</i> . Water currents were high
HB 2	6	24°51'.167"N, 66°50'.734"E	The habitat at this site was similar to HB 1, however covered area was quite large. The area was dominated by <i>Sargassum</i> . Stunted growth of <i>Sargassum</i> was observed following the formation of a mixed community structure. Water currents were moderate
FB	3 - 12	24°50'.163"N, 66°49'.065"E	The site was located about 400 m off from shoreline and was highly exposed. The site consisted of a uplifted huge rocks, however, there are many gullies. No <i>Sargassum</i> species were recorded. However, the southern side of the rock was dominated by <i>Codium fragile</i> while northern side at deeper depth was dominated by newly emerged <i>Ceramium</i> species here. Water currents were high
Bu 1	3	24°50'.319"N, 66°49'.202"E	This site is mentioned as Buleji 3 according to Ali et al. (2019), however included here as Bu 1. The site was very close to shoreline. The habitat was uneven but characterised by bed rocks, boulders and sandy patches. Stunted growth of <i>Sargassum</i> was also observed here following mixed community structure. Water currents were high
Bu 2	3	24°50'.331"N, 66°49'.526"E	This site is mentioned as Buleji 1 according to Ali et al. (2019). The site was located 100 m off from the shore line. Massive changes were observed here followed by stunted growth of <i>Sargassum lanceolatum</i> and mixed community structure. Water currents were strong

Statistical analysis

To establish a link between sites, cluster analysis was conducted on the basis of presence/absence data and Bray-Curtis similarity index (Bray & Curtis, 1957). The dendrogram was constructed using group average linkage techniques (Clarke, 1993; Clarke & Warwick, 2001). Species frequency distribution was observed at five dive sites using K. dominance curves, following the method described by Lamshead *et al.*, (1983). The analyses were made using PRIMER v.6 software (Clarke & Gorley, 2006). A K. dominance curve was used to observe the species frequency distribution from the current and previous studies (Ali *et al.*, 2017, 2019), following the methodology of Lamshead *et al.*, (1983).

Results

Seaweed communities: Thirty macroalgal species were recorded during the current study, belonging to 3 major groups (Phaeophyceae (16 species), Rhodophyceae (8 species), and Chlorophyceae (6 species)). *Sargassum* was recorded as dominant genus at all sites excluding French Beach. High species diversity was recorded at HB 2, followed by HB 1, Bu 1, Bu 2 and FB. A detailed species list with relative abundance and distribution patterns at each dive site is provided in Table 2. Comparing data with Ali *et al.*, (2017, 2019), it appeared that many species (*Solieria robusta*, *Scinaia hatei*, *Calliblepharis* sp., *Codium indicum*) were found in the previous studies but not recorded during the current study. Species such as *Lobophora variegata* and

Ceramium were first time recorded at Bu 1 and FB dive sites (Table 3). A change in community structure was also observed, e.g., from monospecific strands of *Sargassum* to mixed community structure at all dive sites excluding FB. No *Sargassum* species was recorded at this dive site; however, the community was dominated by a newly emerged *Ceramium* species followed by *Codium fragile*, *Caulerpa chemnitzia*, *Caulerpa scalpelliformis*, *Caulerpa chemnitzia*, *Stypopodium shameelii* and to some extent *Stypopodium zonale* and *Codium latum*. Massive changes in community structure was observed at Bu 1 followed by Bu 2, HB 1 and HB 2.

Stunted growth of *Sargassum* thalli was observed at 4 dive sites. Partial impacts (thallus height approximately up to 3 m) were observed at HB 2, while moderate impacts were recorded at HB 1 and Bu 2 (thallus height approximately 1 m). However, severe impacts were recorded at Bu 1 (thallus height approximately 0.5 m) (Fig. 2). Compared to HB 1, Bu 1 and Bu 2, shading effects were observed at dive site HB 2. Reduction in the size of *Sargassum* thallai and change in community structure occurred gradually. The changes at Hawks Bay dive sites started after NILOFAR Cyclone, occurred in the Arabian Sea in 2014, while at Buleji dive sites after 2016.

A cluster analysis conducted for the above-mentioned communities at 5 dive sites indicated that Bu 1 and Bu 2 formed a similar cluster at a similarity level of 85%.

However, HB 1, HB 2 and FB formed separate clusters at a similarity level of 71%, 57% and 38% (Fig. 3). A cluster analysis conducted conducted to compare the obtained from the previous studies with data of current study at 5 dive sites indicated HB 1 BC and HB 2 BC, Bu 1 AC and Bu 2 AC and FB AC and Bu 2 AC formed similar clusters at a similarity level of 86%, 75% and 47% while HB 2 AC, Bu 1 BC, FB BC and HB 1 AC formed separate clusters at a similarity level of 71%, 56 %, 61 % and 70% (Fig. 4). The K dominance curve showed that the species-frequency distribution during the previous studies (before the cyclone) was highest at HB 2, followed by HB 1, FB, Bu 1, and Bu 2. During the current studies (after the cyclone), the highest frequency was at HB 2, followed by HB 1, Bu 2, Bu 1, and FB (Fig. 5).

Monthly mean sea surface temperature data: The monthly mean sea surface temperature data indicated that the maximum mean temperature for the months of October 2019 and 2021 remained 28°C. Similarly, the mean monthly temperature for the months of November, 2014, 2015, 2016, 2017, 2019, 2020, and 2021 remained 26.5°C. The highest mean sea surface temperature for the month of November remained high during the year 2023. The details of monthly sea surface temperature for the months of October and November from 2014 to 2024 are shown in Fig. 6.

Table 2. Relative abundance and distribution of macroalgal communities at 5 dive sites along the Karachi coast.
Abbreviations used: HB 1-2: Hawks Bay dive site 1-2; FB: French Beach; Bu 1-2: Buleji dive site 1-2.

Species	Family	HB		FB	Bu	
		HB 1	HB 2		Bu 1	Bu 2
<i>Dictyota dichotoma</i>	Dictyotaceae	4	4		3	2
<i>Dictyota implexa</i>	Dictyotaceae	3	5			
<i>Dictyota hauckiana</i>	Dictyotaceae		3			
<i>Stoechospermum polypodioides</i>	Dictyotaceae	4	2		3	3
<i>Stypopodium shameelii</i>	Dictyotaceae	1		3	2	
<i>Stypopodium zonale</i>	Dictyotaceae	3		2	3	2
<i>Spatoglossum asperum</i>	Dictyotaceae	1			1	1
<i>Lobophora variegata</i>	Dictyotaceae				4	3
<i>Padina pavonica</i>	Dictyotaceae	2	3		4	2
<i>Sargassum cinctum</i>	Sargassaceae		1			
<i>Sargassum aquifolium</i>	Sargassaceae	3	5			
<i>Sargassum ilicifolium</i>	Sargassaceae	5	6			
<i>Sargassum lanceolatum</i>	Sargassaceae	4	5		4	5
<i>Sargassum swartzii</i>	Sargassaceae				4	
<i>Colpomenia sinuosa</i>	Scytosiphonaceae	2	3		3	3
<i>Iyengaria stellata</i>	Scytosiphonaceae	2	2			
<i>Meristotheca papulosa</i>	Solieriaceae		1	1		
<i>Botryocladia leptopoda</i>	Rhodymeniaceae	2				
<i>Coelarthrum opuntia</i>	Rhodymeniaceae		1		1	1
<i>Tricleocarpa fragilis</i>	Galaxauraceae		2			
<i>Asparagopsis taxiformis</i>	Bonnemaisoniaceae		1			
<i>Halymenia porphyroides</i>	Halymeniaceae		1			
<i>Ceramium</i> sp.	Ceramaceae			6		2
<i>Amphiroa anceps</i>	Corallinaceae		2			
<i>Codium decortcatum</i>	Codiaceae	1				2
<i>Codium fragile</i>	Codiaceae	1	2	5	2	2
<i>Codium latum</i>	Codiaceae			1		
<i>Caulerpa chemnitzia</i>	Caulerpaeaceae			3		
<i>Caulerpa scalpelliformis</i>	Caulerpaeaceae	1	1	3	1	1
<i>Caulerpa taxifolia</i>	Caulerpaeaceae	1	2	3	1	1
Total species		17	20	9	14	14

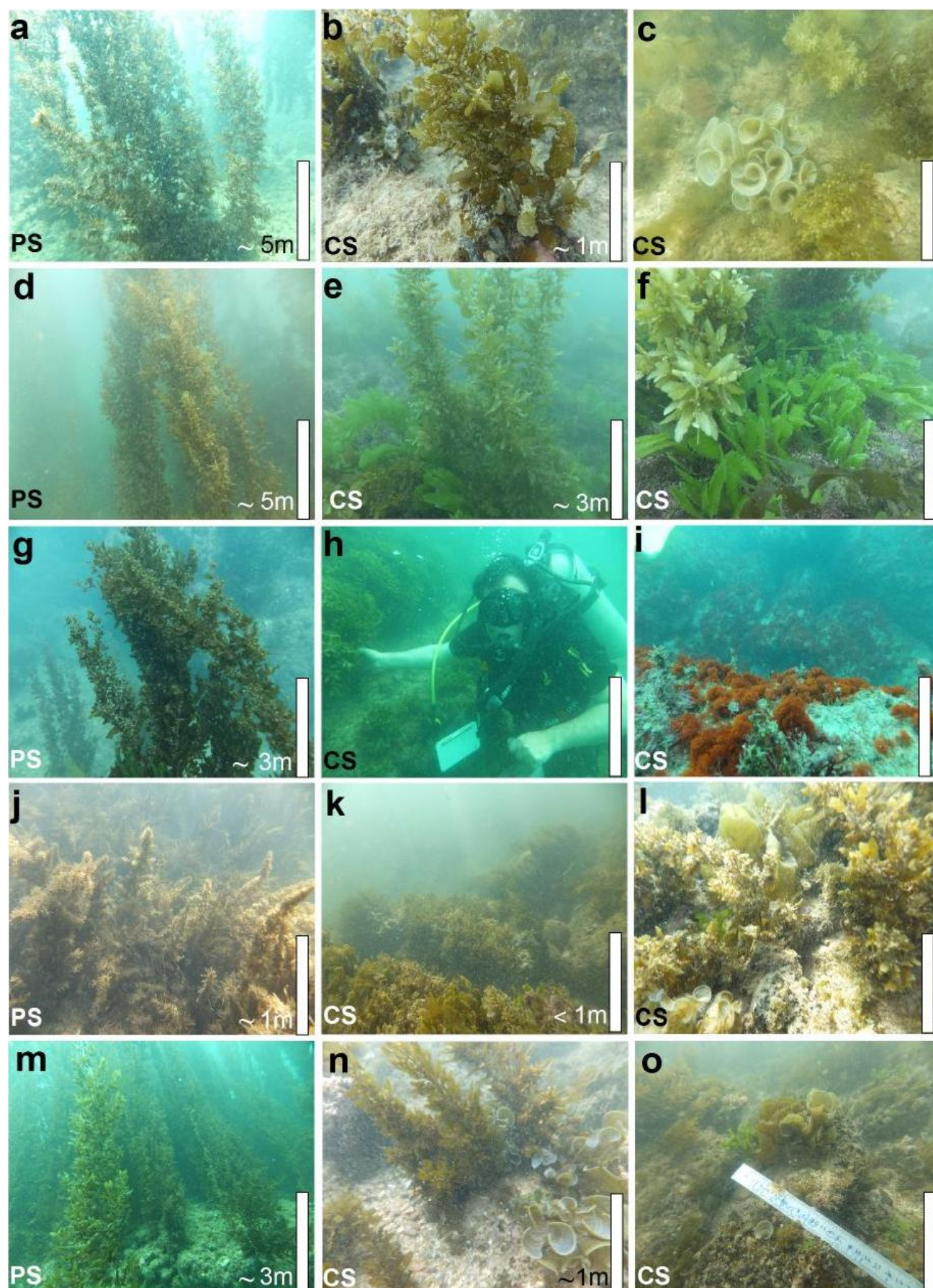


Fig. 2. Impacts of climate change recorded on the growth of *Sargassum* thalli in underwater habitats along the Karachi coast of Pakistan. **a-c**: Moderate impacts at Hawks Bay 1; **d-f**: Partial impacts at Hawks Bay 2; **g-i**: No *Sargassum* species recorded at French Beach; **j-l**: Severe impacts at Buleji 1; **m-o**: Moderate impacts at Buleji 2. Abbreviations used: PS: Previous studies (before NILOFAR Cyclone); CS: Current studies (after NILOFAR Cyclone)

Table 3. Comparison of macroalgal species recorded from 5 dive sites with Ali et al. (2017, 2019). Abbreviations used: HB 1-2: Hawks Bay dive site 1-2; FB: French Beach; Bu 1-2: Buleji dive site 1-2; PC: Previous status; CS: Current status; +: Present; -: Absent

Species	Family	HB				FB		BU			
		HB1		HB2				BU1		BU2	
		PS	CS	PS	CS	PS	CS	PS	CS	PS	CS
<i>Dictyota dichotoma</i>	Dictyotaceae	+	+	+	+	-	-	+	+	-	-
<i>Dictyota implexa</i>	Dictyotaceae	-	+		+	-	-	-	-	-	-
<i>Dictyota hauckiana</i>	Dictyotaceae	-	-	+	+	-	-	-	-	-	-
<i>Stoechospermum polypodioides</i>	Dictyotaceae	+	+	-	+	-	-	-	+	-	+
<i>Stypopodium shameelii</i>	Dictyotaceae	+	+	+	-	+	+	+	+	+	-
<i>Stypopodium zonale</i>	Dictyotaceae	+	+	+	-	+	+	+	+	+	+
<i>Spatoglossum asperum</i>	Dictyotaceae	-	+	-	-	+	-	+	+	-	+
<i>Lobophora variegata</i>	Dictyotaceae	-	-	-	-	-	-	-	+	-	+
<i>Padina pavonica</i>	Dictyotaceae	+	+	+	+	-	-	-	+	-	+
<i>Sargassum cinctum</i>	Sargassaceae	-	-	-	+	-	-	-	-	-	-
<i>Sargassum aquifolium</i>	Sargassaceae	+	+	+	+	+	-	-	-	-	-
<i>Sargassum ilicifolium</i>	Sargassaceae	+	+	+	+	-	-	-	-	-	-
<i>Sargassum lanceolatum</i>	Sargassaceae	+	+	-	+	+	-	+	+	+	+
<i>Sargassum swartzii</i>	Sargassaceae	-	-	-	-	+	-	+	+	-	-
<i>Colpomenia sinuosa</i>	Scytosiphonaceae	+	+	+	+	+	-	+	+	-	+
<i>Iyengaria stellata</i>	Scytosiphonaceae	+	+	+	+	-	-	-	-	-	+
<i>Meristotheca papulosa</i>	Solieriaceae	+	-	+	+	-	+	-	-	+	-
<i>Solieria robusta</i>	Solieriaceae	+	-	+	-	-	-	-	-	+	-
<i>Scinaia hatei</i>	Solieriaceae	+	-	+	-	-	-	-	-	-	-
<i>Botryocladia leptopoda</i>	Rhodomeniaceae	+	+	-	-	-	-	+	-	+	-
<i>Coelarthrum opuntia</i>	Rhodomeniaceae	+	-	+	+	-	-	+	+	+	+
<i>Tricleocarpa fragilis</i>	Galaxauraceae	-	-	+	+	-	-	-	-	-	-
<i>Asparagopsis taxiformis</i>	Bonnemaisoniaceae	-	-	+	+	-	-	-	-	-	-
<i>Halymenia porphyroides</i>	Halymeniaceae	+	-	+	+	-	-	-	-	-	-
<i>Ceramium</i> sp.	Ceramaceae	-	-	-	-	-	+	-	-	+	+
<i>Amphiroa anceps</i>	Corallinaceae	-	-	+	+	-	-	-	-	-	-
<i>Calliblepharis</i> sp.	Cystocloniaceae	-	-	-	-	+	-	-	-	-	-
<i>Codium decorticatum</i>	Codiaceae	+	+	+	-	-	-	-	-	-	+
<i>Codium fragile</i>	Codiaceae	-	+	+	+	+	+	-	+	-	+
<i>Codium indicum</i>	Codiaceae	+	-	+	-	-	-	-	-	-	-
<i>Codium latum</i>	Codiaceae	-	-	-	-	+	+	-	-	-	-
<i>Caulerpa chemnitzia</i>	Caulerpaeae	-	-	-	-	+	+	-	-	-	-
<i>Caulerpa scalpelliformis</i>	Caulerpaeae	+	+	+	+	+	+	-	+	-	+
<i>Caulerpa taxifolia</i>	Caulerpaeae	+	+	-	+	+	+	-	-	-	+

* For the current study, 3 dive sites (HB 1, HB 2, and FB) were reinvestigated from Ali *et al.*, (2017), excluding Mubarak Village and Churna Island, while 2 dive sites (Bu 1 and Bu 3, modified as 1 and 2) were reinvestigated, excluding other dive sites from Ali *et al.*, (2019)

Discussion

Sargassum forests are an endangered ecosystem under climate change (Krumhansl *et al.*, 2016; Smale, 2020). The possible causes of stunted growth and the formation of mixed communities might be due to rising temperatures and changes in wind patterns (5 knots). Rising temperatures increase the frequency of cyclone formation and bring changes in local wind patterns (Debernard *et al.*, 2002; Kulkarni *et al.*, 2013; Peres *et al.*, 2023). Wave height along the Karachi coast is increasing approximately 1% during winter monsoon (Nazeer *et al.*, 2020). Sea surface temperature and wind speed are positively correlated with each other (Ali *et al.*, 2025), and there are upward trends of sea surface temperature (2011-2017) especially during winter-monsoon (Nazeer *et al.*, 2020; Khan *et al.*, 2025). As a result of changes in local wind patterns, the propagules could not settle at the right time due to strong wave action. Wave action impacts the growth of *Sargassum* (Viejo *et al.*, 1995). Removal of canopy cover due to stunted growth of *Sargassum* encouraged the growth of small-sized macroalgae, particularly at shallow depths and exposed sites. Absence of canopy cover

enhances the availability of sunlight and promotes the growth of perennial species. Size, morphology, and flexibility play a key role in surviving algal species in wave action zones (Reed & Foster, 1984; Gaylord *et al.*, 1994; Gaylord & Denny, 1997).

Cyclogenesis within the Arabian Sea region mostly occurs during the pre- and post-monsoon, mainly due to the presence of higher to mid-level moisture, low-pressure, and negative outgoing longwave radiation anomalies. During the rest of the year, strong wind shear followed by high-pressure, low humidity in the middle troposphere and positive outgoing longwave radiation do not permit cyclone formation (Evan *et al.*, 2011; Almahri *et al.*, 2026). Due to anthropogenic warming, the cyclonic storm intensity in the Arabian Sea increased since 2014, and for the first time, winds with a speed of more than 46 m s⁻¹ were recorded over the Arabian Sea region (Evan *et al.*, 2011; Murakami *et al.*, 2017). Overall, from 1881 to 2019, 236 disturbances, including depressions and tropical cyclones, formed in the Arabian Sea. From 1983 to 2015, about 56 tropical cyclones were formed over the Arabian Sea. A majority of these cyclones formed during the post-monsoon period (Sattar & Cheung, 2019), and 16 formed in

the last 20 years (2000 to 2020). The majority of these cyclones formed during the post-monsoon period, a time suitable for the growth of *Sargassum* species along the Karachi coast. There are many factors responsible for the production of storms; among them, a water temperature greater than 26.5°C is necessary (Zehr, 1992). Our results also indicated that the temperature for the month of November from 2014 to 2024 remained close to 26.5°C. The sea surface water temperature in the Arabian Sea is increasing (Sun *et al.*, 2019; Kumari *et al.*, 2021), and many substantial changes regarding the duration and frequency distribution of cyclones have occurred in the Arabian Sea e.g. during 1982-2000, frequency distribution and duration of cyclonic storms was 52%, whereas from 2000 to 2019, increased by a ratio of 80% (Simpkins, 2021). The surface temperature of the Earth is increasing due to anthropogenic activities (Wang *et al.*, 1976; Al-Ghussain, 2019). However, increase or decrease in sea surface temperature depends upon several factors such as the intensity of upwelling in an area and water depth. It is believed that sea surface temperature is high in areas with weak upwelling and shallow depths (Alexander *et al.*, 2000; Park *et al.*, 2015; Piedracoba *et al.*, 2024). Increasing sea surface temperature, especially along the Sindh coast of Pakistan, might be due to shallow depth (due to a large continental shelf) and weaker upwelling. Sindh coast of Pakistan has similar features to the west coast of India, e.g., a wider continental shelf and weaker upwelling. Upwelling mostly occurs below 50 m depth (Banse, 1968; White, 1984; Faruque & Ramachandran, 2014; Nigam & Pant, 2024). Sea surface temperature is an crucial parameter and is a key indicator of upwelling at any place. The strongest upwelling zone in the Arabian Sea is found off the coast of Somalia and Oman, while the weaker was found along the south west coast of India (Ajith Joseph *et al.*, 2018; Ganguly *et al.*, 2024; Nigam & Pant, 2024). Similarly, strong downwelling Kelvin waves bring warmer water due to the intrusion of freshwater from the Bay of Bengal and are a major cause of warming in the eastern part of the Arabian Sea (Albert *et al.*, 2023).

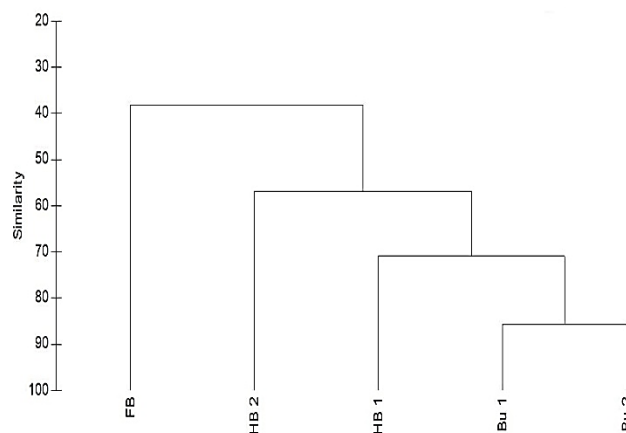


Fig. 3. Cluster analysis of macroalgal communities conducted at five dive sites based on presence/absence data and the Bray-Curtis similarity index. The abbreviations used are as follows: HB 1-2: Hawks Bay dive sites 1 and 2; FB: French Beach; Bu 1-2: Buleji dive sites 1 and 2.

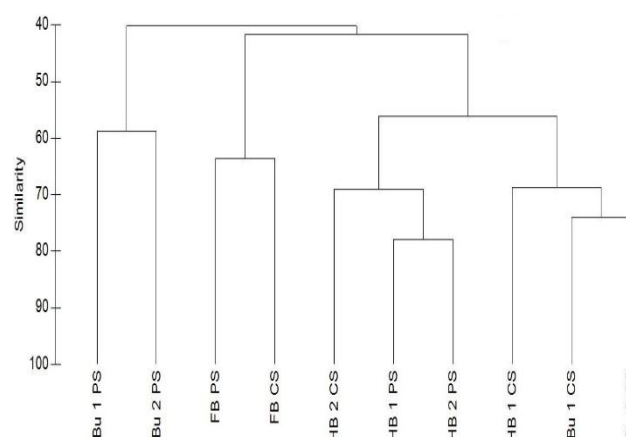


Fig. 4. Cluster analysis of macroalgal communities conducted (recorded during current and previous studies) at five dive sites based on presence/absence data and the Bray-Curtis similarity index. The abbreviations used are as follows: HB 1-2: Hawks Bay dive sites 1 and 2; FB: French Beach; Bu 1-2: Buleji dive sites 1 and 2; PS: Previous study; CS: Current study

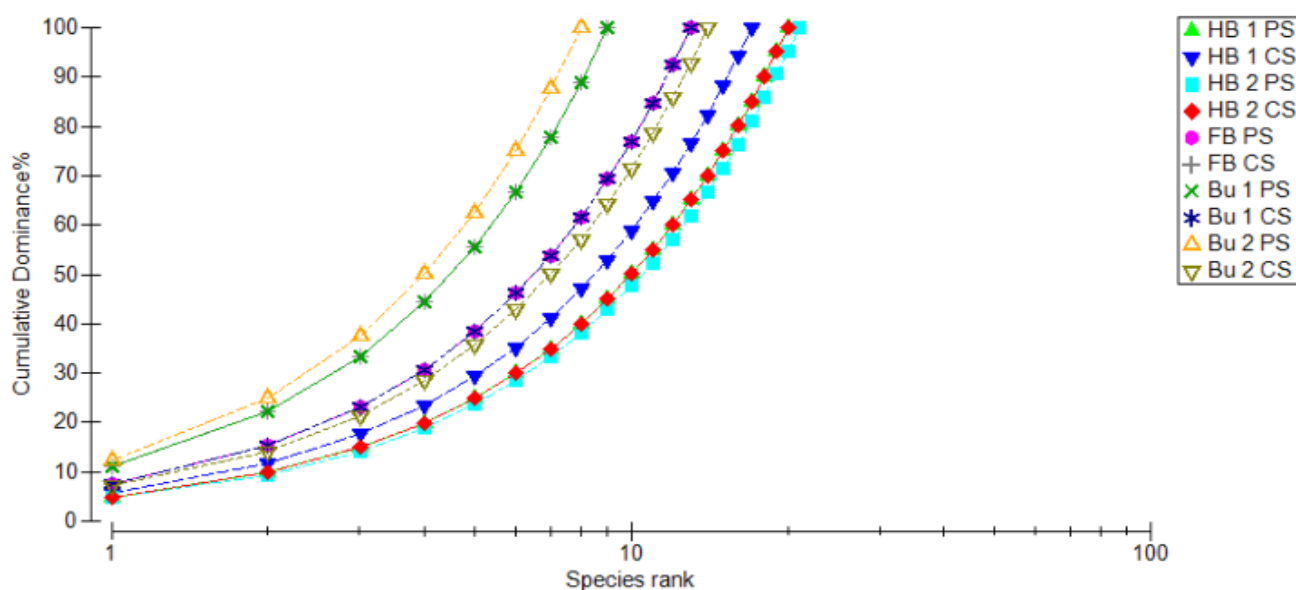


Fig. 5. The K dominance curve showing species-frequency distribution at five dive sites recorded during the previous and the current studies. Abbreviations used are similar to those mentioned in Fig. 4.

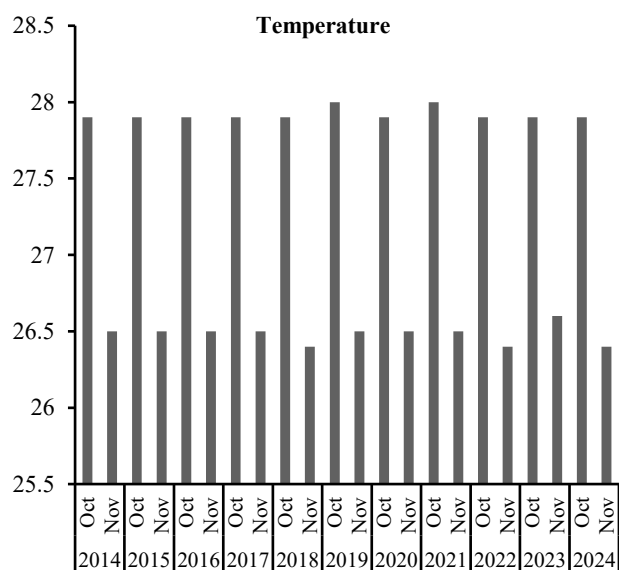


Fig. 6. Monthly mean sea surface temperature data of the Arabian Sea (Gulf of Kutch) during post-monsoon (October–November) from 2014 to 2024. Source, NOAA.

Global warming also synergistically interacts with local stressors such as urbanization, urban heat islands, and negatively impacts on attachment of larvae, growth, existence and post settlement of seaweeds (Casado-Amezúa *et al.*, 2019; Gissi *et al.*, 2021). Karachi is the biggest city of Pakistan and is continuously expanding without appropriate planning (Siddique *et al.*, 2009; Arshad *et al.*, 2020; Mangi *et al.*, 2020). The jungle of concrete buildings traps heat from the surroundings. From 2013-2023, built-up land increased at a rate of 6.24 percent. Due to the accumulation of heat, the intensity of urban heat island production in Karachi metropolis is continuously increasing with the passage of time. During 2023, the maximum temperature recorded was 43°C. (Ejaz *et al.*, 2025). Vehicular exhaust and deforestation are considered other main sources of warming in Karachi. Emission of volatile organic compounds such as ethane (93 ppbv), methane (6.3 ppmv), benzene (0.3–19 ppbv), and Methane (6.3 ppmv) in Karachi is high compared to any other city (Barletta *et al.*, 2002; Arshad *et al.*, 2020). Diesel vehicles are largely responsible for the emission of toxic compounds as well as volatile organic compounds (Nelson *et al.*, 2005).

Possible causes of minimum impacts on the growth of the *Sargassum* species at HB2 might be due to topographic features of the site, e.g., considerable depth, gradual upsloping, and the presence of a larger intertidal sandy area that dissipated the wave energy. Wave energy dissipation rates are high in areas with sandy flats (Houser & Hill, 2010). Complete disappearance of *Sargassum* species at FB might be due to its highly exposed nature of the site, elevated coastline, more wave action, and coastal topography. Compared to flat coastal areas, high waves are generated in areas with cliffs or elevated coastlines compared to other sites (Möller & Spencer, 2002).

Macroalgae, especially *Sargassum* species, play a vital role in the marine environment, e.g., act as primary producers and ecological engineers (Riosmena-Rodríguez *et al.*, 2012; Duarte *et al.*, 2022), help in climate change mitigation, serve as the source of dispersal for intertidal

communities (Ingólfsson, 1995), and provide shelter to several marine communities (Eggertsen *et al.*, 2017). However, their major role is the absorption of carbon dioxide (Gouvêa *et al.*, 2020; Sun *et al.*, 2025). Moreover, *Sargassum* species act as a “biofilter” due to their ability to absorb heavy metals and dissolved nutrients, thus helping in the purification of water (Vijayaraghavan *et al.*, 2009; Yu *et al.*, 2019; Saldarriaga-Hernandez *et al.*, 2020). In addition, macroalgae can inhibit phytoplankton growth and indirectly alleviate harmful algal blooms through nutrient competition, shading, and allelopathy (Ben Gharbia *et al.*, 2017; Xiao *et al.*, 2017; Sylvers & Gobler, 2021). Their decline can disrupt the marine ecosystem by reducing carbon dioxide uptake and altering nutrient balances, resulting in eutrophication due to increased phytoplankton growth. Conservation efforts must prioritize close coordination among government agencies, academia, public awareness campaigns regarding climate change, and capacity building in the field of marine biology. Further, mitigation strategies should focus on reforestation, eco-friendly housing societies, reduced vehicular volatile organic compound (VOC) emissions, and sustainable infrastructure planning.

Conclusions

Rising global warming is driving a continuous increase in sea surface temperatures. Sindh coast of Pakistan is more vulnerable to climate change mainly due to shallow depth and weak upwelling (upwelling occurs mostly in waters deeper than 50 m). Similarly, downwelling might be another cause of increasing sea surface temperature. Strong downwelling Kelvin waves, driven by the intrusion of freshwater from the Bay of Bengal, warm the eastern part of the Arabian Sea. Local warming could be another cause of the increasing sea surface temperature. Global warming and local factors such as urban heat islands and urbanization interact with each other and negatively impact on marine communities. Karachi is the biggest city of Pakistan. Urban heat islands production is increasing in the city due to rapid urbanization and deforestation. During 2023, the temperature reached up to 43°C. Underwater rocky habitats along the Karachi coast typically support a rich biodiversity of algae, historically dominated by monospecific stands of *Sargassum*. However, following Cyclone Nilofar in the Arabian Sea in 2014, these habitats experienced drastic changes. The height of the *Sargassum* thalli decreased significantly, giving way to a mixed community structure, a shift primarily driven by an increase in sea surface temperatures. Rising temperature increased the frequency of cyclone formation and brought changes in local wind patterns. As a result, the propagules could not settle at the right time due to strong wave action. During recent decades, cyclonic intensity increased in the Arabian Sea. A majority of these cyclones formed during the post-monsoon period. *Sargassum* forests play a vital role in the marine environment, e.g., serve as nursery and feeding grounds for some vertebrate and invertebrate species, save the environment by absorbing nutrients, and help to mitigate climate change impacts by absorbing carbon dioxide. A considerable loss has occurred in the biomass of *Sargassum* in submerged habitats along the Karachi coast. It is expected that eutrophication will increase in the future and negatively impact on biodiversity.

Acknowledgements

The first author is highly thankful to Director, Center of Excellence in Marine Biology, University of Karachi for providing logistic support.

Conflict of Interest: There is no potential conflict of interest among authors regarding the publication of this manuscript.

Author's Contribution: A.A. conceptualization, designed the study, data collection, and prepared the original manuscript. N.A and A.R.K. assisted in field work. B. J. statistical analysis. H.H. formal analysis

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