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COVID-19 lockdown improved the health of coastal environment and enhanced the population of reef-fish

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ABSTRACT

Reduction in the impact of human-induced factors is capable of enhancing the environmental health. In view of COVID-19 pandemic, lockdowns were imposed in India. Travel, fishing, tourism and religious activities were halted, while domestic and industrial activities were restricted. Comparison of the pre- and post-lockdown data shows that water parameters such as turbidity, nutrient concentration and microbial levels have come down from pre- to post-lockdown period, and parameters such as dissolved oxygen levels, phytoplankton and fish densities have improved. The concentration of macroplastics has also dropped from the range of 138 ± 4.12 and 616 ± 12.48 items/100 m^2 to 63 ± 3.92 and 347 ± 8.06 items/100 m^2. Fish density in the reef areas has increased from 406 no. 250 m^{-2} to 510 no. 250 m^{-2}. The study allows an insight into the benefits of effective enforcement of various eco-protection regulations and proper management of the marine ecosystems to revive their health for biodiversity conservation and sustainable utilization.

1. Introduction

Intensive human activities have induced extensive degradation of sea-water and coastal habitats globally (Wu et al., 2017). In particular, the near-shore marine ecosystems often suffer by man-made threats such as sedimentation, eutrophication, pollution, and overexploitation of fishing resources (Halpern et al., 2008). Many studies have demonstrated that urbanization, industrialization and overexploitation are the major causes of pollution in every domain of the environment (Masood et al., 2016). According to Jones et al. (2018) about 87–90% of the ocean surface worldwide has been affected by humans. In the past few decades, fishing for livelihood has resulted in dwindling fishery resources and in degrading such vital habitats as coral reefs, seagrasses and mangroves (Luypaert et al., 2020).

The quality of marine water is of utmost importance as it has an immense impact on aquatic ecosystems including marine life. Hence, data on the quality of coastal water is very important for understanding the environmental conditions. When pollutant inflow into sea breaches the threshold level, the coastal organisms are threatened (Puthiya Sekar et al., 2009). The past four decades have witnessed remarkable increase in nutrient inputs into coastal waters, altering the coastal ecosystems rapidly and substantially on a global scale (Boesch, 2002). Further, the issue of marine debris has assumed enormous proportions in the wake of growing coastal human population and fast industrialization in the past few decades (Critchell and Lambrechts, 2016). Sweet et al. (2019) reported that plastics constitute about 60–80% of the marine debris. Being cheap and durable, plastic is produced and used on an ever increasing scale (Rocha-Santos and Duarte, 2015). Plastics have the potential to cause ecological damages. Plastic litter entering the marine systems affects at least 800 marine and coastal species in several ways like ingestion, entanglement and harmful alteration of surroundings (Sweet et al., 2019).

Growing human population and escalating demand for plastic have brought about the present plight. However, there is only paucity of

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measures to conserve and manage the environment (Lotze et al., 2011). Timely intervention initiatives have recovered many ecosystems in the past (Moreno-Mateos et al., 2017). The health of ecosystems can certainly be improved by removing human-induced threats (Lotze et al., 2011). Hence, all the conservation initiatives work toward reducing human impacts. Due to the ongoing pandemic of COVID-19, many countries around the world have imposed strict lockdowns. These lockdowns have restricted and halted human activity, reducing thus the anthropogenic stress to nature. This is a great opportunity to compare the health of ecosystems before and after lockdown to understand the magnitude of ecological recovery without human intervention.

In India, countrywide lockdown was imposed from 24th March 2020. During this period, there was less activity in sectors like industries, transports and business establishments, while no activity in sectors like fishing, hotels, tourism, and places of worship, which are the major sources of marine pollution. Thus the lockdown helped to reduce the human-induced impacts. The coast of Gulf of Mannar (GoM) is 365 km long, extending from Rameswaram in the north to Kanniyakumari in the south bordering the districts of Ramanathapuram, Thoothukudi (Tuticorin), Tirunelveli and Kanniyakumari. This coast harbours a rich biodiversity of 4223 species of marine plants and animals (Balaji et al., 2012). It is endowed with key coastal habitats like coral reefs (with 117 coral species), seagrass meadows (with 14 seagrass species) and mangrove forests (with 11 species). There are 21 islands in GoM surrounded by coral reefs (Edward et al., 2007). The reef region of GoM is one of the four major reef areas in India. In 1986 Government of Tamil Nadu created Gulf of Mannar Marine National Park comprising these islands and the coastal waters surrounding them. In 1989 Government of India formed Gulf of Mannar Marine Biosphere Reserve out of the entire GoM. Small-scale fishermen, numbering over 100,000, depend solely on the coral and seagrass associated fishery resources of the coast for livelihood (Edward et al., 2012). Due to the increasing demand,

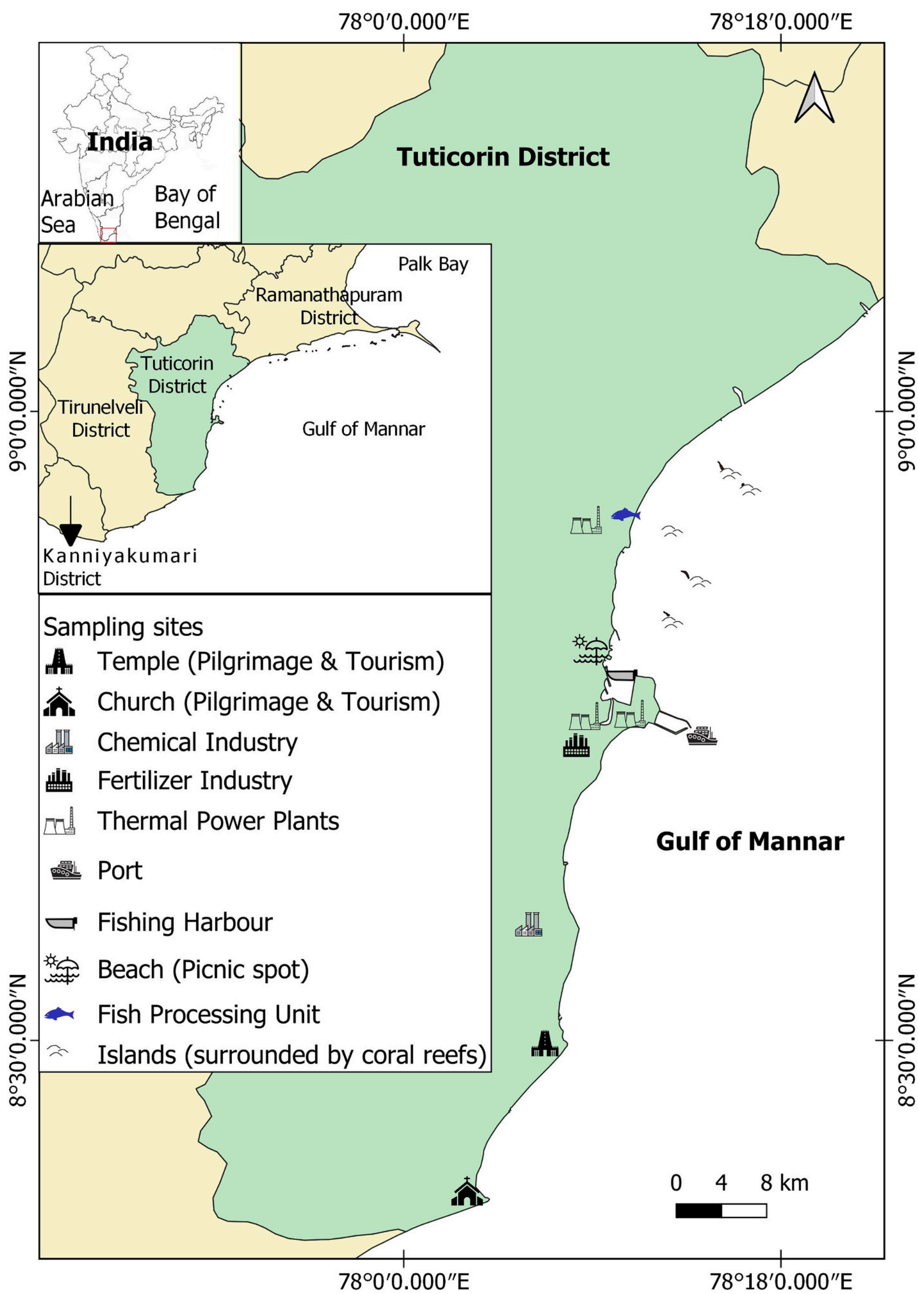

Fig. 1. Map of Gulf of Mannar focusing on the 164 km long coast of Thoothukudi district.

livelihood-linked destructive fishing activities such as trap fishing, shore seine, purse seine and bottom trawling are common in GoM (Patterson et al., 2016; Raj et al., 2017).

We have pre-lockdown data on water and sediment quality, plastic pollution and underwater fish assemblages collected without anticipating lockdown. After 60 days of lockdown, we collected post-lockdown data from the same sites. On analyzing and comparing the two sets of data the present work studied the changes in the health status of the coastal ecosystems in the absence of anthropogenic impacts.

2. Materials and methods

2.1. Study area

The study was conducted in Gulf of Mannar (GoM) focusing on the coast of Thoothukudi district, which is located between latitude 9° 5′37.63″N to 8°20′11.65″N and longitude 78°23′10.20″E to 77°58′37.31″E in the southeast of India. Endowed as it is with a wealth of biota including the once famous pearl oysters, chanks, coral reefs, seagrasses, and mangroves apart from the perennial Punnakayal estuary, the 164-km long Thoothukudi coast is important not only to GoM but also to the entire state of Tamil Nadu as the district is commercially preeminent and important with a major port, fishing harbour, thermal power plants, fertilizer and chemical industries, heavy water and desalinization plants, many seafood processing units and salt pans. The city of Tuticorin has a population of 237,830 as per 2011 census. With dense habitation the city produces around 18 MLD of domestic sewage, which, untreated, continuously flows into the sea (Meiaraj and Jeyapriya, 2019), aggravating the condition of the already stressed marine environment. Further, the coast has very important pilgrimage/tourist destinations (Tiruchendur and Manapad), local recreational beaches (Harbour and Muthu Nagar) and fish-landing sites (Fig. 1).

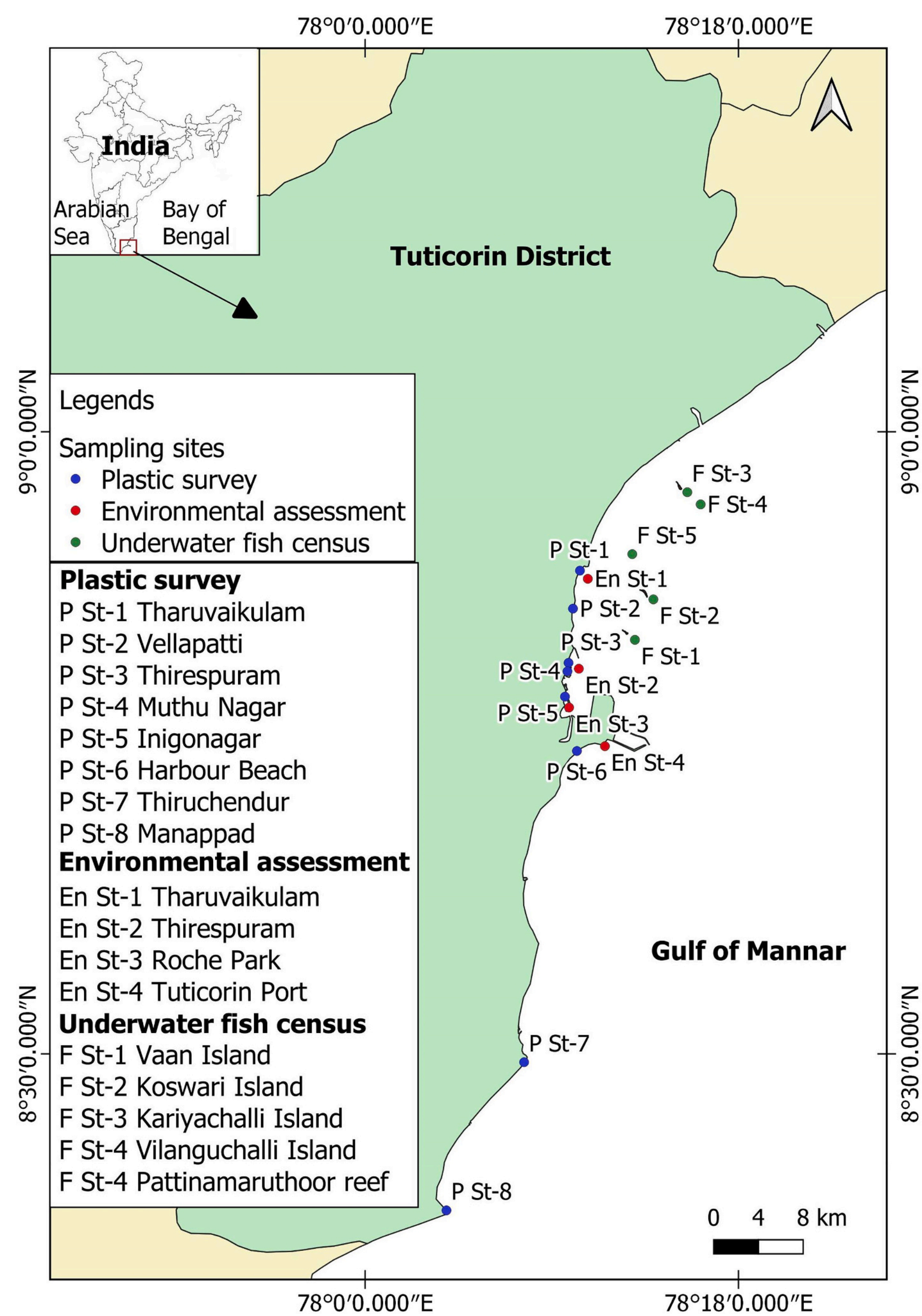

Fig. 2. Map showing the study sites.

Tuticorin is traditionally a fishing hotspot with a great multitude of fishermen engaged in different modes of fishing. Hundreds of fishing boats including trawlers and country boats are operated every day in Tuticorin town. Tuticorin is adjudged one of the most polluted urban centres of India (The Hindu, 2015). The coastal waters bear the brunt of the ill effects of pollution by receiving untreated or partially treated sewage and industrial effluents. We had collected data on the physical, chemical and biological parameters of sediment and water samples at the selected locations during February–March 2019. During the same period, data were also collected on the macro, meso and micro plastics at 8 sites (Jeyasanta et al., 2020). Further, underwater visual census of fish was done during January–February 2020 at five locations as part of regular monitoring. To identify the environmental changes specifically due to the lockdown, the second data collection was done in the same locations using the same protocols during May–June 2020.

2.2. Study sites

Quality analysis of water and sediment was performed in four sites namely Thirespuram, Roche Park, Tuticorin Port and Tharuvaikulam. Plastic debris survey was carried out at eight locations namely Tharuvaikulam, Vellapatti, Thirespuram, Muthu Nagar Beach, Inigonagar, Harbour Beach, Thiruchendur and Manappad. Underwater visual assessment of fish was done in the reef areas of Vaan, Koswari, Kariyachalli and Vilanguchalli islands and Pattinamaruthoor patch reef. The locations of the sampling sites and description of the study area are shown in Fig. 2 and Table 1.

2.3. Water and sediment quality analysis

Three samples of water and sediment were collected from each site. Samples of surface water were collected at a distance of 500 m from the shore in all four study sites, using a Niskin water sampler. The following parameters were measured in the field (the instruments used shown in parenthesis): pH (pH meter), salinity (Refractometer), conductivity (Hanna HI 8033) and turbidity (ELICO PE 138). Gravimetric method was used to measure total suspended solids (TSS) and total dissolved solids (TDS) (Rodger et al., 2017). Dissolved oxygen level in the water samples was estimated by Winkler's method (Strickland and Parsons, 1972). Dilution method was followed to determine the BOD. For all the analyses we followed the protocols of American Public Health Association (APHA, 1995). Spectrophotometry (Agilent Cary UV) was used for the analysis of nutrients such as nitrates, nitrites, phosphates, silicates and ammonia following Strickland and Parsons (1972). Nitrites in the samples were allowed to react with sulphanilamide in phosphoric acid solution. The resulting diazo compound was treated with N-(1-napthyl)-ethylene diamine dihydrochloride to form a diazo compound dye, which was measured at 543 nm. Nitrates in the samples were reduced to nitrites by being run through a column containing copper coupled cadmium filings, with ammonium chloride used as a buffer to maintain a stable pH. The nitrites thus produced were measured at 543 nm. The estimation of phosphates was done by treating the samples with ammonium molybdate, potassium antimonyl tartrate and ascorbic acid solution and the measurement was done at 883 nm. For the analysis of silicates, 25 ml of water samples were treated with ammonium molybdate to form molybdo-silicic acid. This was followed by reduction with metol and oxalic acid to form a blue dye, which was measured at 810 nm. Indo-phenol method was used for the determination of ammonia in water samples. Oil and grease in water samples were analyzed following SANS (2007). Sediment samples were collected using a van Veen grab. The upper 5-cm layer of sediment was sampled at each site. Three such sediment samples were collected, and stored at −20 °C for analysis. The content of organic matter in the sediment samples was determined by titration method (Walkley and Black, 1934), total nitrogen with Kjeldahl's method (Bartlett et al., 1994) and total phosphorus following Ruban et al. (1999).

Table 1
Details of study sites.

Name of the site	Latitude & longitude	Description of the study area and type of access
Sites selected for water and sediment quality analysis		
1.Thirespuram	8°48′51.60″N, 78° 9′48.64″E	Closer to sewage outlet where untreated domestic wastewater and solid wastes are dumped into the sea. Fishing activities are also intensive.
2. Roche Park	8°46′51.32″N, 78° 9′50.43″E	Closer to Tuticorin Fishing Harbor and Tuticorin Thermal Power Station (TTPS), with fishing activities.
3. Tuticorin Port	8°44′54.40″N 78°11′28.97″E	Closer to the major port where shipping traffic is heavy.
4. Tharuvaikulam	8°53′18.51″N, 78°10′21.70″E	13 km from Tuticorin town with fishing activities
Sites selected for plastic debris survey		
1. Tharuvaikulam	8°53′18.51″N, 78°10′21.70″E	13 km from Tuticorin town with fishing activities
2. Vellapatti	8°51′28.52″N, 78°10′1.62″E	10 km from Tuticorin town with fishing activities
3. Thirespuram	8°48′51.60″N, 78° 9′48.64″E	Closer to sewage outlet where untreated domestic wastewater and solid wastes are dumped into the sea. Fishing activities are also intensive.
4. MuthuNagar Beach	8°48′27.03″N, 78° 9′45.63″E	Recreational beach
5. Inigonagar	8°47′22.13″N, 78° 9′40.53″E	Closer to Tuticorin Fishing Harbor and Tuticorin Thermal Power Station (TTPS), with fishing activities
6. Harbour beach	8°44′36.49″N, 78°10′13.02″E	Recreational beach
7. Thiruchendur	8°29′35.76″N, 78° 7′40.16″E	Activities related to pilgrimage and tourism
8. Manappad	8°22′27.89″N, 78° 3′55.50″E	Activities related to pilgrimage, tourism and fishing
Sites selected for underwater fish visual census		
1. Vaan Island	8°50′17.61″N, 78°12′36.38″E	4 km from the mainland
2. Koswari Island	8°52′15.35″N, 78°13′29.66″E	6 km from the mainland
3. Kariyachalli Island	8°57′19.76″N, 78°15′10.22″E	3 km from the mainland
4. Vilanguchalli Island	8°56′30.16″N, 78°16′10.99″E	6 km from the mainland
5. Pattinamaruthoor reef	8°54′6.06″N, 78°12′52.95″E	4 km from the mainland

To assess the concentration level of metals in the environment, three samples each of water (20 ml) and sediment (1 g) were collected from each sampling site. Nitric acid (5 ml) and hydrochloric acid (15 ml) were used for the mineralization of the samples (Chester, 1969) and the samples were kept at room temperature for 24 h. The samples were then heated in a sand bath on a hot plate at 50 °C for 5 h and then were refluxed at 130 °C for 3 h. The samples were then filtered, washed with double-distilled water, and placed in 50 ml volumetric flasks. The digested samples were then analyzed for metals such as lead (Pb), nickel (Ni), chromium (Cr), zinc (Zn), iron (Fe), copper (Cu) and cadmium (Cd) with an Atomic Absorption spectrophotometer (AAS), Agilent 200 series AA. National Institute of Standards and Technology (NIST) standard (1640a) was used as reference for quality assurance and quality control (QA/QC). Phytoplankton samples were collected from the surface water by towing a plankton net number 30 of mesh size 60 μm (Sukhanova, 1978), for half an hour and the density was measured using a Sedwick Rafter counting chamber. The content of chlorophyll-a was determined spectrophotometrically following Parsons et al. (1984).

For the bacteriological analysis of water and sediment samples, sterile screw cap tubes were employed and the analysis was done within 6 h. The population of microorganisms was assessed by the pour plate method as described by Aneja (2003). Total heterotrophic bacteria

(THB) were measured using Zobell marine agar, and the plates were incubated at 35 ± 2 °C for 24 h. Total coliform bacteria (TC) were determined on MacConkey agar, and the plates were incubated at 35 ± 2 °C for 24 h. Faecal coliform bacteria (FC) and *Escherichia coli* (EC) were counted on M-FC medium plates incubated at 44 ± 2 °C for 24 h. Faecal Streptococcus (FS) were enumerated on KF Streptococcus agar medium, and the plates were incubated at 44 ± 2 °C for 24 h.

2.4. Plastic debris survey

Plastic debris collected from the sampling sites was categorized according to size as microplastics (≤5 mm), mesoplastics (between 5 mm to 2.5 cm) and macroplastics (>2.5 cm). For the survey of macroplastics, 100 m transect lines were laid along the beach with 5 m on each side of the transect (100 × 10 m) following Lippiatt et al. (2013). Five transects were laid in each study site parallel to the high tide line and all the available macroplastics within the transects were collected. Collected macroplastics were assorted, weighed and the concentration of macroplastic items (number of items/m^2) was calculated. Evaluation of coastal cleanliness was done with clean coast Index (CCI) (Alkalay et al., 2007). Pre-lockdown data for plastic debris survey had already been published (Jeyasanta et al., 2020) and hence the results of post-lockdown survey were compared with the published data in this study.

For quantifying micro and mesoplastics, sediment samples were collected along the high tide line in all study sites (8 locations). Three 1 m^2 quadrats were laid and approximately 1 kg of sediment was collected from the top 3 cm in each quadrat from each site. First, the samples were sieved for initial separation of mesoplastics. Then a density separation was performed using NaCl solution ($\rho = 1.2$ g/cm^{-3}). In this method the heavier sediment grains and the lighter plastic particles are separated by virtue of the weight gradient (Gündoğdu and Çevik, 2017). The weight of the mesoparticles was found with a Shimaduzu AUW220D analytical balance and the values were converted to mean weight as g/m^2. The concentration of mesoplastics (no. of debris items/m^2) was calculated as: C = n/a ('n' being no. of debris items observed, and 'a' the area sampled.

For the measurement of microplastics, samples were collected within three microquadrats (25 × 25 × 3 cm) at each site (Klein et al., 2015). Approximately 1 kg of sediment samples were collected within 3 cm from the top. In the laboratory 200 g of each sediment sample was treated with 30 ml of 10% hydrogen peroxide for 72 h at room temperature to remove natural organic materials present in them. Microplastic particles were extracted via density separation using supersaturated sodium iodide solution (1.6 g/l^{-1} density at 3.3 M). The upper parts of the solution were filtered using 0.8 μm cellulose nitrate filter papers and the papers were dried at room temperature and observed under a dissecting microscope at 40× magnification.

2.5. Underwater fish visual census

The belt transect method (English et al., 1997) was employed for the underwater visual census of reef fishes involving scuba diving. At five sites namely Vaan, Koswari, Kariyachalli, Vilanguchalli islands and Pattinamaruthoor patch reef, three transects (50 × 5 m) were laid randomly at depths between 1 and 3 m. Fishes were counted visually. Each census area covered 250 m^2 extending 2.5 m at each side of 50 m transect lines. A diver holding PVC rods of 2.5 m swam slowly along the transect line within 2.5 m corridor on either side, counting the individual fishes for the duration of 30–40 min. The fishes observed were counted and identified by using standard underwater fish ID cards (Myers, 1991; Khalaf and Disi, 1997). Parrot fishes play an essential role in maintaining ecological balance in a reef area by grazing on macroalgae which compete with corals for space. Though the reef areas are protected under Marine National Park, these fishes are exploited heavily through targeted trap fishing in GoM. Hence, the data on the densities of parrot fishes were analyzed exclusively to identify the positive or negative change due to the imposed lockdown.

2.6. Statistical analyses

The simple *t*-test was used to determine the deviation of values between pre- and post-lockdown sampling. The *t*-tests were computed using statistical package SPSS Ver.16.0. Multivariate analysis was performed to estimate the analysis of similarity (ANOSIM) in fish abundance between pre-lockdown and post lockdown periods. Fish data were fourth root/log (x + 1) transformed to down-weigh extremely abundant species. The PERMANOVA analysis was applied and Bray-Curtis similarity matrix was calculated for fish abundance after the fourth root transforming the raw data to calculate deviations. SIMPER analysis was performed to analyze the differences in fish assemblages using primer 6.0.

3. Results

Results of physical and chemical parameters of water samples are presented in Table 2. Almost all the analyzed parameters showed deviation between the two (pre- and post-lockdown) scenarios. Among the water quality parameters, salinity did not deviate much between the pre- and post-lockdown periods while pH level increased slightly. Electrical conductivity, TDS, Turbidity and TSS were found to have reduced significantly due to the imposed lockdown. While dissolved oxygen level increased significantly from 3.87 ± 1.56 to 5.73 ± 3.24 mg/l, BOD level decreased. The *t*-test analysis showed significant ($p > 0.05$) deviations for salinity, turbidity, TSS, TDS, and DO between the two data sets, while deviation in the values of pH, EC and BOD were not statistically significant ($p < 0.05$). Nutrient levels in water decreased during the lockdown. The concentrations of nitrates, nitrites, phosphates, silicates and ammonia fell significantly. For example, nitrate value decreased from 8.32 ± 2.10 to 2.66 ± 0.36 and nitrite level from 4.34 ± 1.23 to 1.58 ± 0.41 μm/l. Oil and grease content in water also decreased with the mean value going down from 12.46 ± 4.55 to 6.28 ± 0.69 mg/l.

The values of sediment quality parameters are presented in Table 3. Organic matter in the sediment samples did not deviate much between the two scenarios, while total nitrogen and total phosphorus decreased slightly. All the analyzed heavy metals in the water and sediment samples were found to have decreased during lockdown period. Nutrient values for water and sediment samples did not show statistically significant deviation ($p > 0.05$) between the two sampling periods. Heavy metal concentration in water and sediment samples showed only insignificant variations ($p > 0.05$) between the two samplings, except for copper level in sediment samples ($p < 0.05$).

The assessed values of the biological and microbial parameters are presented in Table 4. Phytoplankton density and chlorophyll-a content increased from pre-lockdown to post-lockdown period. Phytoplankton density showed statistically significant variation ($p < 0.05$), while chlorophyll content did not vary significantly ($p < 0.05$). The mean value recorded for phytoplankton was 31,766.3 ± 236.5 cells/l in 2019 and it increased to 70,781.3 ± 145.2cells/l in 2020. Likewise, chlorophyll-a was 0.7 ± 0.01 mg/m^{-3} in pre-lockdown samples and it increased to 1.8 ± 0.55 mg/m^{-3} after the lockdown. All the microbial parameters were comparatively lower in the post-lockdown samples. In water samples, mean THB count decreased to 6.6×10^3 from 7.1 x 10^4CFU/ml. Similarly, total coliform count fell from 4.8×10^3 to 2.6×10^2 CFU/ml, faecal coliform from 6.1×10^2 to 3.3×10^2 CFU/ml, faecal streptococci from 5×10^2 to 4.3×10^1 CFU/ml and *E. coli* (EC) from 9.45×10^1 to 0.9×10^1 CFU/ml. Likewise, in the sediment samples, THB, total coliform, faecal coliform and *E. coli* and faecal streptococci were found to be lower in the post-lockdown period.

The results of paired *t*-test showed significant deviation between the pre- and post-lockdown surveys in terms of the amount of macro, meso and microplastics ($p < 0.05$). The concentration of macroplastics during

Table 2
Physico-chemical parameters of water samples in the study sites before and after lockdown.
(PrLD = pre-lockdown; PoLD = postlockdown.)

	Thirespuram		Roche Park		Tuticorin Port		Tharuvaikulam	
	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD
Physical parameters								
pH	8.1 ± 1.50	8.32 ± 1.26	7.9 ± 1.17	8.12 ± 1.82	8 ± 1.22	8.26 ± 1.86	7.89 ± 1.74	8.09 ± 1.45
Salinity (ppt)	35 ± 12.14	36 ± 9.85	35 ± 17.52	35.5 ± 19.68	35 ± 14.25	36 ± 9.56	33.5 ± 9.58	35 ± 15.36
EC (mS/cm)	88.4 ± 32.1	59.2 ± 21.45	64.5 ± 35.69	44.2 ± 11.25	71.3 ± 23.54	42.8 ± 11.25	57.32 ± 14.14	39.3 ± 10.11
Turbitity (NTU)	42.3 ± 11.25	12.5 ± 6.58	15.2 ± 7.25	8.7 ± 1.58	37 ± 28.47	10.1 ± 2.36	13.5 ± 7.41	4.5 ± 1.11
TSS (mg/l)	290 ± 102.5	158 ± 65.2	215 ± 5.24	127 ± 54.2	187 ± 95.54	119 ± 53.25	122 ± 36.41	99 ± 32.2
TDS (g/l)	47.69 ± 16.47	35.23 ± 10.2	29.68 ± 6.58	17.32 ± 5.24	27.56 ± 9.87	20.12 ± 6.58	19.68 ± 6.12	15.33 ± 5.23
Chemical parameters								
Nitrate (μmol/l)	11.97 ± 3.25	4.08 ± 1.05	6.25 ± 2.14	2.04 ± 0.89	9.17 ± 3.65	2.97 ± 0.58	5.88 ± 1.78	1.55 ± 0.56
Nitrite (μmol/l)	5.33 ± 1.45	2.93 ± 1.13	3.86 ± 1.08	0.87 ± 0.36	6.21 ± 3.22	2.04 ± 0.78	1.96 ± 0.69	0.48 ± 0.12
Phosphate (μmol/l)	8.03 ± 2.69	2.39 ± 0.56	3.48 ± 2.11	1.16 ± 0.45	4.57 ± 1.56	1.68 ± 0.78	2.36 ± 0.99	0.92 ± 0.03
Silicate (μmol/l)	42.91 ± 13.58	25.91 ± 8.55	35.29 ± 12.4	14.14 ± 6.25	54.66 ± 16.58	29.22 ± 9.75	27.84 ± 9.63	17.93 ± 3.25
Ammonia (μmol/l)	6.09 ± 1.47	4.37 ± 1.22	3.17 ± 1.14	2.35 ± 0.65	3.89 ± 1.47	2.82 ± 0.36	1.22 ± 0.58	0.97 ± 0.08
Oil & grease (mg/l)	9.93 ± 2.11	4.22 ± 1.54	22.4 ± 4.56	10.8 ± 4.23	11.9 ± 3.45	7.35 ± 1.45	5.6 ± 1.15	2.75 ± 0.89
Heavy metals								
Lead (μg/l)	19.56 ± 5.23	8.33 ± 2.56	22.64 ± 5.68	15.41 ± 4.36	15.78 ± 6.58	7.27 ± 2.58	12.37 ± 3.12	7.18 ± 1.58
Nickel (μg/l)	6.5 ± 2.11	2 ± 0.36	4.6 ± 1.25	1 ± 0.23	2.6 ± 0.87	0.85 ± 0.15	1.80 ± 0.66	0.73 ± 0.06
Iron (μg/l)	392 ± 96.85	51.69 ± 23.65	361.86 ± 101.2	33.45 ± 11.36	65.11 ± 11.56	12.36 ± 4.22	96.76 ± 29.45	10.36 ± 3.25
Chromium (μg/l)	23.87 ± 6.33	10.15 ± 4.55	12.23 ± 6.54	3.23 ± 1.02	4.14 ± 1.25	1.35 ± 0.33	1.78 ± 0.88	1.21 ± 0.87
Cadmium (μg/l)	1.28 ± 0.56	1.05 ± 0.69	1.5 ± 0.67	1.16 ± 0.62	1.22 ± 0.36	0.93 ± 0.11	0.93 ± 0.05	0.75 ± 0.06
Zinc (μg/l)	5.22 ± 2.15	3.15 ± 1.11	3.86 ± 1.06	3.1 ± 0.96	4.19 ± 1.06	3.79 ± 1.13	3.12 ± 1.19	2.45 ± 1.24

Table 3
Physico-chemical parameters of sediment samples in the study sites before and after lockdown.
(PrLD = pre-lockdown; PoLD = postlockdown.)

	Thirespuram		Roche Park		Tuticorin Port		Tharuvaikulam	
	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD
Physical parameters								
Organic matter (g/kg)	49.07 ± 14.02	48.35 ± 20.12	34.02 ± 1.36	33.26 ± 11.23	40.11 ± 16.58	41.37 ± 12	26.15 ± 11.63	26.04 ± 10.23
Total nitrogen (g/kg)	0.38 ± 0.02	0.36 ± 0.03	0.27 ± 0.08	0.25 ± 0.08	0.33 ± 0.14	0.32 ± 0.09	0.21 ± 0.04	0.2 ± 0.02
Total phosphorus (g/kg)	0.55 ± 0.07	0.51 ± 0.01	0.33 ± 0.05	0.32 ± 0.09	0.37 ± 0.17	0.34 ± 0.07	0.19 ± 0.02	0.17 ± 0.04
Heavy metals								
Lead (μg/g)	18.93 ± 4.12	12.45 ± 4.65	26.22 ± 9.87	21.15 ± 7.77	13.79 ± 5.55	9.77 ± 1.69	12.39 ± 4.58	9.03 ± 2.36
Nickel (μg/g)	14.3 ± 6.22	10.3 ± 3.69	9.5 ± 2.56	6.2 ± 3.15	7.3 ± 2.56	6.9 ± 2.22	3.5 ± 1.16	2.89 ± 0.56
Iron (μg/g)	951.92 ± 241.5	750.24 ± 148.5	749.56 ± 235.1	600.31 ± 259.6	455.54 ± 109.58	385.46 ± 102.56	200.62 ± 97.25	256.27 ± 66.59
Chromium (μg/g)	69.31 ± 19.58	45.25 ± 17.56	37.57 ± 11.25	28.23 ± 10.5	18.67 ± 5.66	0.15 ± 0.06	16.02 ± 8.52	12.59 ± 3.69
Cadmium (μg/g)	2.81 ± 1.08	2.55 ± 0.89	2.03 ± 0.47	1.87 ± 0.56	1.95 ± 0.69	1.61 ± 0.23	1.15 ± 0.56	1.08 ± 0.23
Zinc (μg/g)	73.45 ± 45.25	68.74 ± 26.58	64.4 ± 28.74	54.28 ± 18.56	70.21 ± 31.45	65.32 ± 29.85	52.05 ± 18.56	44.18 ± 16.25

pre-lockdown ranged between 138 ± 4.12 and 616 ± 12.48 items/100 m^2 and the concentration was found reduced at the end of the lockdown with a range of 63 ± 3.92 to 347 ± 8.06 items/100 m^2 (Fig. 3). The weight of macroplastic litter was also found to have decreased in the post-lockdown period (Fig. 4). The encountered macroplastics were placed under 16 categories (Table S1) and all the categories were found reduced in quantity after the lockdown. Generally, plastic spoons, cups and ropes were the predominant categories during the study period. During 2019, all the study sites were dirty with a high value of CCI (>20) and the value of this index was observed to be reduced after the lockdown. CCI was the highest for Thirespuram during both the study periods (Fig. 5). The concentration of mesoplastics ranged between 2 ± 0.58 and 17 ± 4.69 items/m^2 before the lockdown in 2019, and the range was from 1 ± 0.0.2 to 15 ± 4.05 items/m^2 after the lockdown (Fig. 6). The weight of the mesoplastic litter ranged between 1 ± 0.03 and 2.8 ± 0.87 kg/100 m^2 in 2019 and the range was from 0.41 ± 0.12 to 2.37 ± 0.99 kg/100 m^2 after the lockdown (Fig. 7). Types of mesoplastics observed were hard plastics, foam plastics, films and fibers (Table S2). In contrast to the trend in macro- and mseoplastics, the concentration of microplastics was found to have increased comparatively after the lockdown. The concentration of microplastics ranged between 25 ± 9.58 and 83 ± 20.5 items/m^2 in 2019, and the range was from 37 ± 6.58 and 101 ± 41.25 items/m^2 in 2020 (Fig. 8).

Density and diversity of fish registered an increase from pre- to post-lockdown period in the study sites. The result of ANOSIM showed that the fish community structure changed significantly between the two periods ($R = 0.901$, $p < 0.01$). SIMPER test indicated that fish species diversity did not fluctuate much, but the density fluctuated due to the increased abundance of certain species such as *Lutjanus fulviflamma*, *L. fulvus* and *Scarus ghobban*. An increase of 31% in fish density was observed in Vaan Island whereas the increase was 11, 18, 29 and 20% respectively for Koswari, Kariyachalli and Vilanguchalli islands and Pattinamaruthoor patch reef (Fig. 9). Overall species diversity in the study sites was 151 in January–February 2020 and 155 in May–June 2020. Similarly, overall fish density in the study sites increased from 405.6 no. 250 m^{-2} to 510.2 no. 250 m^{-2}. The most common fish species during the study period were *Chaetodon octofasciatus*, *Scarus ghobban*, *Abudefduf saxatilis* and *Lutjanus fulviflamma* (Table S3). A total of three parrot fish species belonging to the family Scaridae were observed during pre- and post-lockdown surveys, which are *Scarus ghobban*, *Chlorurus gibbus* and *Leptoscarus vaigiensis*. Total density of parrot fishes before the lockdown was 56 no. 250 m^{-2} and it increased to 88 no. 250 m^{-2} after the lockdown, an increase of 36%. The increase in parrot fish density in Vaan, Koswari, Kariyachalli and Vilanguchalli islands and

Table 4
Biological parameters of water and sediment samples before and after lockdown.

	Thirespuram		Roche Park		Tuticorin Port		Tharuvaikulam	
	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD	PrLD	PoLD
Water								
THB (CFU/ml)	9.5×10^4	8.7×10^3	7.8×10^4	7.2×10^3	6.0×10^4	5.8×10^3	5.2×10^4	5.0×10^3
Total coliform (CFU/ml)	7.7×10^3	3.4×10^2	5.9×10^3	3.1×10^2	3.6×10^3	2.2×10^2	2.2×10^3	2.0×10^2
Faecal coliform (CFU/ml)	8.6×10^2	6.4×10^2	8.1×10^2	3.9×10^2	5.2×10^2	2.7×10^2	2.5×10^2	0.2×10^2
E. coli (CFU/ml)	10.2×10^2	7.1×10^1	9.3×10^2	5.6×10^1	6.5×10^2	3.4×10^1	3.2×10^2	1.3×10^1
Faecal Streptococci (CFU/ml)	1.5×10^2	2.0×10^1	1.2×10^2	0.9×10^1	1.0×10^2	0.6×10^1	0.8×10^2	0.1×10^1
Sediment								
THB (CFU/g)	12.4×10^5	12.1×10^5	10.5×10^5	9.8×10^5	6.2×10^5	5.4×10^5	4.8×10^5	4.5×10^5
Total coliform (CFU/g)	5.6×10^4	5.5×10^4	4.4×10^4	4.1×10^4	4.0×10^4	3.7×10^4	3.8×10^4	3.5×10^4
Faecal coliform (CFU/g)	7.3×10^4	7.1×10^4	5.9×10^4	4.3×10^4	3.5×10^4	2.5×10^4	2.8×10^4	2.4×10^4
E. coli (CFU/g)	6.6×10^3	5.9×10^3	6.2×10^3	4.7×10^3	4.7×10^3	1.7×10^3	3.5×10^3	2.6×10^3
Faecal Streptococci (CFU/g)	4.5×10^3	3.9×10^3	4.1×10^3	3.8×10^3	2.9×10^3	2.5×10^3	2.3×10^3	2.0×10^3
plankton								
Phytoplankton (cells/l)	21,390 ± 210.52	63,284 ± 216.58	44,000 ± 120.5	82,900 ± 154.2	28,795 ± 102.6	62,355 ± 126.2	32,880 ± 115.3	74,586 ± 155.2
Chlorophyll (mg/m^3)	0.92 ± 0.05	1.92 ± 0.12	0.17 ± 0.07	1.53 ± 0.02	0.66 ± 0.05	1.71 ± 0.36	1.11 ± 0.69	1.98 ± 0.88

PrLD = Pre-lockdown; PoLD = Postlockdown.

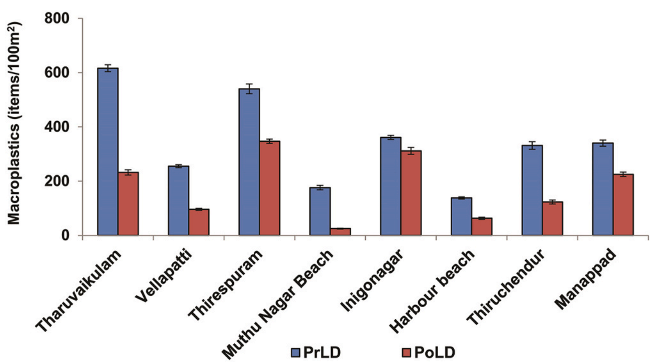

Fig. 3. Concentration of macroplastics before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

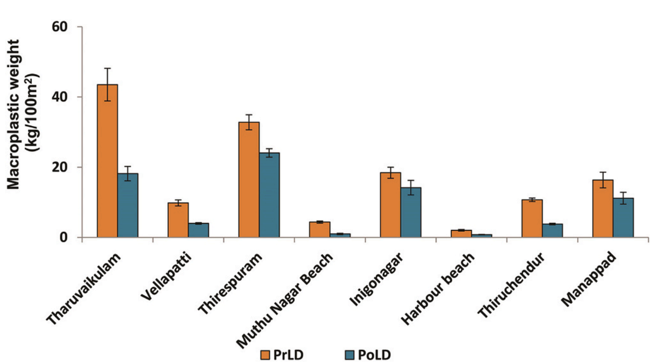

Fig. 4. Weight of macroplastics before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

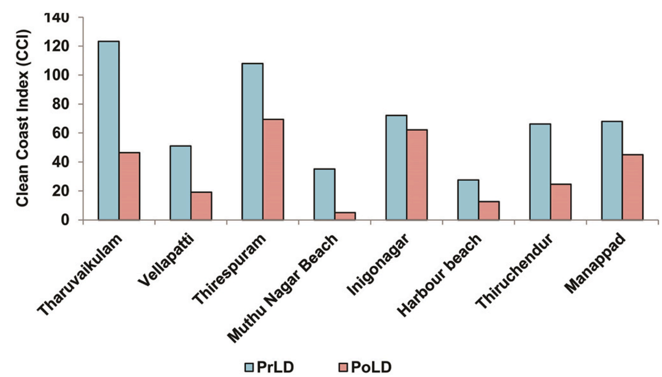

Fig. 5. Clean coast index before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

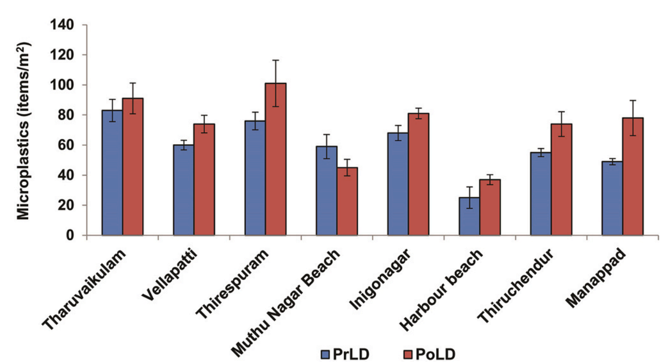

Fig. 6. Concentration of mesoplastics before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

Pattinamaruthoor patch reef was 60, 18, 27, 64 and 28% respectively (Fig. 10).

4. Discussion

The scaling down of adverse man-made factors in number and intensity leads to improved environmental health. There are several reports highlighting the positive role of the lockdown implemented in the wake of COVID-19 helping the environment, habitats and associated biodiversity in many countries (Henriques, 2020; Stone, 2020; Mani, 2020). The most important gain is in the improvement of air quality (Shi and Brasseur, 2020; Bauwens et al., 2020). Remarkable improvement in the water quality has also been reported (Link, 2020; Selvam et al., 2020; Yunus et al., 2020; Sangita et al., 2020). Healthier water has led to healthier aquatic ecosystems (Mandal, 2020; Ankita et al., 2020). The results of the present study clearly demonstrate that the lockdown due to

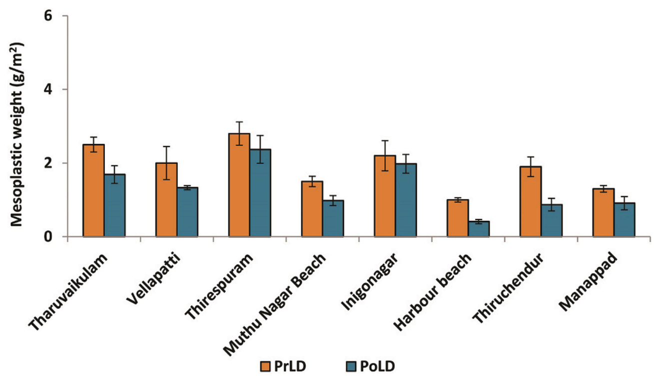

Fig. 7. Weight of mesoplastics before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

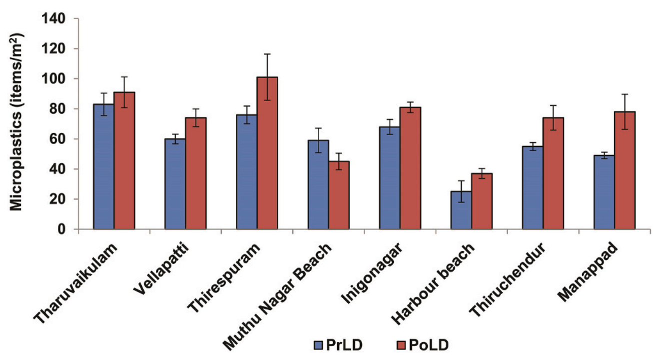

Fig. 8. Concentration of microplastics before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

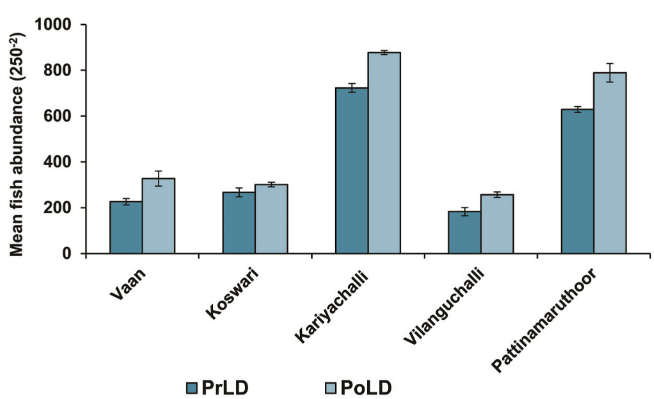

Fig. 9. Average fish density before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

COVID-19 had brought about an overall improvement in many parameters governing the health of the marine ecosystems in GoM.

The hydro-biological parameters of the environment in general are governed by factors like pH, temperature, nutrient level, tidal actions, monsoonal flow etc. and these factors can alter the productivity of an area. The present work studied some of these parameters and found the positive changes in them caused by the imposed lockdown. In the context of acidifying oceans, pH levels in the study increased during post-lockdown and this might be due to the increased impact of photosynthesis on account of the denser phytoplankton population (Das et al., 1997). At the end of the lockdown the values of EC and TDS declined considerably, which is obviously due to the shutdown of industries that release dissolved inorganic substances in ionized form

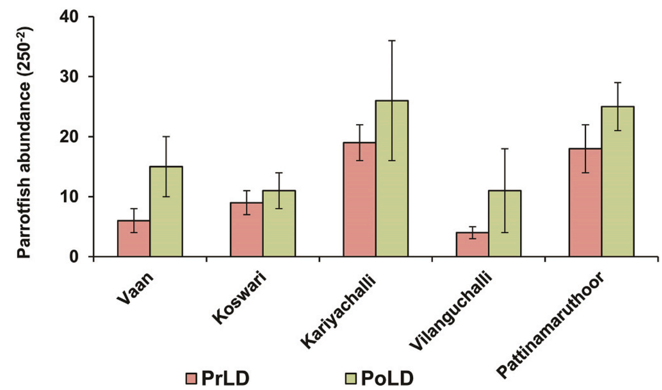

Fig. 10. Average density of parrotfishes before and after lockdown (PrLD = Pre-lockdown; PoLD = Postlockdown).

(Mishra and Saksena, 1993). Reduced human activities caused reduction in the levels of TSS and turbidity, which are pollution indicators in an aquatic ecosystem (Luis et al., 2019). There is a general decline in the dissolved oxygen levels in all the oceans of the world affecting coastal ecosystems (Laffoley and Baxter, 2019). Ambient oxygen concentrations are classified as sufficient (>6.0 mg/l), deficient (<6.0 mg/l), hypoxic (<2.0 mg/l), and anoxic (<0.5 mg/l) (Okbah et al., 2013). Being an industrial hotspot, Tuticorin region has been deficient in DO levels (Rajendran et al., 2018) as higher TSS, TDS and turbidity tend to reduce the amount of dissolved oxygen in water. Reduced industrial activities and reduced oil discharge due to restricted fishing activities have helped to enhance the DO and reduce the BOD levels in Tuticorin coastal region. Short-term decline in DO levels have been reported to be detrimental to benthic organisms in GoM (Raj et al., 2020), and in the same way short-term improvement of DO levels due to the imposed lockdown has helped the marine organisms.

The seawater, the sediment of the seabed and the marine organisms are all contaminated by many anthropogenic activities like industrial discharge, untreated and partially treated sewage disposal, land runoff, fertilizer disposal and oil spill. The last few decades have witnessed increased inflow of nutrient into coastal waters leading to quick and vast changes to coastal ecosystems worldwide (Boesch, 2002). The combination of more nutrient and warmer waters act to reduce the oxygen levels in the oceans (Breitburg et al., 2018). In the present study, nutrients such as nitrates, nitrites, phosphates, silicates and ammonia have decreased due to the reduced human interference during the lockdown. Shutdown of industries has cut down the supply of nutrients on the one hand. On the other, more utilization of nutrients by the greater population of phytoplankton has also lowered nutrient levels (Satpathy et al., 2010). Oil spillage is an important contributor to marine pollution (Ankita et al., 2020) and the diminished industrial and fishing activities due to lockdown have brought down the oil and grease levels in the study area.

Water is a primary factor in the transfer of pollutants to higher trophic level, but pollutants settling down on the sediments are taken by the benthic organisms. The contaminants in the seawater may either stay in the water column in dissolved form or settle down to the sediment (Diez et al., 2005) and so sediment acts as the ultimate sink of all pollutants discharged into the marine environment (Bettinetti et al., 2003). Some of the chemical parameters like total organic matter, total phosphorus and total nitrogen determine the property of marine sediment to an important degree, and so they can be used as pollution indices to understand soil quality and productivity (Avramidis et al., 2015). These parameters have always been higher in Tuticorin region due to the continuous supply of pollutants (Singaraja et al., 2014). However, the present study did not record notable changes in the levels of these sediment parameters during lockdown period and this could be due to the time taken for sediments for self-purification (Vignesh et al., 2013).

More than 95% of the primary production in the oceanic waters is contributed by phytoplankton alone. Nutrient level and physical properties of seawater like temperature, salinity, light, and turbidity are limiting factors that determine the density of phytoplankton (Tiwari and Nair, 1998). By virtue of their short lifespan and rapid reproduction rate they can function as indicator of water quality (Pradhan et al., 2008). In the present study a pronounced variation in phytoplankton and chlorophyll-a concentration between pre-lockdown and post-lockdown periods was noticed. The reduced concentrations of TDS, TSS and turbidity brought about by lockdown have contributed to the increased phytoplankton density as these parameters reduce the light intensity, which leads to decrease in the rate of uptake of ammonia and nitrate, which ultimately affects the growth of phytoplankton. In a region phytoplankton abundance has a direct bearing on the productivity and biodiversity (Vallina et al., 2014). Thus the enhanced phytoplankton levels during the lockdown would presumably help the associated biodiversity.

Heavy metal contamination of the environment is a serious global issue because these metals are persistent. Most of the metallic pollutants are toxic and their concentrations beyond the threshold level prove lethal to organisms (MacFarlane and Burchett, 2000). They are highly toxic to humans too (Johnson, 1998). There is a continuous flow of heavy metal pollutants into the sea of Tuticorin from the sources of industrial operations, fishing and shipping activities (Rajendran et al., 2018). Cargo handling, dredging, and oil spill also contribute to heavy metal accumulation in the coastal waters of Tuticorin (Mitra, 2019; Anand and Kala, 2015; Asha et al., 2010; Fernandez et al., 2008; Jonathan et al., 2004; Palanichamy and Rajendran, 2000). The general upward trend in heavy metal concentrations in the water and sediments of the study sites has been reversed during the lockdown period as evidenced by the results of the present work. Microorganisms are found everywhere in nature, and their abundance and diversity may indicate the health status of ecosystems (Okpokwasili and Akujobi, 1996). Significant reduction in microbial load was observed in water samples between the pre- and post-lockdown periods in Tuticorin, a clear result of the reduced human activities. An exception to this trend was Thirespuram region, where discharge of untreated domestic wastes continued even during the lockdown. The fluctuations in microbial load were very slight in the case of sediment samples.

Marine debris is ubiquitous in the marine environment not excepting even the faraway regions. Terrestrial sources release plastic pollutants into the marine systems (Sweet et al., 2019). It has time and again been demonstrated that most of the plastic waste found on the sea floor is connected to fishing or aquaculture (Edward et al., 2019; Ballesteros et al., 2018; Law, 2017; Jambeck et al., 2015). Historically, improper waste management coupled with harmful fishing practices and tourism affects the coastal health of Tuticorin district (Raj et al., 2017). The lockdown halted and in some cases placed restrictions on fishing and completely banned beach visits and pilgrimage, which has brought notable reduction in macroplastic items in the study sites. The drastic reduction in the number of 'use and throw' type of plastics along the coast is the direct result of the ban on beach visit. Reduced values of clean coast index after the lockdown explain the impact of lockdown on macroplastic debris. Only minor variations in the quantities of meso- and microplastics were observed during the lockdown period. Jayasiri et al. (2013) reported that numerically mesoplastic debris formed the major class of plastic pollutants in the recreational beaches of India. Macroplastics take long to disintegrate into meso and microplastics (Dris et al., 2016). Hence, in spite of the reduction in the amount of macroplastics during the lockdown, there was no corresponding lowering in the quantities of meso and microplastics. Microplastics are persistent and cannot be easily removed from the marine environment (Zarlf et al., 2011). Microplastics are more harmful than bigger plastic particles to marine organisms because by way of ingestion they enter the food web of the marine systems (Qiu et al., 2015). Most microplastic particles identified in this study were smaller than 1 mm, and thus available for ingestion by marine organisms.

Fishing being the most extensive and exploitative activity in the sea (Kaiser and De Groot, 2000), its escalating intensity globally has had a bearing on the species targeted and on the habitat supporting them (Raj et al., 2017). The coast of Tuticorin district itself has over 85,000 active fishermen, whose survival is based on the fish catch from the region. Control and management of fishing activities is neither proper nor systematic in many countries, and the present status of fisheries may be depicted as too many men chasing too few fish (Pauly et al., 2002). Tuticorin has a long history of being a fishing centre. The recent advancement in fishing technology and the widespread use of modern equipments and mechanized fishing vessels have completely altered the whole picture of the fishing scenario. The outcome of this is the declining fishery, which is witnessed especially since the 1980s (Venkatachalam, 2004). Underwater visual census carried out in this study in the coral reef areas before and after the lockdown clearly showed a positive trend in terms of fish diversity and density post lockdown. This increase in fish abundance can directly be correlated with the absence of fishing activities, in particular trap fishing in reef areas, and shore seine and gill net operations near the reef areas. Corals in GoM, the primary source of fishery, tend to bleach during every summer between April and June when the temperature level goes higher than 30 °C. During the season of higher water temperatures the reef fishes move out to deeper waters (Habary et al., 2017). This summer (in April and May, 2020) water temperature reached 31.9 °C in GoM, with an average coral bleaching prevalence of 28.2% (The Hindu, 2020). In spite of bleaching and the probable migration of reef fishes, fish density and diversity have improved due to the absence of fishing stress. Practice of destructive fishing methods is a perennial problem in the reef areas of GoM throughout the year. Hence, the current increase of fish diversity and density during bleaching season can easily be attributed to the absence of fishing in the reef areas. However, more monitoring is needed to verify the increasing trend in fish abundance. Increase in the density of commercially important fishes would provide reasonable catch for the fishermen after the lockdown.

Parrot fishes are indiscriminately targeted and overexploited through trap fishing in GoM (Patterson et al., 2016). These herbivorous fishes are commercially much valuable. About 300 traps are illegally deployed every day in the reef areas of the Tuticorin region of GoM (The News Minute, 2020). *Scarus ghobban* a species of parrot fish is of critical importance to maintain the health of coral reefs (Katie et al., 2017). Corals have to compete with algae for space on the reefs, and parrot fishes help corals by grazing on the encroaching macroalgae. The overexploitation of the alga-eating parrot fishes (Fig. 11) leads inevitably to the proliferation of macroalgae, which overgrow and take the space from coral. Upset of this ecological balance leads to what is called coral-algal phase shift, in which the coral-dominated system is gradually converted into an algal-dominated one (Katie et al., 2017). The coral bleaching of 2016 caused by climate change resulted in a severe coral mortality (16.2%) in GoM (Edward et al., 2018). In the aftermath of this mortality, algal cover (36.1%) exceeded the coral cover (22.7%) overturning the ecological equilibrium in the reef areas (Edward et al., 2018). The targeted removal of parrot fishes further worsened the situation in GoM. The increase of parrot fishes during COVID-19 lockdown due to the absence of fishing in the reef areas particularly trap fishing would help corals to fight their space-competitors.

5. Conclusion

The overall results of the study clearly indicate an improvement in the environmental health of coastal Tuticorin district in GoM. General qualities of water and sediments have improved because of the reduction in the supply of contaminants. Many dynamic ecosystems such as coral reefs, seagrasses and mangroves exist and thrive in the coastal waters of this region. But degradation of these systems due to several natural and

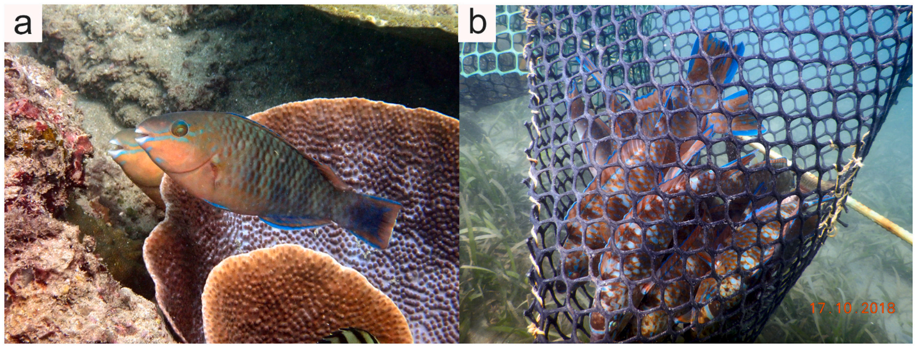

Fig. 11. Parrot fishes in the reefs of Gulf of Mannar; a. *Scarus ghobban* swimming freely; b. *S. ghobban* caught in a fish trap.

anthropogenic factors has been severe in the past few decades (Edward et al., 2018). The present significant improvement in coastal environmental health will be helpful to the biodiversity in this region, and if the positive scenario continues it will make a considerable difference in habitat recovery and fishery enhancement. In order to fully understand the implications of the lockdown on fish abundance and populations of targeted species in the GoM, repeated surveys and long-term monitoring of fish populations should be carried out. The study is also an eye opener, because based on its results we are able not only to recognize how human-induced disturbances particularly fishing practices in the reef areas turn out to be threats to the harmony of marine ecosystem, but also to understand the possibility of ecosystem recovery when anthropogenic impact is reduced. The COVID-19 lockdown reminded the conservation managers and researchers that the health of coastal ecosystems in GoM and other similar coastal regions could be restored if well-planned conservation and management initiatives are implemented for biodiversity conservation and sustainable utilization. The study has also brought home to us the need for the treatment of domestic and industrial effluents before discharge, the need for the effective implementation of the rules and regulations on fishing activities, the need for alternate livelihood options, the need for integrated marine debris management and the need for awareness building among the public. These needs are to be fulfilled to ensure the health of the coastal ecosystems, the richness of the biodiversity associated with them and the human livelihood dependent on them.

CRediT authorship contribution statement

J.K. Patterson Edward - Conceptualization, Supervision, Writing - review & editing.

M. Jayanthi - Conceptualization, review & editing.

H. Malleshappa - Conceptualization, review & editing.

K. Immaculate Jeyasanta - Formal analysis, Methodology, Writing - original draft & editing.

R.L. Laju - Field sampling, formal analysis.

Jamila Patterson - Formal analysis, Writing - draft & editing.

K. Diraviya Raj - Field sampling, writing - draft & editing.

G. Mathews - Statistics, graphs.

A.S. Marimuthu - Supervision, editing.

Gabriel Grimsditch - Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112124.

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