Abstract

The interaction of marine debris with the structurally intricate coral reef communities of the Indian subcontinent has not been investigated in detail. Here, we examined the distribution and density of marine debris in the coral reef areas of Palk Bay and their interactions with coral reefs from five locations along two depth zones (T1 and T2) during 2018 to 2020 period. Derelict Fishing Gears (DFG), with ropes (51 ± 2%) and fishing lines (43 ± 2.5%) were the dominant debris forms recorded. Among the reef-forming corals, *Acropora* sp. colonies experienced the maximum physical injury and mortality due to DFG entanglement. While there was no evident mortality, plastic materials and anchors caused considerable physical harm and tissue loss in *Porites* sp. In addition, an impact assessment study was conducted by routinely removing the accumulated debris from the five locations of the test site (T1), whereas the locations of control site (T2) were left undisturbed. The study revealed noticeable variability in the benthic conditions of the test site and control site. In comparison to control sites (T2) where the debris was not removed, test sites (T1) showed a significant increase in live coral cover and coral recruit density in 2020, against that in 2018. As there was no significant variability in the water and sediment quality between the test and control sites, the significant reduction in the live coral cover and coral recruit density at control sites can be attributed to the accumulation and interaction of marine debris with the coral reef ecosystem. This study throws light on the impact of unsustainable fishing activities and other anthropogenic pressures such as tourism and waste disposal on coral reef ecosystems like Palk Bay. The livelihood of fishermen and coastal communities depends on essential fish habitats like coral reefs; hence, it is important to tackle the marine debris issue through regular debris removal mechanisms as well as through strict legal and management measures.

1. Introduction

Marine debris, defined as the manufactured or processed solid waste materials in the marine environment, is a major threat to the marine ecosystem because of its low degradability (Yoshikawa and Asoh 2004; Bo et al. 2014). Studies show that the marine ecosystems worldwide receive an annual supply of millions of tonnes of debris (Barboza et al., 2019) derived from a variety of anthropogenic activities like commercial shipping, aquaculture, tourism, river discharge, fishing activities etc. (Cau et al. 2017; Shealvy and Register 2017). Benthic regions with complex geomorphology such as the coral reefs are the prime areas of debris accumulation (Galgani et al. 2000).

Coral reefs are under significant stress due to climatic and anthropogenic factors (Gardner et al. 2003; Wilkinson 2006). Reduced coral resilience, recovery capability and increasing reef degradation have resulted in the effective loss of about 19% of global coral cover, whereas about 60% of coral reefs worldwide are under continuous threat (McCook 2002). The coral reefs of Indian subcontinent are also affected due to frequent high intensity bleaching events (Krishnan et al. 2018) and coral disease outbreaks (Sreeraj et al. 2017). In addition, marine pollution in the form of anthropogenic marine debris is also damaging the sensitive coral reef communities (Donohue et al. 2001).

Though land-based sources like river discharge are considered as the major contributors of the anthropogenic marine debris to the coral reefs, recent studies have shown that derelict fishing gear (DFG) is one of the highest contributor, accounting to 60–90% of total litter obtained from benthic communities (Watters et al. 2010; Angiolillo et al. 2015; Oliveira et al. 2015). DFG gets entangled and remain within the benthic communities for a long time, resulting in abrasion, breakage, reduced gas exchange, and an increase in disease outbreaks (Brown and Macfadyen 2007; Lamb et al. 2018). Some of this debris, when accumulated and trapped in the benthic system, could serve as a fake substratum for larval settlement, jeopardising the ecosystem diversity and recruitment (Deudero and Alomar 2015; Ballesteros et al. 2018). Frameworks for managing coral reefs are typically established by considering the regional stressors which are prevalent and by determining the hierarchy of stress that all those stressors impart on coral reefs (Ranith et al. 2017).Though there are various studies detailing the impact of marine debris in organisms like seabirds, fish and turtles through ingestion and toxicity, there are few studies examining the details of physical interactions of debris with benthic invertebrates, especially reef forming corals, which provide ample ecosystem services (Galgani 2015, Patterson et al. 2020).

Palk Bay's benthic environment is habitat to a large spread of coral reefs and seagrasses (Venkataraman et al. 2007). Palk Bay has also been declared as a dugong conservation reserve, to protect the valuable coastal biodiversity (Tamil Nadu Government order number 34 dated 15.02.2022- http://cms.tn.gov.in/sites/default/files/go/env_e_34_2022_D.pdf).

The significance of this study is increased by the fact that the baseline data on marine litter from a potentially designated MPA will be of enormous benefit for the long-term management of debris in these fragile ecosystems. Further, the impact on coral reefs could cascade down to the fishery and biodiversity of the region. In order to measure the effectiveness of debris removal as a mitigation approach to enhance the health and quality of the coral reef ecosystem, we also performed an experimental investigation to assess the impact of debris removal in the live coral cover and coral recruitment.

2. Materials And Methods

2.1 Study area

The study area, Palk Bay is situated along the south east coast of India in the southwest Bay of Bengal, covering a coastline of about 296 kilometres(Arun et al. 2020). It is a shallow flat basin with an average depth of 9 meters, the maximum depth reaching up to 15 meters. This bay is one of the five major permanent sediment sinks along the Indian coast, owing to the sediment transport into the bay by long-shore currents from the Bay of Bengal in the north and Gulf of Mannar in the south. The Palk Bay is characterized by high biodiversity association of benthic flora, invertebrates and fishery resources. Availability of rich benthic seagrass communities, macro-invertebrate population and other associated organisms are significantly influenced by the physical, morphological and environmental characteristics of the region (Hullas et al. 2023).

2.2 Assessment of marine debris abundance and interactions with coral reefs

The abundance and composition of anthropogenic marine debris in the coral reef ecosystem were assessed by benthic surveys conducted along five reef sites in Palk Bay (Olakkuda – R1, Villoonditheertham – R2, Thangachimadam – R3, Pamban – R4, and Mandapam North – R5) from January to March 2018. (Fig. 1). At each site, sampling was done from two depth zones—T1 (0.5 to 3 m) and T2 (3 to 8 m), with similar benthic composition, to assess the variability in marine debris abundance and interaction with coral reefs. Marine debris abundance and interactions with the coral communities were recorded using belt transects (30m×2m). Marine debris collected from the field surveys were broadly categorized as plastics, derelict fishing gears (DFG), rubber, and glass materials (Melli et al. 2017). By modifying the Angiolillo et al. (2015) classification system, the interactions of marine debris with coral colonies were categorized into four levels (Table 1). Coral colonies with varying levels of debris interaction were counted and recorded from the belt transect. Using a Garmin handheld GPS with waterproof case and metallic plugs, we fixed the transect locations for follow-up visits and monitoring.

Table 1
Categories of debris interaction with coral colonies used in the present study

Debris interaction levels	Description
Abrasion	Debris causing evident tissue injury in coral colonies.
Covering	Debris entirely or partially covers the coral colonies.
Entanglement	Debris intertwined with coral colonies.
Lying	Debris lying on or among coral colonies or substratum without any evident physical damages.

Live cover of major coral communities existing in the surveyed locations were identified upto the genus level using coral finder underwater identification keys (Kelley 2011) and quantified as mean percentage from multiple 20-meter line intercept transects (English et al. 1997). Average coral recruit density was quantified from replicate belt transects (30m×2m). Considering the 1 to 3 mm growth rate per month (Moulding 2005), corals less than 5cm diameter were defined as coral recruits in this study.

2.3 Experimental investigation on impact of debris association with coral reefs

Follow-up visits were made to the study sites bi-monthly for a period of two years from March 2018 to March 2020, during which the debris accumulated in the coral reefs of test sites (T1 depth zone) were removed without disturbing the coral colonies (Fig. 2), while the coral reefs of control sites (T2 depth zone) were left undisturbed, allowing the coral colonies in control sites to have continuous physical interactions with marine debris. Knives and scissors were used to carefully cut away the entangled debris from the T1 reef sites. Hereafter, test sites are referred to as T1 zones and control sites as T2 zones. Physical damages (evident tissue loss, but no mortality) and mortality (dead coral colonies with overgrowth of macroalgae) in coral colonies due to debris interaction were counted and recorded based on visual assessment at each transect. The data collected were used to estimate the changes in live coral cover and coral recruitment density at T1 and T2 zones based on standard protocols (English et al., 1997; Moulding 2005).

Ambient environmental conditions were monitored and assessed at T1 and T2 zones to confirm that the variability in the live coral cover and coral recruitment recorded was majorly from the debris interaction. Water and sediment temperature were measured *in-situ* with a digital thermometer, water salinity with an ATAGO refractometer, and water pH with a Lutron digital pH meter equipped with an LH side deep vision water pH electrode. Water and sediment samples were collected in triplicate from T1 and T2 zones and stored at 4ºC before being analysed for nitrate, nitrite, inorganic phosphate, reactive silicate, chlorophyll-a, and total suspended matter using standard procedures of Strickland and Parsons (1972). Water proof WTW Profiline with SenTix 41® probe meter (3110) was used to measure the Eh and pH of the water and sediments clogged over the coral colonies. The clogged sediments were extracted into glass vials with a 100 ml syringe without damaging coral tissues for immediate analysis.

2.4 Statistical analysis

One-way ANOVA with Welch's degree of freedom correction followed by Games-Howell non-parametric multi comparison analysis were conducted to compare the debris accumulation among the five locations surveyed. The variability in debris accumulation between T1 and T2 zones were analysed using paired t-test. Spatial distribution of corals, interactions exhibited by the debris materials, and its impact on coral communities were studied using the factorial analysis of mixed data (FAMD). FAMD is a principal component method used to analyse the association of qualitative and quantitative variables.

All statistical analyses were done using the statistical tool R version 3.4.3(Team 2018). The FactoMineR package (Lê et al. 2008) was used for FAMD. The eigenvalues and proportion of variances exhibited by different dimensions were obtained using the factoextra package (Kassambara and Mundt 2017). The average eigenvalue was calculated, and those with an eigenvalue above the calculated average value were retained for further analysis (Bendixen 1995). The quared cosine (cos^2) explained the representation of qualitative and quantitative variables on the factor map, which in turn revealed the relationship between qualitative and quantitative variables. It also explained the interaction and impact of debris on coral colonies using a 2-dimensional factorial map. The response of live coral cover and recruit density at T1 and T2 zones during the primary and follow-up surveys were tested using an independent sample t-test with 95% level of significance. The variability in the distribution of the environmental variables along the two depth zones was tested using an independent sample t-test with 95% level of significance.

3. Results

3.1. Abundance, distribution and composition of marine debris

Surveys along the five coral reef sites (T1 and T2 zones combined) in Palk Bay provided an estimate of the distribution and density of marine debris. The mean debris density varied significantly across sites (Welch $F_{(4,21.66)} = 202.95$, $p < 0.05$), with the highest density at R1 (15.12 ± 2.42 nos./m^2). R1 had significantly higher marine debris density than R3 (mean difference = 6.89 ± 0.78 nos./m^2, $p < 0.05$), R4 (mean difference = 10.41 ± 0.79 nos./m^2, $p < 0.05$), and R5 (mean difference = 4.76 ± 0.77 nos./m^2, $p = 0.001$) reef sites (Fig. 3.A). There was no significant difference in debris density between the R1 and R2 sites (mean difference = 2.29 ± 0.8nos./m^2, $p = 0.093$).

The debris density of R2 (12.83 ± 0.78 nos./m^2) was significantly higher than that at R3(mean difference = 4.61 ± 0.29 nos./m^2, $p < 0.05$), R4(mean difference = 8.12 ± 0.32 nos./m^2, $p < 0.05$) and R5 (mean difference = 2.47 ± 0.27 nos./m^2, $p < 0.05$).

R3 ranked fourth in terms of debris density (8.22 ± 0.48 nos./m^2), with significantly lower density than R5 (mean difference = -2.14 ± 0.19 nos./m^2, $p < 0.05$) and significantly higher density than R4 (mean difference = 3.51 ± 0.26 nos./m^2, $p < 0.05$). R4 had the lowest debris density (4.71 ± 0.65 nos./m^2), which was significantly lower than that of R5 (Mean = 10.361 ± 0.37 nos./m^2, mean difference = 5.65 ± 0.24 nos./m^2, $p < 0.05$). Paired t-test analysis showed no statistically significant variability ($p > 0.05$) in the debris abundance between T1 and T2 zones (Fig. 3B).

Derelict fishing gears and plastics accounted for the majority of anthropogenic marine debris collected from T1 and T2 zones at all reef sites (Fig. 3). DFG was more in T1 zones with highest record from R1_T1 (56.9 ± 8.1%) followed by R3_T1 (46.3 ± 6.1%), and R5_T1 (45 ± 1.4%). Plastic debris dominated in four of the T2 zones (R4_T2 (56 ± 1.7%); R2_T2 (51 ± 3.1%); R3_T2 (45 ± 1.2%); R1_T2 (44 ± 4.2%)) and two T1 zones (R4_T1 (55.5 ± 3.5%); R2_T1 (41.3 ± 9.2%)). The abundance of rubber and glass materials was relatively lower than DFG and plastics among the surveyed reef locations. R1_T1 had the highest abundance of rubber materials (20.9 ± 2.8%) and the least abundance of glass materials (3.3 ± 2.8%); whereas, R4 recorded least abundance of rubber materials (5 ± 1.4%) and highest abundance of glass materials (15 ± 2.1%), at both T1 and T2 zones (Fig. 4).

The most common DFG collected during the surveys were ropes, fishing lines, anchors, floats and nets/traps (Fig. 5). Ropes were the dominant DFGs at both zones of R3 (33 ± 2% at T1 and 39 ± 1.6% at T2) and R4 (51 ± 2% at T1 and 49 ± 1.5% at T2), as well as at the T2 zone of R1 (37 ± 2.6%). Fishing lines were the major component of DFG at R5 (43 ± 2.5% at T1 and 30 ± 2.2% at T2), and R2 (35 ± 1.5% at T1 and 39 ± 1.2% at T2) (Fig. 4). Floats were most abundant at R2_T1 (24 ± 2.5%) and least at R1_T2 (11 ± 1.3%). Nets/ traps were the dominant forms at R3_T1 (27 ± 1.53%), and the least abundant forms at R4_T1 (8 ± 1.73%). While no anchors contributed to the total DFG at R2_T1, highest contribution of anchors were recorded from R2_T2 (8 ± 3.1%) and R4_T2 (8 ± 2.9%).

3.2. Marine debris – coral reefs interaction

The mixed data factorial analysis identified five dimensions that explained 87.18% of the total variation within the dataset. Dimensions 1 and 2 explained about 45.14% and 28.39% of total inertia respectively, resulting in a cumulative variance of 73.53%. The inertia explained by other dimensions was low and unlikely to give any significant interpretations. The distribution of major coral forms and the interaction of debris with them varied significantly across the surveyed locations (Fig. 6).

The quality of representation of variables (cos^2) gives the association between qualitative and quantitative variables. At R1 T1, R2 T1, and R2 T2 zones, the coral *Acropora* sp. was dominant. Apart from *Acropora* sp., these locations were also rich in corals such as *Pocillopora* sp. and *Favites* sp. Debris such as fishing lines, ropes, hooks, nets/traps were found entangled with the *Acropora* sp. causing death to coral colonies. Plastic materials and anchors played a significant role in abrasion and physical damage among *Porites* sp. colonies. *Porites* sp. was abundant in the T2 zones of R1, R3, R4 and R5 reef sites. Ropes were the dominant debris in these locations and in many a case, they were found wrapped around the base of the massive coral *Porites* sp causing physical damages. Even though physical damage was rampant in colonies of *Porites* sp., there was no mortality due to debris interactions. Unlike entanglement and abrasion, covering of coral reefs by debris and lying of debris among the reef substratum did not cause considerable physical damage to the corals in the locations surveyed. While coral colonies of *Porites* sp. and *Acropora* sp. suffered significantly from marine debris interaction, colonies of *Pocillopora* sp. and *Favites* sp. were unaffected. The coral reef – marine debris association as observed from the field survey is illustrated in Fig. 7.

3.3. Experimental investigation on the impact of debris interactions on coral reefs

Two years after the primary survey, a follow-up survey in 2020 revealed significant change in live coral cover and coral recruit density at T1 and T2 zones. A statistically significant increase in live coral cover was observed at all T1 zones ($p < 0.05$), with a maximum increase of 5.991.44% at R1 T1 (Fig. 8).

Except for R1 T2, which had a $2.31 \pm 1.08\%$ increase in live coral cover, all T2 zones had a significant reduction in live coral cover ($p < 0.05$). The increase in live coral cover at R1 T2 was, however, only about half of what was observed at R1 T1. R4 T2 had the greatest reduction in live coral cover ($-2 \pm 1.16\%$). When compared to the results of the 2018 survey, recruitment density observations showed a statistically significant increase at all reef locations along the T1 locations ($p < 0.05$) (Fig. 9). R1_T1 had the maximum increase in recruitment density (2.14 ± 0.78 nos.m^{-2}). Even though some T2 locations showed an increase in recruitment density during the follow-up survey, the increase was not statistically significant ($p > 0.05$).

Except for the Chl-a concentration and dead coral with algae (DCA) cover, there were no significant differences in the quality of environmental variables ($p > 0.05$) between T1 and T2 zones during the study period (Table 2). The concentration of chlorophyll-a was statistically different between the T1 and T2 locations of R1 (mean difference = 0.62 ± 0.24, $p = 0.02$) and R3 (mean difference = 0.55 ± 0.23, $p = 0.03$); and DCA was significantly different between T1 and T2 locations of R1 (mean difference = 2.76 ± 1, $p = 0.02$) and R2 (mean difference = 1.89 ± 0.49, $p = 0.002$), with values being higher at T2 zones. None of the environmental variables showed a significant difference in concentration between the T1 and T2 locations of reef sites R4 and R5 ($p > 0.05$).

Table 2
Difference between T1 and T2 depth zones in the quality of major environmental variables during 2018–2020 as obtained from independent sample t-test. Results are presented as mean difference (T1-T2), standard error of mean difference, t value and p-value.

Location	Environmental variables	Mean Difference (T1-T2)	Standard Error	t value	P-value
R1	Water-temp	0.09	0.63	0.14	0.89
	Salinity	-0.13	0.47	-0.27	0.79
	Sed-pH	-0.05	0.04	-1.13	0.28
	IP	0.17	0.20	0.85	0.41
	RS	-2.66	6.20	-0.43	0.67
	Nitrite	-0.05	0.04	-1.36	0.20
	Nitrate	-1.12	0.59	-1.90	0.08
	DCA	-2.76	1.00	2.75	0.02
	TSM	1.69	2.15	0.78	0.45
	Chl-a	0.62	0.24	2.58	0.02
	Sed-Eh	-1.50	1.56	-0.96	0.35
	Water_pH	-0.01	0.04	-0.29	0.78
R2	Water-temp	-0.25	0.14	-1.74	0.10
	Salinity	-0.25	0.25	-0.98	0.34
	Sed-pH	0.02	0.09	0.29	0.78
	IP	-0.25	0.59	-0.42	0.68
	RS	-0.25	1.81	-0.14	0.89
	Nitrite	-0.01	0.01	-1.66	0.12
	Nitrate	-0.25	0.21	-1.21	0.25
	DCA	-1.89	0.49	3.88	0.00
	TSM	-0.31	0.72	-0.43	0.68
	Chl-a	-0.10	0.10	-1.03	0.32
	Sed-Eh	2.75	1.94	1.41	0.18
	Water_pH	-0.02	0.03	-0.86	0.41
R3	Water-temp	0.07	0.48	0.15	0.89

Location	Environmental variables	Mean Difference (T1-T2)	Standard Error	t value	P-value
	Salinity	-0.13	0.47	-0.27	0.79
	Sed-pH	0.04	0.04	0.97	0.35
	IP	-0.11	0.25	-0.45	0.66
	RS	3.16	3.73	0.85	0.41
	Nitrite	-0.03	0.06	-0.63	0.54
	Nitrate	0.51	0.84	0.60	0.56
	DCA	1.78	2.70	0.66	0.52
	TSM	-3.84	2.17	-1.77	0.10
	Chl-a	0.55	0.23	2.39	0.03
	Sed-Eh	1.00	1.03	0.97	0.35
	Water_pH	-0.01	0.03	-0.45	0.66
R4	Water-temp	0.16	0.39	0.41	0.69
	Salinity	-0.38	0.47	-0.80	0.44
	Sed-pH	0.03	0.05	0.48	0.64
	IP	0.13	0.22	0.58	0.57
	RS	5.33	2.41	2.21	0.04
	Nitrite	0.03	0.04	0.91	0.38
	Nitrate	0.04	0.33	0.11	0.91
	DCA	1.03	6.23	0.17	0.87
	TSM	-2.05	1.61	-1.28	0.22
	Chl-a	-0.04	0.25	-0.16	0.88
	Sed-Eh	0.38	1.29	0.29	0.78
	Water_pH	-0.04	0.04	-0.97	0.35
R5	Water-temp	-0.09	0.22	-0.39	0.70
	Salinity	0.25	0.31	0.80	0.44
	Sed-pH	0.04	0.04	0.94	0.36
	IP	0.03	0.11	0.29	0.78

Location	Environmental variables	Mean Difference (T1-T2)	Standard Error	t value	P-value
	RS	0.15	4.98	0.03	0.98
	Nitrite	0.01	0.04	0.15	0.88
	Nitrate	-0.02	0.30	-0.07	0.94
	DCA	0.20	4.02	0.05	0.96
	TSM	0.02	1.98	0.01	0.99
	Chl-a	0.05	0.13	0.37	0.72
	Sed-Eh	-2.88	4.03	-0.71	0.49
	Water_pH	-0.05	0.04	-1.13	0.28

4. Discussion

The density of marine debris in coastal ecosystems is supposed to be directly related to increasing urbanisation and human interactions (Galgani et al. 2000; Mordecai et al. 2011). The debris density and composition collected during the present study from various reef sites in Palk Bay demonstrate the impact of anthropogenic activities in the coastal ecosystem.

Derelict fishing gear, such as lost, abandoned, or discarded nets, lines, and traps, is becoming a major marine pollutant (Macfadyen et al. 2009; Bilkovic et al. 2014; Angiolillo et al. 2015; Wilcox et al. 2015). The presence of high percentage of DFG among the marine debris recorded in this study demonstrates that Indian coastal waters are no better than coastal ecosystems worldwide in terms of marine debris input (Watters et al. 2010; Angiolillo et al. 2015; Oliveira et al. 2015). Palk Bay experiences increased fishing pressure due to its shallow waters, abundance of coral reef fish resources, and free access to the waters, as opposed to the Gulf of Mannar, which is a marine protected area (Manikandan et al. 2017). Ramanathapuram district, in which the study sites are included, was one of the first districts where mechanized fishing was introduced, as early as 1960 (Scholtens et al. 2012). According to the 2011–2012 statistics from the Tamil Nadu department of fisheries, about 70% of total fish catch in the Ramanathapuram district is from the Palk Bay – Gulf of Mannar region. Mechanised and motorised fishing activity is very prominent in the region with about 38236 mechanised and 13270 motorised crafts compared to the neighbouring fishing districts. Number of non-motorised crafts were also significantly higher in Ramanathapuram (9045 Nos.). More over Ramanathapuram was the only district in Tamilnadu reported with 237 shore seiners (Kasim 2015). This evidently shows the high fishing activity in the region and potential source of DFG accumulation in the bottom. We found that nylon lines and ropes dominated the DFG at Palk Bay reef locations, similar to California coastal waters (Watters et al. 2010) and Mediterranean waters (Mordecai et al. 2011). Common fishing methods in Palk Bay, such as drift-gill net and bottom-set gill net fishing, as well as hook and line fishing from the shores, explain the high prevalence of lines and ropes identified in the DFG. When fishing gear get entangled on coral colonies, fishermen cut the ropes before retrieving the gear, and the rope falls to the bottom and sinks out of sight in the water (Ballesteros et al. 2018). Given the cost, fishermen typically retrieve the majority of heavy gear, such as anchors, that are lost in the shallower region. However, the chances of recovering lost gears are lower in deeper bottoms with complex benthic cover, which explains the increased density of heavy gears such as anchors in T2 locations of the studied reef sites. Non-biodegradable fishing gear, most of which is made of synthetic materials such as nylon or plastic, is either lost or discarded into the marine system while fishing (Galgani et al. 2015). These persistent debris decompose slowly (O'Brine and Thompson 2010), and over time may get entangled or associated with benthic sessile organisms such as coral reefs, resulting in large-scale ecosystem degradation (Yoshikawa and Asoh 2004; Pham et al. 2013; Woodall et al. 2015). Furthermore, synthetic debris can degrade over time into smaller fragments that can enter the marine food web (Laist 1987).

The type of anthropogenic activity determines the type of debris that accumulates in the waters. At Olakkuda (R1), which is a major fishing region, the dominant debris is DFG. Similar reports exist on the abundance of polypropylene and polystyrene debris originating from fishing activities along the north western beaches of Rameswaram island (Vidyasakar et al. 2018). On the contrary, Villoonditheertham (R2) and Pamban (R4) regions of Rameswaram island are important pilgrimage and tourist destinations (James et al. 2021). Tourism-heavy areas are associated with the careless disposal of plastic materials such as covers and packing materials (Krishnakumar et al. 2018). Plastic materials accumulated on beaches can enter the benthic marine system via tidal incursion or terrestrial runoff during the monsoon. The large number of pilgrims, as well as their religious and recreational activities, may have contributed to the high plastic accumulation in the benthic regions of R2 and R4 locations.

All four categories of debris interactions, as mentioned in Table 1 were evident at the reef locations of Palk Bay. Lost lines and ropes get entangled primarily on *Acropora* coral colonies, resulting in high mortality. The tall branching structure of *Acropora* coral colonies can entrap derelict fishing lines and ropes more efficiently than small non-branching coral forms, resulting in large scale entanglement and debris interaction (Yoshikawa and Asoh 2004; Fabri et al. 2014). The weaker and fragile branches of the branching coral forms such as *Acropora* sp. get intertwined with debris materials and become vulnerable to breakage from wave action. Similar degradation of coral communities by the entanglement of lost lines was reported from Florida Keys National Marine Sanctuary (Chiappone et al. 2002) and other parts of the world (Pham et al. 2013; Angiolillo et al. 2015; Oliveira et al. 2015; Woodall et al. 2015). Differences in physical architecture render the various coral species differentially vulnerable to the interaction with debris. Small *Pocillopora* and *Favites* coral colonies of Palk Bay without prominent protruding branches and with strong skeleton had less impact from the debris interaction. Coral reef strength and skeletal characteristics also influence how the coral reefs interact with marine debris (Bo et al. 2014). Strong structures such as *Porites* sp. are reportedly less vulnerable to breakage from debris entanglement, as the resistant skeletal structure allows them to withstand mechanical breakages. Debris interaction caused only abrasion and tissue loss and no mortality in the *Porites* sp. colonies, which is in agreement with previous studies (Bo et al. 2014; Angiolillo et al. 2015).

Live coral cover of Palk Bay has reportedly declined in the recent decades due to high-frequency coral bleaching events and regional stressors (Marimuthu et al. 2016). It was recently reported that the abundance of stress-tolerant coral forms in the Palk Bay coral reef system has significantly increased, improving the ecosystem's resilience and recovery potential (Thinesh et al. 2019). Regular debris removal from the test reef sites bimonthly from the primary survey (2018) to the second survey (2020) would have aided in the rapid recovery of resilient coral colonies, resulting in a significant increase in percentage cover after two years. Continuous interaction of coral colonies with accumulating debris materials at the control (T2) reef sites may have exacerbated physical damage and tissue loss in the coral colonies. Besides tissue loss, continuous abrasion of debris materials on corals can tear open the coral surface, allowing pathogens to infect and cause coral diseases and mortality. It has been demonstrated that the interaction of marine debris with corals can increase the disease probability from 4–89%. (Lamb et al. 2018). Frequent physical stress on coral colonies can quicken the degradation process and impede coral recovery. This could have contributed to the significant decline in live coral cover at T2 locations. It has to be noted that there were no marked changes in the DHW of the Palk Bay waters between 2018 and 2020, ruling out the possibility of coral bleaching and subsequent decline in coral cover (Supplementary Fig. 1).

The continuous supply of coral larvae, successful larval settlement, and larval survivability are critical for maintaining the diversity and structural complexity of coral reef ecosystems (Graham et al. 2011) and determining the resilience and recovery capability of coral reefs (Bramanti and Edmunds 2016). Even if there is an abundance of larvae, failure of coral larvae to find suitable settlement space and metamorphosis results in early larval mortality (Ritson-Williams et al. 2009). The successful settlement and growth of coral larvae are governed by ecological cues such as suitable substratum availability, substratum texture, and chemical composition (Mason and Cohen 2012; Tebben et al. 2015). Except for DCA at locations R1 and R2 and chlorophyll-a at locations R1 and R3, the T1 and T2 locations showed no statistically significant variability in environmental quality. Recently, the significant roles of substratum pH and Eh in modulating coral larval settlement in the Gulf of Mannar coral reef system have been reported (Machendiranathan et al. 2016). The distribution of sediment pH and Eh along the T1 and T2 depth zones in our study was similar, indicating similar chemical cues for coral larval settlement (Machendiranathan et al. 2016).

The regular removal of debris from R1T1 and R2T1 may have increased the settlement space for coral larvae, resulting in a higher recruit density than at T2 locations. Insufficient settlement space caused by high debris abundance and physical barriers to larvae identifying settlement cues may have resulted in lower larval settlement and recruitment density at T2 locations compared to T1 locations. A similar decrease in larval settlement rate was observed on Caribbean reefs with reduced settlement space (Bruno et al. 2009). Debris materials may also serve as pseudo-substrata for coral larvae, and settlement on unstable surfaces may result in physical damage and early mortality. As shown in Fig. 6.a, coral recruits were found attached to unstable debris surfaces such as ropes, plastic traps, and other debris materials during field survey. Larval settlement and settlement survivability are more likely on mechanically stable natural settlement structures than on unstable surfaces (Manikandan et al. 2017). Coral recruits settled over unstable surfaces may get dislodged as the substratum topples or becomes unstable with higher water movement and an increase in the weight of the growing recruits (Arthur et al. 2006).

Palk Bay corals reportedly have high resilience and recovery potential due to sufficient coral larval supply from nearby healthy reefs (Manikandan et al. 2017). This explains why, despite continuous debris accumulation and interaction, recruitment at some of the control stations increases, though insignificantly. During the two-year period, regular removal of debris materials from T1 locations may have provided more settlement space, resulting in significantly improved larval settlement and recruitment density. It is clear that in a coral reef system with a surplus larval supply, such as Palk Bay, systematic removal of debris materials can significantly improve structural complexity, biodiversity, and health status through recovery and successful recruitment.

Considering the local population's direct reliance on the coastal system in the form of fishing and tourism, it is not sensible to stop the anthropogenic interaction completely. However, as demonstrated by the current case study, regular scientific removal of accumulated debris from coral colonies and the benthic realm will help to reduce the threat from debris interaction. A small network of volunteers trained and assigned by regional stakeholders to monitor and remove marine debris could help sensitive coral communities overcome the challenges posed by accumulated debris.

5. Conclusion

Our research provides an estimate of the diversity and abundance of anthropogenic marine debris accumulated in the Palk Bay coral reef ecosystem. The type of debris accumulated was directly linked to the anthropogenic activity prevalent at the location, like fishing, tourism, pilgrimage etc. Marine debris actively interacted with coral colonies, resulting in reduced coral cover and low coral recruitment in the Palk Bay region. The abundance of derelict fishing gear in marine debris indicates intense fishing activity and a lack of awareness among fisherman communities. Locations from where debris materials were regularly removed showed improved live coral cover and high recruit density. Continuous surveys and monitoring programmes are required to estimate debris distribution variability along the region and assess debris interaction with vulnerable benthic ecosystems. As evident from the present study, manual removal of debris materials from the reef system without disturbing the coral communities has to be adopted as a mitigation plan to allow the disturbed coral reef locations to recover and recruit successfully. There is an increasing need for environmental outreach activities to improve awareness among the local fisher communities on the importance of litter management in marine systems. Through scientific awareness and systematic training, the local fisher communities could be equipped to serve as volunteers for safe removal of debris from coral reef ecosystem. Baseline information obtained from the present study would be relevant for policy makers to evaluate the efficiency of existing management plans and develop improved monitoring programs to conserve the coral ecosystems.

Declarations

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Data and code availability: Datasets used and/or analysed and codes during the current study are available from the corresponding author on reasonable request

Conflict of Interest: The authors declare that they have no competing interests.

Authors Contribution

NM was a major contributor in conceptualizing the work and in writing and editing the manuscript, RR did the benthic surveys, data sampling, statistical analysis and manuscript writing, GG contributed to the scientific explanations, manuscript preparation and proof reading, LS and MM assisted with the benthic surveys and data collection. All authors read and approved the final manuscript.

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Figures

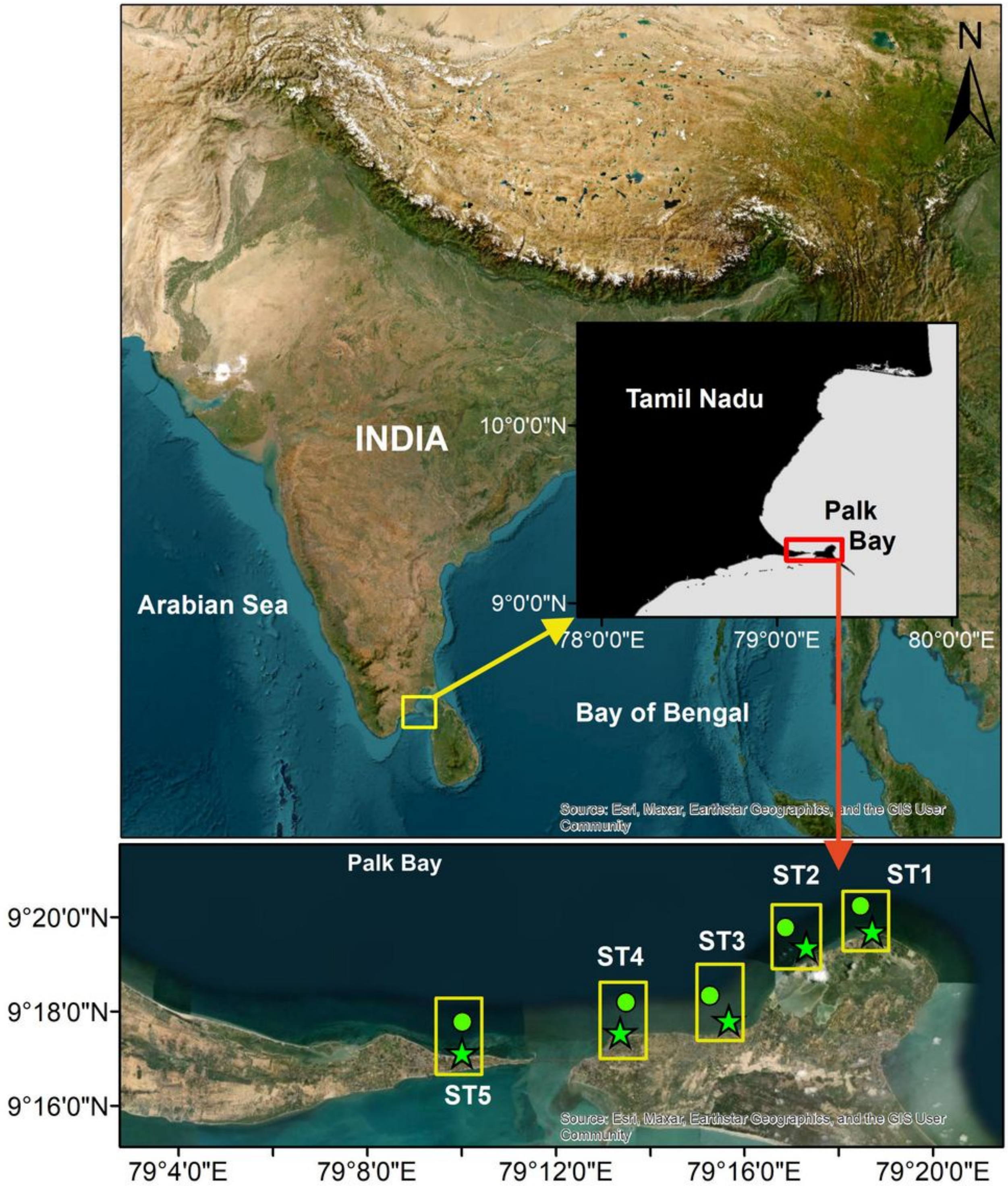

Figure 1

Study area map showing the survey locations. Star symbol represents test stations ('T1' depth zones) and circle symbol represents control stations ('T2' depth zones).

Figure 2

Debris removed from the test sites

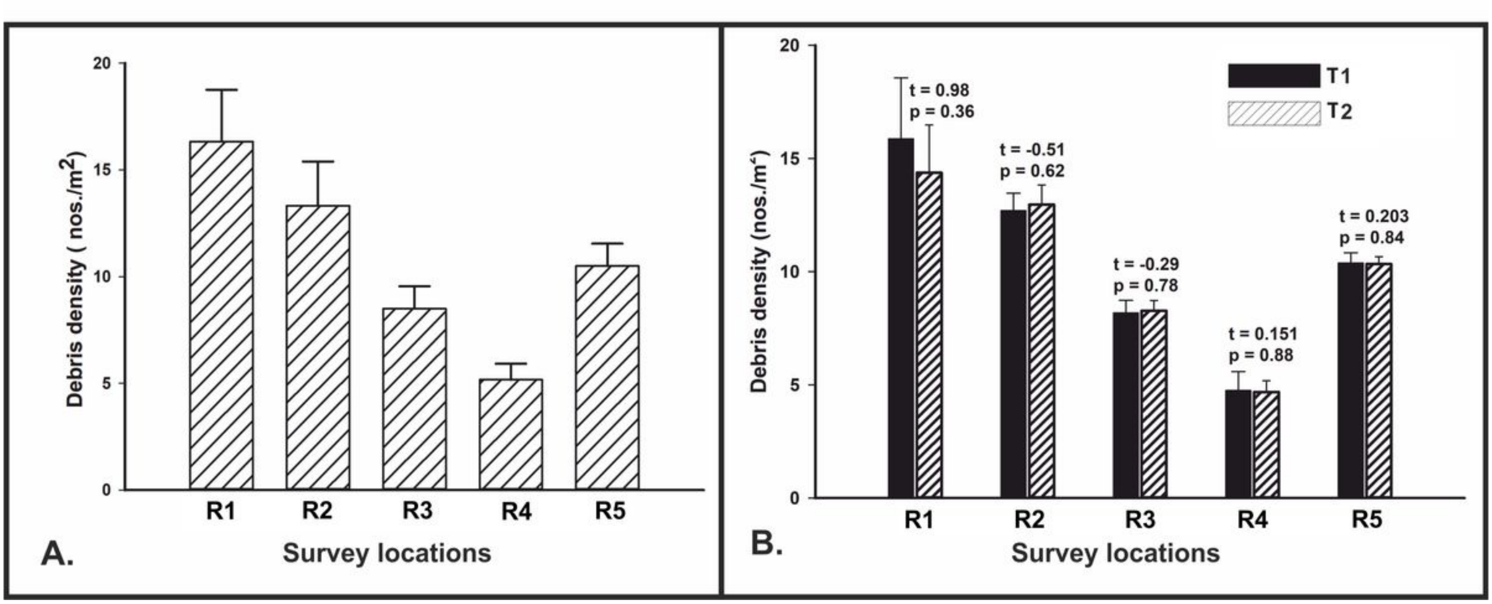

Figure 3

(A)Mean marine debris density at different survey sites along Palk Bay; (B) variability in debris density at T1 and T2 locations of surveyed sites.

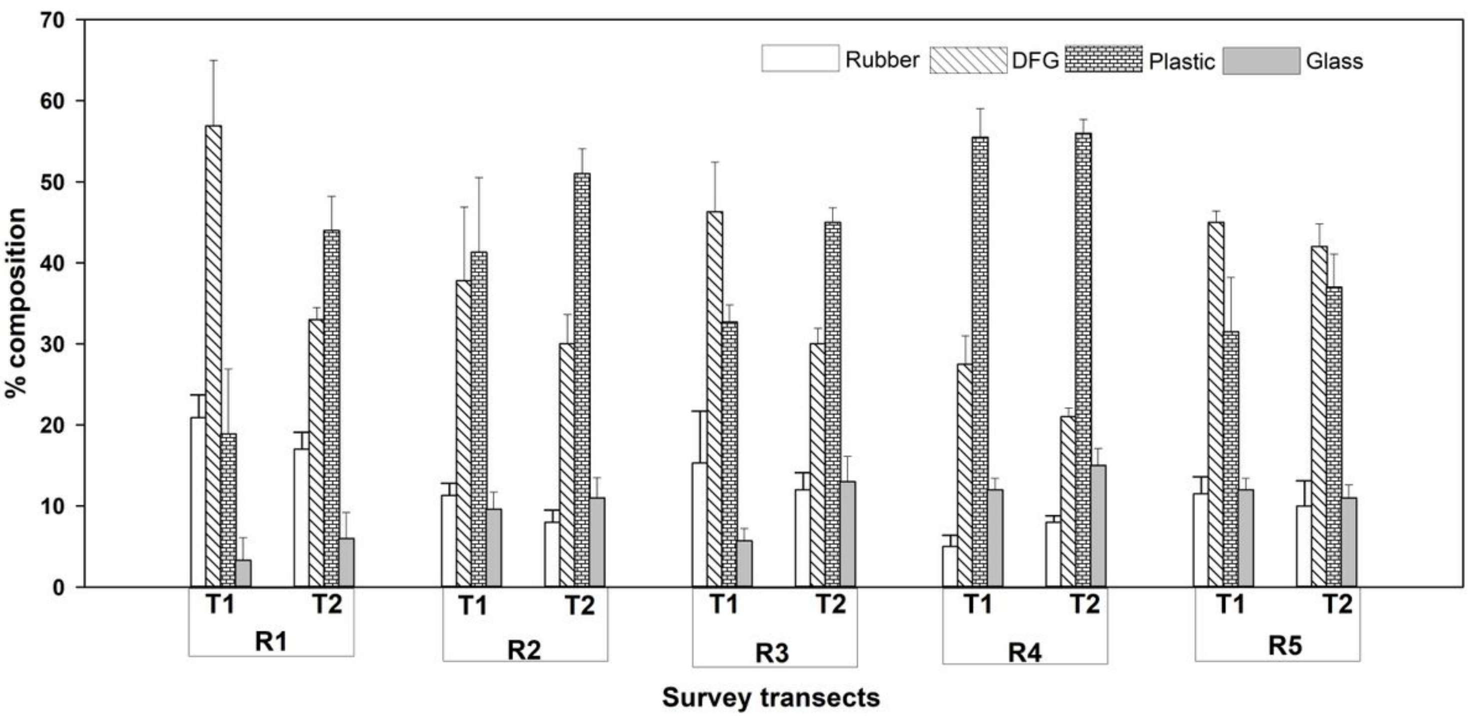

Figure 4

Debris composition at the depth zones of the surveyed locations at the Palk Bay. Error bar represents the standard deviation (SD).

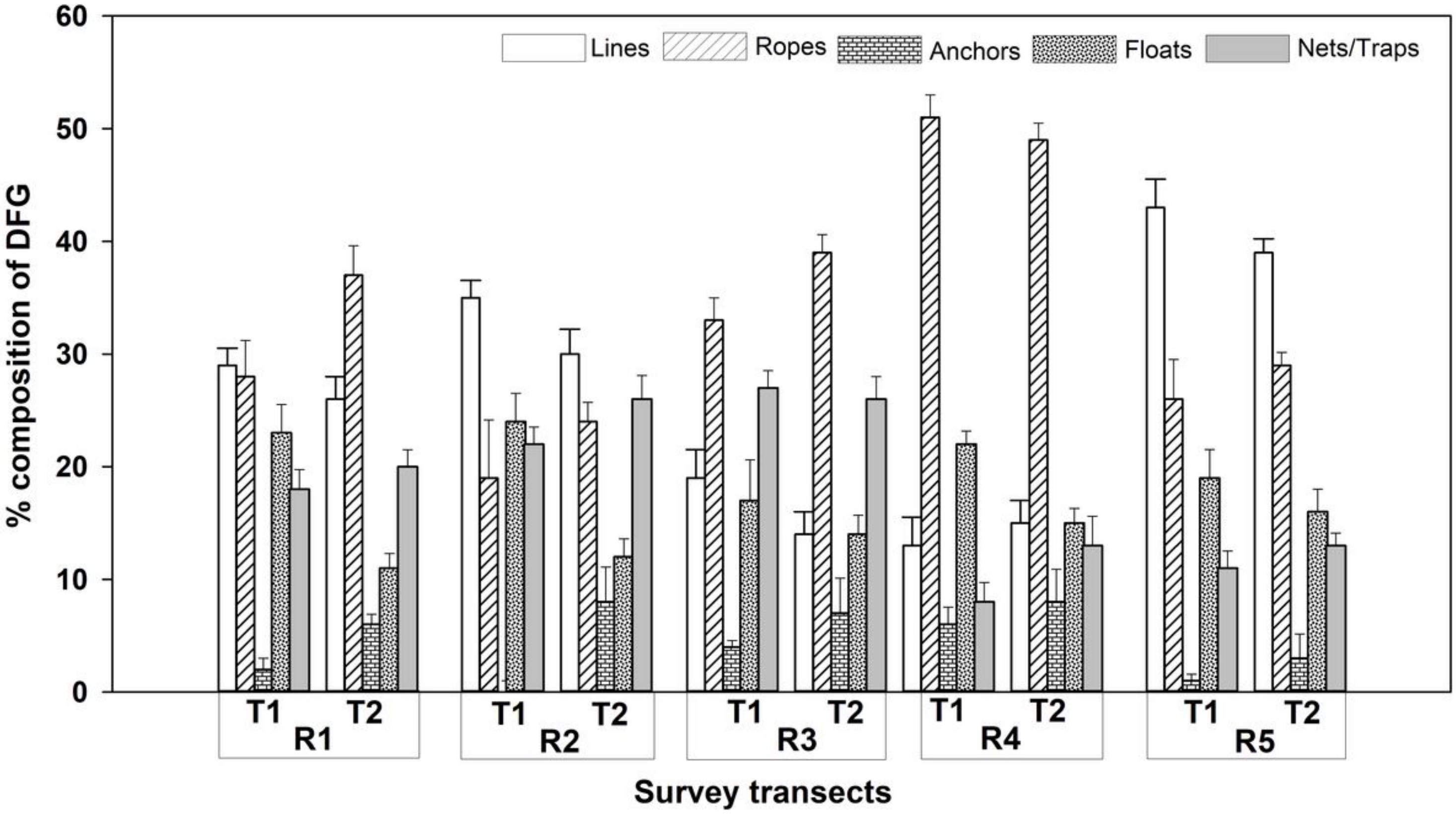

Figure 5

Components of derelict fishing gears in the benthic system of Palk Bay. Error bar represents the standard deviation (SD).

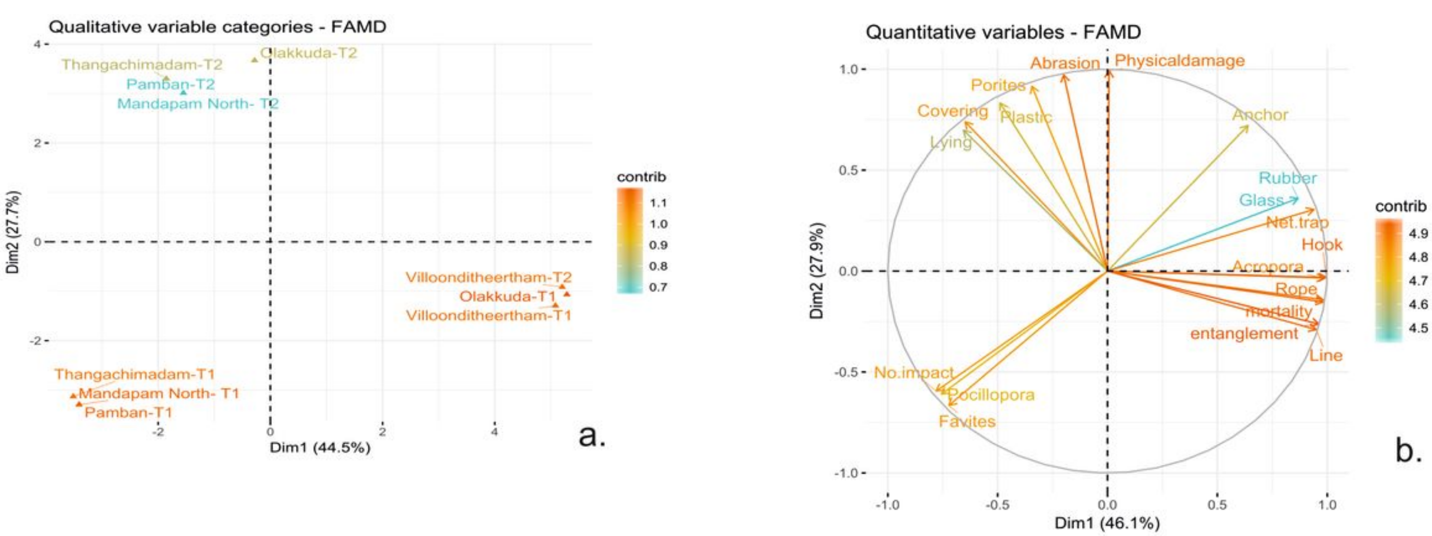

Figure 6

Distribution of major coral forms, debris materials and interaction (quantitative variables) along the surveyed reef locations (qualitative variables).

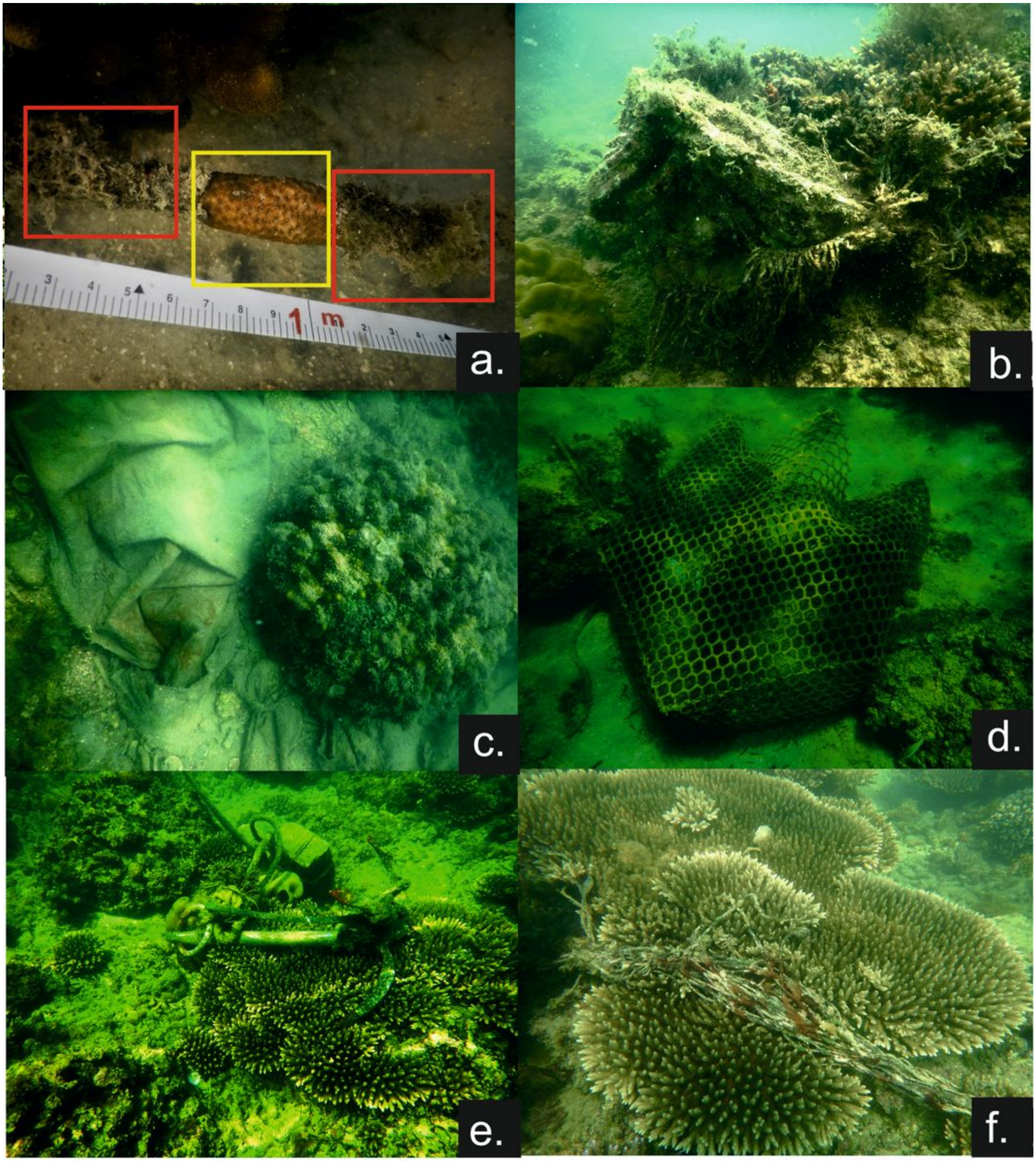

Figure 7

Few examples of coral-marine debris interactions: (a) Pseudo-substratum -coral recruit settled on a rope (yellow box) that is overgrown by macroalgae (red box); (b) Entanglement - plastic sac entangled on *Acropora humilis* with evident mortality; (c) Lying - Plastic sheet aside the coral reefs; (d) Covering -fibre fish trap covered on a *Porites* sp.; (e) Abrasion - abandoned anchor and resultant physical damage on *Acropora hyacinthus*; (f) Entanglement - discarded rope entangled on *Acropora cytherea*.

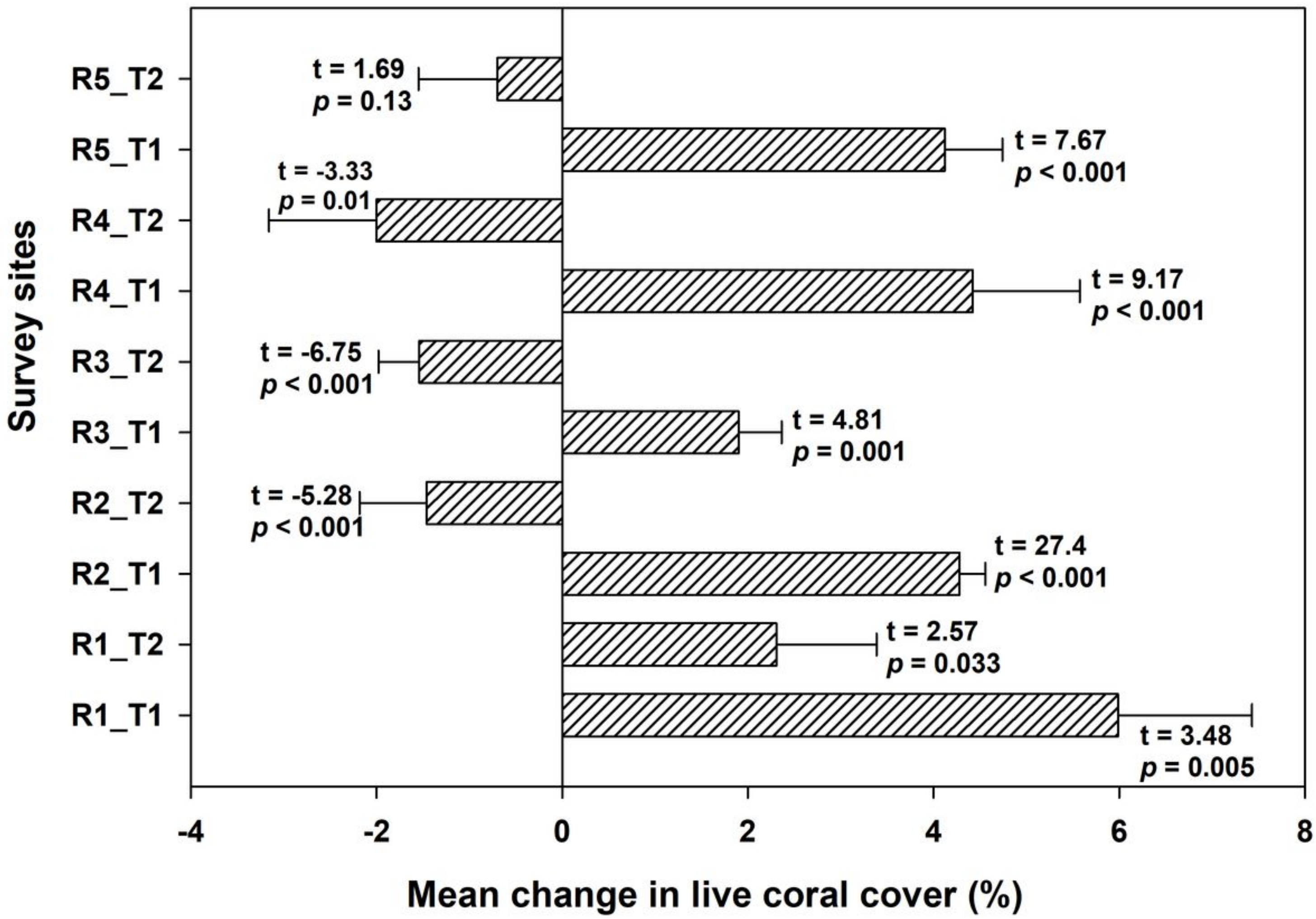

Figure 8

Mean change in live coral cover at the test (T1) and control (T2) zones of Palk Bay during the primary and follow-up survey. Error bar represents the standard deviation (SD).

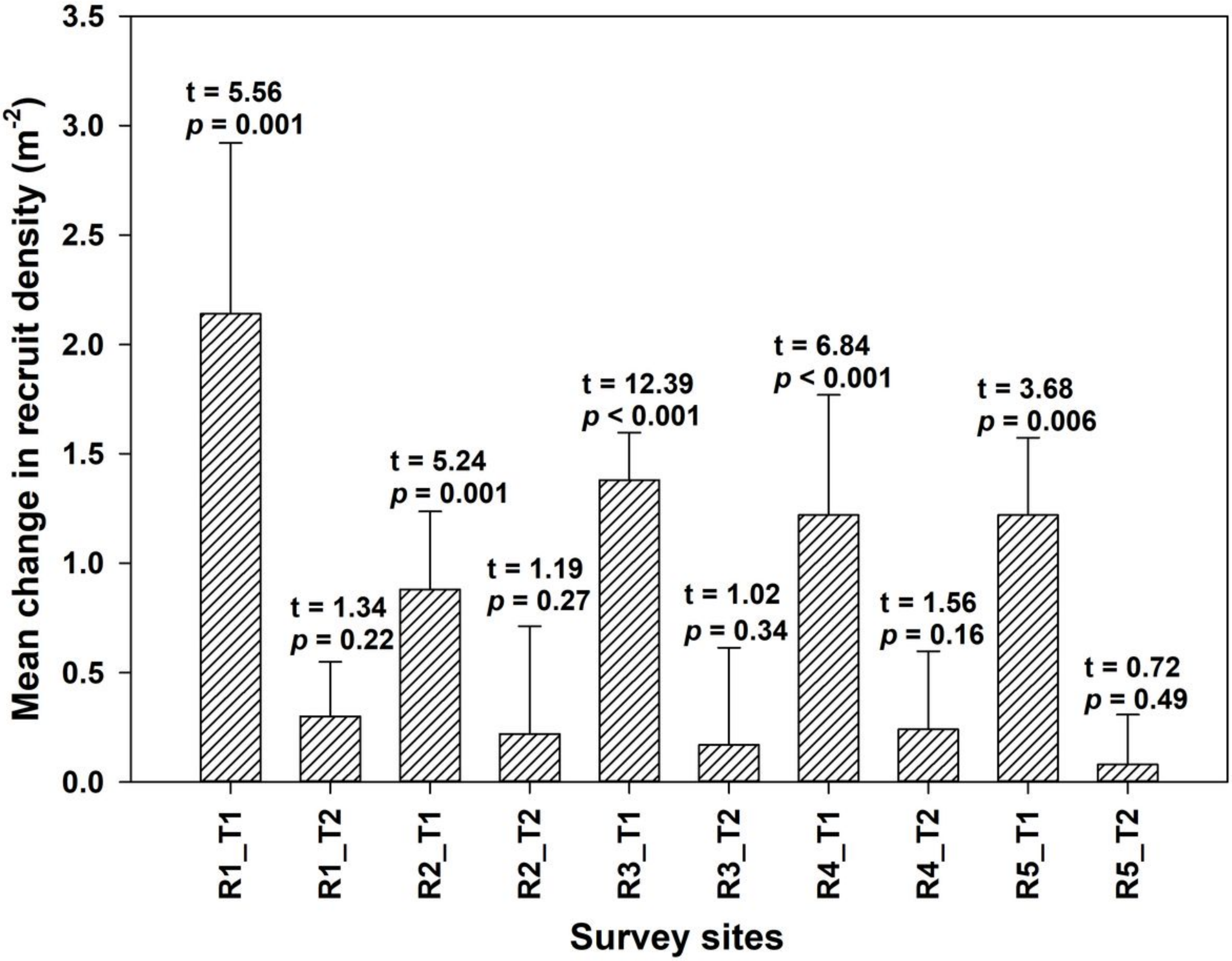

Figure 9

Mean change in recruit density at surveyed locations during the first (2018) and follow-up (2020) survey. Error bar represents the standard deviation (SD).

Supplementary Files

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- Supplementaryfigure1.jpg