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COVID-19 restrictions and their influences on ambient air, surface water and plastic waste in a coastal megacity, Chennai, India

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ABSTRACT

Anthropogenic activities experienced a pause due to the nationwide lockdown, imposed to contain the rapid spread of COVID-19 in the third week of March 2020. The impacts of suspension of industrial activities, vehicular transport and other businesses for three months (25 March-30 June) on the environmental settings of Chennai, a coastal megacity was assessed. A significant reduction in the key urban air pollutants [$PM_{2.5}$ (66.5%), PM_{10} (39.5%), NO_2 (94.1%), CO (29%), O_3 (45.3%)] was recorded as an immediate consequence of the reduced anthropogenic activities. Comparison of water quality of an urban river Adyar, between pre-lockdown and lockdown, showed a substantial drop in the dissolved inorganic N (47%) and suspended particulate matter (41%) during the latter period. During the pandemic, biomedical wastes in India showed an overall surge of 17%, which were predominantly plastic. FTIR-ATR analysis confirmed the polymers such as polypropylene (25.4%) and polyester (15.4%) in the personal protective equipment.

1. Introduction

Anthropogenic impacts on the environment include changes in natural resource availability, loss of biodiversity and change in the biophysical environment. Environmental regulations to minimize these impacts are often useful for restoration and management initiatives. Cessations of the considerable volume of anthropogenic activities due to restrictions imposed during the spread of COVID-19 has provided an opportunity to estimate its immediate consequences on the environment. In India, the world's 2nd largely populated country with growing demand for energy, public life came to a sudden halt as all the states shut themselves out of work to control the rapid spread of novel coronavirus (COVID-19) in the third week of March 2020. It is reported that the emission of air contaminants (such as PM, NO_2, SO_2, CO, O_3) primarily from the energy sector (Gunasekaran et al., 2012) and rapid urbanization activities (garbage burning, industrial and vehicular exhaust, construction works) leads to an estimated 4.2 million deaths globally (World Health Organization, 2020a). A significant improvement in the ambient air quality due to restrictions imposed during the pandemic has been reported from several megacities around the globe (Mahato et al., 2020; Dantas et al., 2020; Kanniah et al., 2020; Gao et al., 2021). However, limited information is available in India, on the ambient air quality in response to a rapid decline in anthropogenic activities (Mahato et al., 2020; Ravindra et al., 2021; Garg et al., 2021; Rahaman et al., 2021; Pal et al., 2021).

Additionally, several urbanized coastal cities have reported improvement in surface water quality triggered by a drastic reduction in the inputs from industrial, agricultural and domestic sewage to the adjacent coastal and marine ecosystem (South Asia Network on Dams, 2020; Yunus et al., 2020; Somani et al., 2020). For an anthropogenically stressed river, the impacts of reduced point source inputs on water quality might become evident (Robin et al., 2013; Karthik et al., 2020) within a short period while, the impacts of the reduced nonpoint source of inputs could take much longer to measure (Hallema et al., 2020). Temporal changes in surface water quality due to COVID-19 lockdown related reduction in these point source inputs are limited in India. In contrast to ambient air and surface water quality, the generation of biomedical waste (BMW) in India has shown approximately a 17% increase during the COVID-19 pandemic, compared to its normal BMW generation (609 MT per day; Central Pollution Control Board (CPCB), 2020). As most of the plastic waste ends up in the ocean and other coastal ecosystems as microplastics, the food web will be severely

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altered due to their improper disposal and the subsequent risk posed by its ingestion by aquatic organisms (Karthik et al., 2018; Robin et al., 2020). These biomedical wastes mostly made up of single-use, non-biodegradable polymeric material (mostly PPE) (Schnurr et al., 2018; Fadare and Okoffo, 2020) poses a potential threat to marine biota. Despite the globally estimated requirements of additional 89 million masks (World Health Organization, 2020b) in each month of the pandemic, limited information is available on the composition of these single-use medical wastes and their potential contribution to microplastic pollution in India.

Chennai, a coastal megacity, is the 4th most populous urban agglomeration in India after Mumbai, Delhi and Kolkata, with a population of about 10 million distributed in an area of 1189 km^2 (CMDA, 2008). During the nationwide lockdown, a complete pause in various industrial activities (17 industrial estates and numerous small-scale industries) and cessation in air, water and surface transport in the megacity has provided an opportunity to validate the change in the ambient air and coastal water quality. Despite the availability of a few reports on the temporary improvement in urban ambient air (Mahato et al., 2020) and surface water quality (Somani et al., 2020; Yunus et al., 2020), simultaneous assessment of air and water quality and the polymer composition of single-use plastic wastes during COVID-19 lockdown in India is lacking. Efforts have been made to compare the environmental conditions before COVID-19 lockdown and lockdown conditions to determine the impact of the recess in human activity on the overall environmental quality of Chennai megacity with the following objectives: (i) assess the changes in the ambient air quality of Chennai megacity from pre-lockdown to the lockdown (ii) determine the changes in water quality associated with the reduced human activities in a highly impacted estuarine system (iii) assess the chemical composition of polymer-based PPE, extensively used during the pandemic and their potential impacts in the form of microplastics to the coastal environments and (iv) to analyse the impact of the pandemic on India's blue economy sectors.

2. COVID-19: India's response

In India, the basic reproductive number R0 (R naught) of SARS-CoV-2 is estimated to be 3.36 on March 24, and by May 16 it has dropped to 1.27 (India Today, 2020). As the reproductive value dropped, the Government of India initiated minor relaxation in the lockdown. The log scale increase in the spread of infection started in April 2020 and reached nearly one lakh positive cases on 16th May 2020. The frequency plot indicating the progression of COVID-19 among people of different age groups (COVID-19 patients $n = 7528$) in India is shown in Fig. S1a. The histogram also indicates the highest number of frequency falls between the age group $21 - 66$. Though men and women are equally likely to contract the novel coronavirus, the data across the country (COVID-19 patients ($n = 8405$) shows that more men succumbed to COVID-19 than women (Fig. S1b). National capacities and readiness in facing medical emergencies of India are in line with International Health Regulations (World Health Organization, 2016). States have strengthened their health to safeguard their economic interests from crises. As a national issue, the union government laid greater emphasis on enhanced healthcare capacities (e.g. new hospitals, manufacturing of PPE, testing kits, masks and ventilators; augmenting the supply chain of critical health-related products), community-level preparedness from all stakeholders to address the present and future health emergencies.

3. Impact of lockdown on key urban air pollutants

3.1. Site characteristics

Chennai, the capital city of the state of Tamil Nadu, is a coastal megacity located on the southeast coast of India. It is also known as a major financial and commercial hub of South India. Taking advantage of the long-term air quality monitoring facilities available at Chennai, three strategic sites (i) Alandur (with intense vehicular transport, industrial and residential hub); (ii) Velachery (exclusive residential area) and (iii) Anna University campus (relatively pristine with canopy cover) were selected to assess the changes in air quality (Fig. 1).

3.2. Real-time monitoring and HYSPLIT trajectory model

Real-time data of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and ground-level ozone (O_3) from the above three sites were compared for a period from January 2020 (pre-lockdown) to May 2020 (during lockdown). Data for Site 1 (12°59'49.61"N, 80°11'29.46"E) and Site 2 (13°00'18.79"N, 80°14'23.33"E) were obtained from the continuous ambient air quality monitoring network of the Central Pollution Control Board (CPCB) under the National Air Quality Monitoring Programme (NAMP). Data for Site 3 (13°0'48.54"N, 80°13'59.40"E) is based on the long-term observations monitored by the National Centre for Sustainable Coastal Management (NCSCM) located within the Anna University campus, using an Ambient Air Quality Monitoring System (AAQMS). All meteorological variables (atmospheric temperature (°C), relative humidity (%), wind speed (m/s) and direction) were collected from the automated weather station (AWS) located at NCSCM and were generalized for the city.

Long-distance pollutant transport along with air mass was determined using HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) backward and forward trajectory model of the Air Resources Laboratory (ARL), NOAA (https://ready.arl.noaa.gov/ HYSPLIT.php). The trend of pollutants and their concentration that are mostly anthropogenic were analysed and compared from January 2020 to May 2020, where, 1st January 2020 to 23rd March 2020 is taken as pre-lockdown phase and 24th March 2020 to 15th May 2020 is taken as a lockdown phase. Computation of 120 h backward and 24 h forward trajectory models was made for all sites at a predetermined elevation of 50, 500, and 1000 m above ground level (AGL) before and during lockdown to assess the transportation of pollutants via air mass.

3.3. Variation in meteorological conditions and air trajectory

Chennai is located at the flat coastal plain and the thermal equatorial belt experiences a tropical wet and dry climate. The hottest part of the year is during the end of May to early June and during this period, the temperature reaches its maximum up to 42 °C. The variation between the meteorological variable before and during lockdown phases signifies the differences between the two sampling sessions. Around 14 °C variations in extreme limits of atmospheric temperature were observed before and during the lockdown. The pre-lockdown phase indicates the onset of summer and further, the characteristic of atmospheric temperature and relative humidity showed a gradual increase in later time due to the peak summer conditions (Fig. S2). An increase in mean atmospheric temperature (+9.84%), relative humidity (+5.94%), and steady rise in wind speed (+17.98%) was observed from pre-lockdown to lockdown period (Table 1).

During the air mass movement over land, the air pockets may be influenced based on the surface characteristics and meteorological variables (wind speed and direction) depending on changes in temperature and humidity (Pérez et al., 2015). High surface temperature press forwards the vertical upward movement of air (Zhang et al., 2015; Cichowicz et al., 2017). These vertical movements of air mass often disperse toxic gases resulting in the reduction in the concentration of ground-level pollutants. Similarly, high humidity may result in a drop in the concentration of respirable suspended particulate matter (RSPM) due to the adhesion and deposition of particles (Hernandez et al., 2017). Air mass trajectory and pollutant source reception episodes of before and during the lockdown conditions in Chennai city has been analysed (Fig. 2). The back trajectory indicates that air mass originates both from

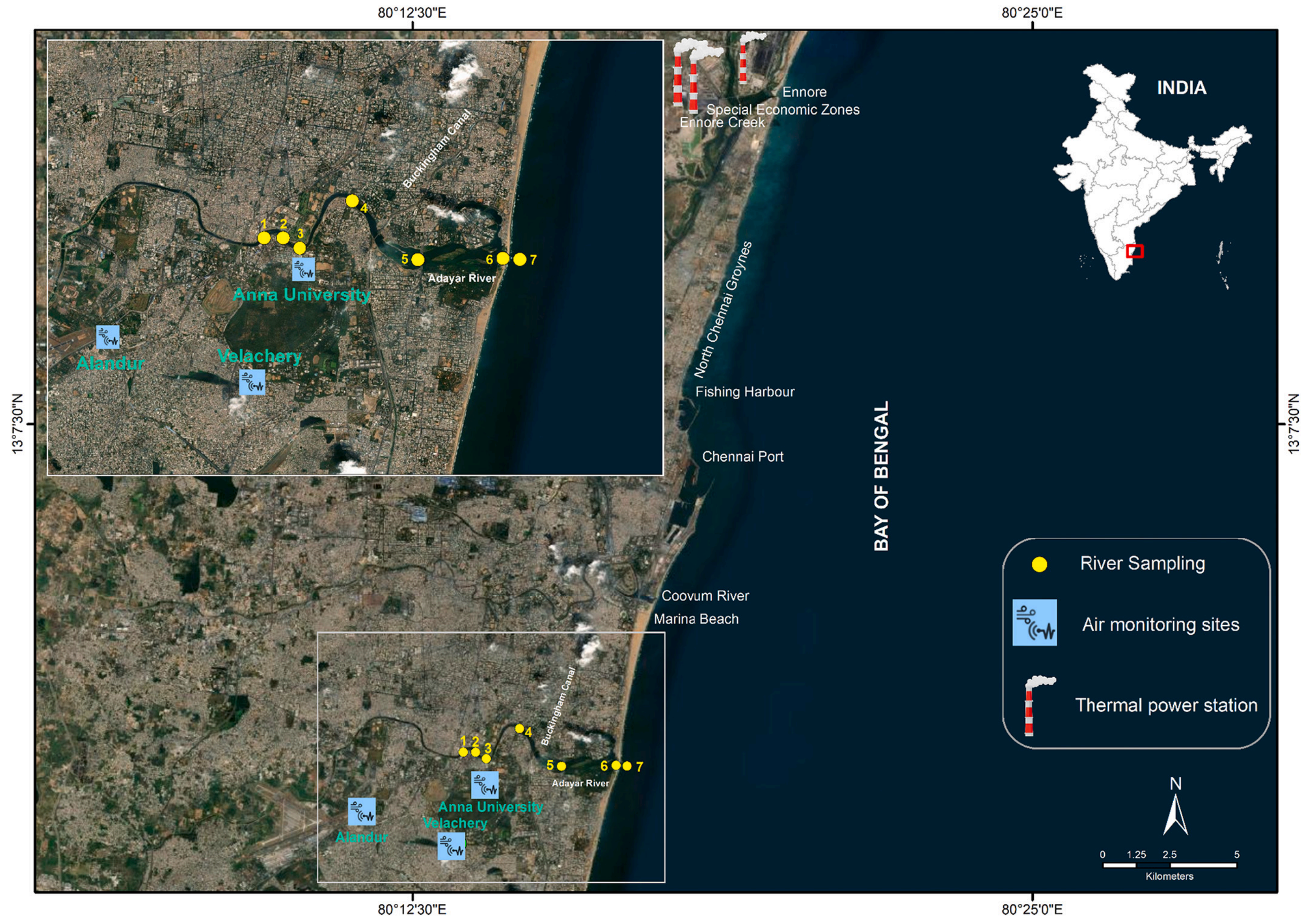

Fig. 1. Study area with ambient air and water quality monitoring stations at Chennai megacity.

Table 1
Mean meteorological conditions before and during COVID-19 lockdown phases in Chennai megacity.

Meteorological parameters	Before lockdown	During lockdown	Difference (%)
	Mean	Mean	
Temperature (°C)	27.85	30.59	(+9.84)
Relative Humidity (%)	77.47	82.07	(+5.94)
Wind Speed (m/s)	0.89	1.05	(+17.98)

the continent as well as from the ocean. Under these circumstances, only the trajectory pathways determine whether the air pocket carries pollutants or not (Shan et al., 2009), for instance, if the air mass passes through industries and other polluted areas, then they will carry the pollutants along with the air mass.

The continental air mass before lockdown originates at an altitude of 6000 m AGL from Western Asia, passes through the Arabian sea and enters into India at the state of Maharashtra and continues to flow through Deccan Plateau and into the Bay of Bengal and enters Chennai in the third week of March 2020. The air mass at 4000 m AGL starts from the Bay of Bengal and move into Chennai, these air mass trajectories seem to corroborate with the study made by Singh and Chauhan (2020). During the lockdown, the first week of April 2020, the air mass at an altitude of 4000 and 2000 m AGL originates from arid regions of South Asia, enters India through the desert of Rajasthan, travels through the industrial belt of central India, and enters into Tamil Nadu. In the present observation, the ocean basins played a crucial role, since the air masses enter the northern part of Tamil Nadu from the Bay of Bengal, which could result in dilution in the atmospheric concentrations of the trace gases. All the present trajectories of air mass originated at 50 m AGL at the ocean basin.

3.4. *Changes in air pollutants*

Most cities around the world witnessed a notable decrease in the atmospheric concentration of air pollutants after the lockdown was implied. Variation in concentration of key urban air pollutants before and during COVID-19 lockdown at Chennai megacity is shown in (Table 2). During the lockdown, the restriction of vehicular movement, industrial and economic activities resulted in the overall improvement in the ambient air quality of Chennai. A magnificent diminution of atmospheric NO_2 concentration up to 94.13% was observed during the lockdown at NCSCM (Fig. S3), Anna University, followed by Alandur (89%; Fig. S4) and Velachery (65.9%; Fig. S5) respectively. This reduction in NO_2 concentrations is in the same range as observed in Sale city, Morocco (96%, Otmani et al., 2020), due to a pause in the industrial and vehicular exhaust during the lockdown. Globally, vehicular emission and a growing industrial development turndown the ambient air quality (Kambalagere, 2020). The high concentration of NO_2 may contribute to various health hazards and can lead to the formation of nitrate aerosols and acidic precipitation (Biswas et al., 2019; Otmani et al., 2020). At the same time, the concentrations of RSPM ($PM_{2.5}$) showed a sharp decline up to 66.5% within 24 h of lockdown at heavy traffic and industrial zone of Alandur (Fig. S4) followed by Velachery residential area (60.52%; Fig. S5) and NCSCM, Anna University

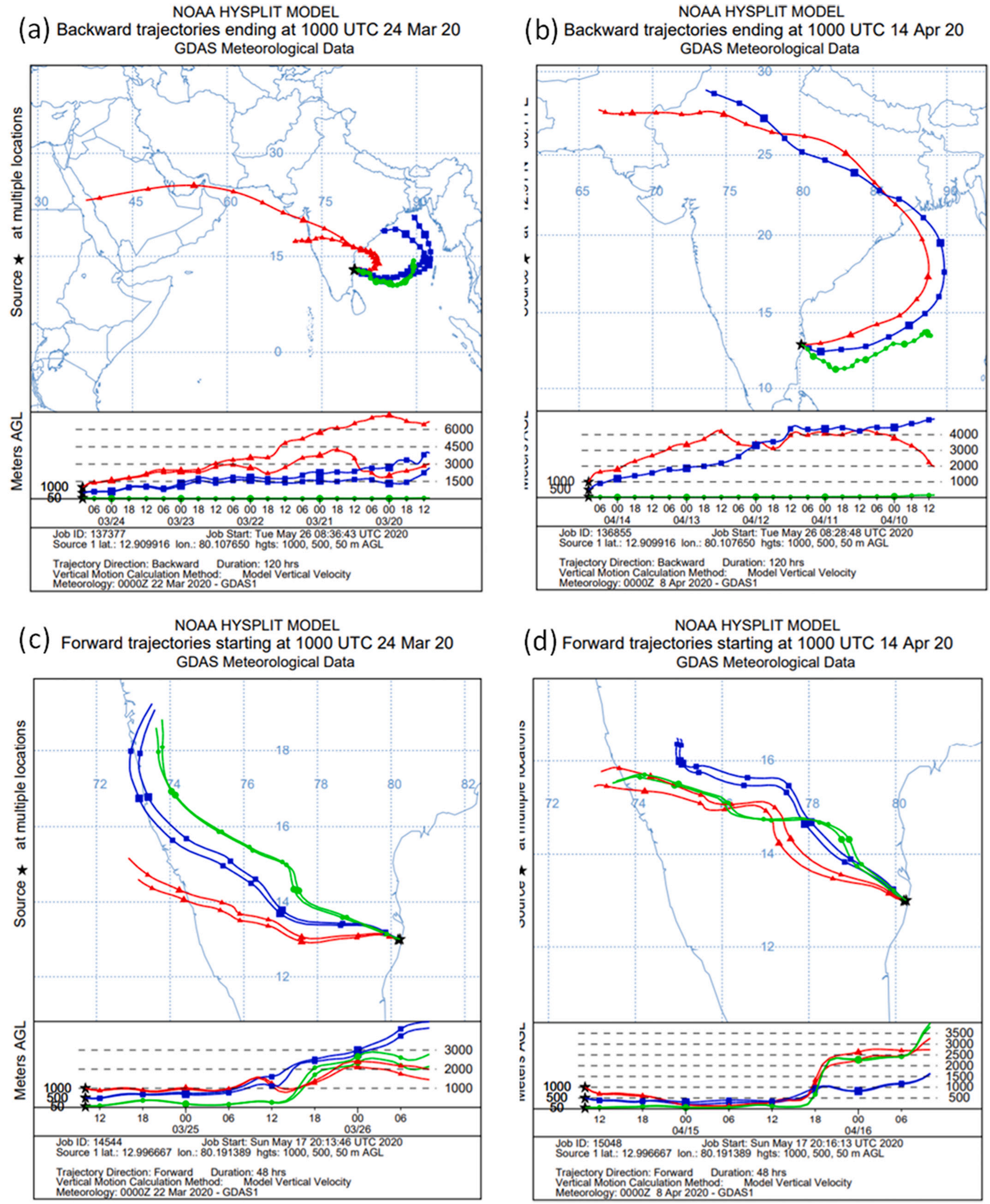

Fig. 2. Trajectory model at Alandur (industrial and residential area) and Velachery (residential area) (red – 1000 m AGL, blue – 500 m AGL, green – 50 m) (a) 120 h back trajectory model before lockdown, (b) 120 h back trajectory model during the lockdown, (c) 24 h forward trajectory model before lockdown and (d) 24 h forward trajectory model during COVID-19 lockdown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Variation in concentrations of key air pollutants before and during of COVID-19 lockdown (Mean ± SD). Values in parenthesis indicate the observed range.

Parameters	Before lockdown			During lockdown		
	Alandur	Velachery	NCSCM, Anna University	Alandur	Velachery	NCSCM, Anna University
$PM_{2.5}$ (μg/m^3)	38.86 ± 19.23 (0.24 – 168.67)	29.56 ± 17.61 (0.21 – 193.53)	15 ± 4.2 (2.1 – 31)	13 ± 9.4 (0.01 – 68.21)	11.67 ± 10.16 (0.05 – 63.96)	8.54 ± 0.85 (0.7 – 10.7)
NO_2 (μg/m^3)	77.66 ± 11.51 (0.04 – 150.66)	5.05 ± 4.17 (0.01 – 37.17)	6.98 ± 12.45 (0 – 79.9)	8.88 ± 7.75 (0.04 – 64.41)	1.72 ± 1.08 (0.02 – 12.66)	0.41 ± 1.38 (0 – 17.72)
O_3 (μg/m^3)	24.81 ± 22.42 (0.04 – 154.73)	26.81 ± 26.55 (0.02 – 161.26)	4.5 ± 1.97 (0 – 23.48)	15.75 ± 17.1 (1.92 – 89.96)	16.79 ± 17.5 (0.24 – 91.2)	2.46 ± 1.37 (0.71 – 8.19)
CO (mg/m^3)	0.58 ± 0.31 (0.03 – 3.22)	0.81 ± 0.31 (0.24 – 1.73)	0.12 ± 0.10 (0 – 1.01)	0.41 ± 0.14 (0.08 – 1.1)	0.75 ± 0.10 (0.36 – 1.11)	0.12 ± 0.08 (0.07 – 0.92)
SO_2 (μg/m^3)	5.14 ± 3.99 (0.01 – 57.73)	5.90 ± 3.42 (0.01 – 37.86)	2.8 ± 1.34 (0.01 – 17.45)	3.81 ± 4.41 (0.01 – 36.82)	5.97 ± 6.11 (0.01 – 51.79)	7.78 ± 1.41 (5.3 – 10.87)

(49.97%; Fig. S3). This drop-in RSPM concentrations were in agreement with the studies made at Sale city, Morocco (Otmani et al., 2020), Barcelona, Spain (Tobías et al., 2020), Rio de Janeiro, Brazil (Dantas et al., 2020) and New Delhi, India (Mahato et al., 2020). Global comparison of the change in the concentration (% variation) of air pollutants from various cities during COVID-19 lockdown is shown in Table 3.

The ozone is known to protect the earth from harmful radiation from the sun, but inhalation of ground-level ozone triggers various health issues and considered to be harmful to people having ailing breathing diseases such as bronchitis, asthma etc. (Salonen et al., 2018). This tropospheric ozone is a direct by-product of incomplete combustion of fuel and is formed when the oxides of nitrogen react with volatile organic carbon in the presence of sunlight (Marais et al., 2014). The percentage decrease in ground-level ozone between pre-lockdown and lockdown period was highest at NCSCM, Anna University campus (45.33%) followed by Alandur (36.5%) and Velachery (37.37%). However, for SO_2, the other pollution indicator, firmly linked to the combustion of fossil fuels, coal, petroleum and other chemicals, did not show any noticeable temporal change in its concentration. The mean concentrations of atmospheric SO_2 indicated an increase during the lockdown period (5.8 ± 3.97 μg/m^3) from the pre-lock down conditions (4.6 ± 2.9 μg/m^3) in the city. Moderate increment in atmospheric SO_2 concentrations in the city was primarily due to the continuous emissions from the essential commodities such as coal fed thermal power plants around the Ennore region in the northern part of Chennai city, with limited restriction during the lockdown (Sharma et al., 2020). Similar variations in concentration were also spotted in Barcelona, Spain (Tobías et al., 2020 and Sao Paulo, Brazil (Nakada and Urban, 2020). An increase in the atmospheric concentration of SO_2 during the latter part of the lockdown was attributed to the relaxation of the restrictions in vehicular movement and other anthropogenic activities (Somani et al., 2020).

3.5. *Air Quality Index (AQI)*

The air quality index transforms the concentrations of various air pollutants and communicates to the public with a single integer value, ranges from 0 – 500. Based on the overall condition of the air, the quality of air is classified into six categories i.e., Good (0 – 50), Satisfactory (51 – 100), Moderate (101–200), Poor (201–300), Very poor (301 – 400) and Severe (401 – 500). Mostly, the AQI during pre-lockdown is characterized under "moderate", the index was in the range between 101 and 200 at high traffic zones such as Alandur and Velachery, whereas, during the lockdown, AQI falls under "good" and index is confined between 0 and 50 at all the three sites (Fig. 3). Lockdown resulted in a significant reduction in key air pollutants, which in turn, lead to significant improvement in the Chennai air quality (up to 70%). Moreover, improvement in AQI during lockdown indicates that the reduction in vehicular and industrial exhaust significantly improved the regional ambient air quality. For a better understanding of air quality improvement in the Indian context during the lockdown, a comparison of AQI between the National Capital Territory of Delhi (single largest contributor of urban pollution (Mahato et al., 2020) and Chennai was made. The result showed that before lockdown, the mean National Air Quality Index (NAQI) at Delhi and Chennai was 186 (Mahato et al., 2020) and 94 respectively, whereas during lockdown the mean of NAQI reduced to 72 and 28. This demonstrates that Delhi and Chennai showed 61% and 70% improvement in their ambient air quality during the lockdown.

4. Impact of lockdown on the coastal water quality

4.1. *Study area*

The Adyar River (~40 km in length) originates near the Chembarambakkam Lake in Kanchipuram district, passes through Chennai megacity, Tamil Nadu, India, and joins the Bay of Bengal at the Adyar estuary (Figs. 1 & S6). Adyar River, traversing across Chennai, has been

Table 3
Global comparison of changes in the concentration (% variation) of air pollutants reported from various cities around the globe during COVID-19 lockdown.

S. No	Location	Variation (%)						Reference
World Scenario		$PM_{2.5}$	PM_{10}	NO_2	CO	O_3	SO_2	
1	Barcelona, Spain	–	–31	–51.4	–	–57.7	1.8	Tobías et al., 2020
2	Sao Paulo, Brazil	–	–	+54.3	–64.8	–30	16.2	Nakada and Urban, 2020
3	Sale city, Morocco	–	–75	–96	–	–	–49	Otmani et al., 2020
4	Almaty, Kazakhstan	–21	–	–35	–49	+15	+7	Kerimray et al., 2020
5	Cities in northern China	–5.93	–13.66	–24.67	–4.58	–	–6.76	Bao and Zhang, 2020
Indian Scenario								
6	Delhi	–53.11	–51.85	–52.68	–30.35	+0.78	–17.97	Mahato et al., 2020
7	Alandur, Chennai	–66.5	–	–89	–29	–37	–26	Present study
8	Velachery, Chennai	–60.52	–	–65.94	–7.41	–37.37	+1.18	Present study
9	NCSCM, AU, Chennai	–49.97	-39.5	–94.13	0	–45.33	+177	Present study

- Data not available.

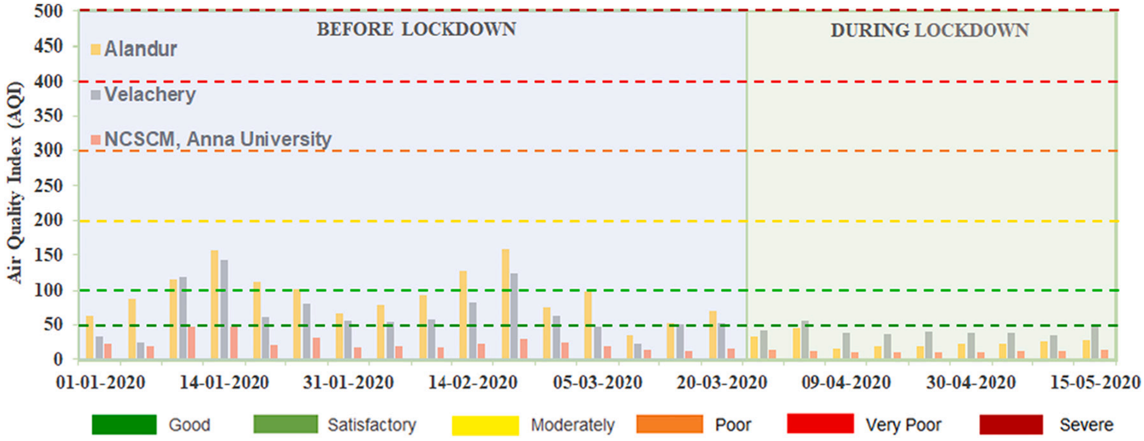

Fig. 3. Air Quality Index (AQI) at Chennai megacity (Alandur, Velachery and NCSCM, Anna University campus) before and during COVID-19 lockdown.

reported as one of the most anthropogenically stressed riverine systems due to the high discharge of wastewater and sewage from various sectors through its course to the Bay of Bengal. The environmental conditions in the estuary are characterized by low salinity, the diurnal flow of tidal water and high plankton density. However, with the domestic sewage and effluence from various industries, frequently emptying into the river, causing detrimental effects to the estuarine and coastal ecosystems. The river is almost stagnant and does not carry enough water except during the monsoon. The existing sewage treatment plants are not adequate for managing the heavy domestic discharge and at many points, domestic effluents are entering the river, which leads to the present level of degradation of the Adyar River.

4.2. Sampling and analytical methods

As part of NCSCM regular monitoring of coastal ecosystems, two independent observations were carried out before and during the lockdown. To understand the influence of lockdown on the surface water quality, environmental data collected during the lockdown phase (26th June 2020), were compared with the observation made just before the onset of lockdown (3rd March 2020). During the lockdown, activities such as public transport, tourism, hotels and other hospitality services, education institutions, shopping malls, theatres, restaurants, slaughterhouses were completely banned in the state. Surface water samples (in duplicate) from six stations within the estuarine part of Adyar River and one station in the coastal waters were collected during the daytime (8 am−12 pm) to offset the impact of the time factor on physicochemical variables (Fig. 1).

Measurement of physicochemical properties, surface water (water temperature, salinity, pH, dissolved oxygen [DO]) were carried out in-situ using a pre-calibrated multi-parameter Hydrolab® sonde equipped with an optical probe. Water samples for dissolved inorganic nutrients were collected using a 5 l Niskin bottle at the depth of ~0.2 m. Water samples were collected in acid-washed HDPE, 250 ml bottles and samples were stored at −20 °C until analysis. Suspended particulate matter (SPM) was measured by filtering a known volume of water through 0.45 μm Millipore® membrane filters, rinsed with Milli-Q® water and by taking the difference of initial and final weights of the filter in terms of mg/l (Anandavelu et al., 2020). For estimation of chlorophyll *a* (chl-*a)*, 1 l of water was filtered onto 47 mm Whatman® GF/F filter, extracted in 90% acetone for 12 h, and analysed using a spectrophotometer (Gupta et al., 2008). Dissolved inorganic nutrients such as nitrate (NO_3^-N), ammonium (NH_4^+-N) and phosphate (PO_4^{3-}P) in surface water samples were estimated using continuous flow analyser SAN++ SKALAR® following the analytical methods of Grasshoff et al. (1999).

4.3. COVID-19 lockdown and changes in surface water quality

4.3.1. Change in physicochemical parameters

As a result of the changing natural and anthropogenic factors such as alterations in hydrological regimes, domestic and industrial inputs, urbanized estuaries and surrounding coastal waters experience various spatio-temporal changes. In the present study, field data were collected during the dry season (March and June 2020) where the monthly rainfall was <50 mm. The monthly mean freshwater flow during the dry season from the Chembarambakkam Lake, nourishing Adyar River, was found to be ~0.95 cumecs. Variation in physicochemical parameters (salinity, pH, DO and SPM), nutrient concentrations (NH_4^+-N, NO_3^-N, PO_4^{3-}P) and algal biomass (chl-*a*) was measured during the pre-lockdown and lockdown conditions and results were presented in Fig. 4. The mean salinity and pH of the estuarine waters during March (pre-lockdown) were marginally higher (14.95 and 7.52) than that of June (13.29 and 7.48). A significant decrease in the concentrations of SPM was recorded (~41%) from March to June both in the estuary and the adjacent coastal waters. DO saturation during the pre-lockdown period in the estuarine region varied from a minimum of 4.3% to a maximum of 76.6%. The corresponding chl-*a* concentration varied from 1.9 μg/l to 31.7 μg/l with a mean concentration of 13.76 ± 11.03 μg/l. Even though, the estuarine water remained highly undersaturated for dissolved oxygen in June, a significant increase was observed in mean dissolved oxygen saturation from 25.3% (in pre-lockdown) to 43.9% in the last week of June (lockdown phase). The subsequent increase of DO saturation for coastal waters was found to be from 64.1% in March to 98.5% in June. A substantial improvement in water quality was recorded during the lockdown, with a significant increase in DO saturation (1.7 times) in the surface water of the Adyar urban estuary.

4.3.2. Variation in dissolved inorganic nutrient load

During pre-lockdown, the average concentrations of ammonium, nitrate and phosphate in the estuarine region were 474 ± 236, 6.1 ± 5.1 and 23.1 ± 16.8 μmol/l, respectively. The mean water quality parameters of the surface water were compared (Table 4) with studies done during the dry season (March 1998 and 2006) by Gowri et al. (2008). An environment with high ammonium concentrations indicated the predominance of decomposers and reduction processes, generally found in oxygen-depleted waters. Significantly, higher dissolved NH_4^+-N concentration in the surface water, found during March 2020 (pre-lockdown), indicated microbial turnover of organic nitrogen from municipal/industrial wastewaters (Saeed and Sun, 2012). During the pre-lockdown condition, severe oxygen-depleted conditions (estuarine part and it coincide with the highest NH_4^+-N concentrations. High nutrient concentrations, SPM and chl-*a,* recorded during pre-lockdown sampling, indicated intense heterotrophy associated with

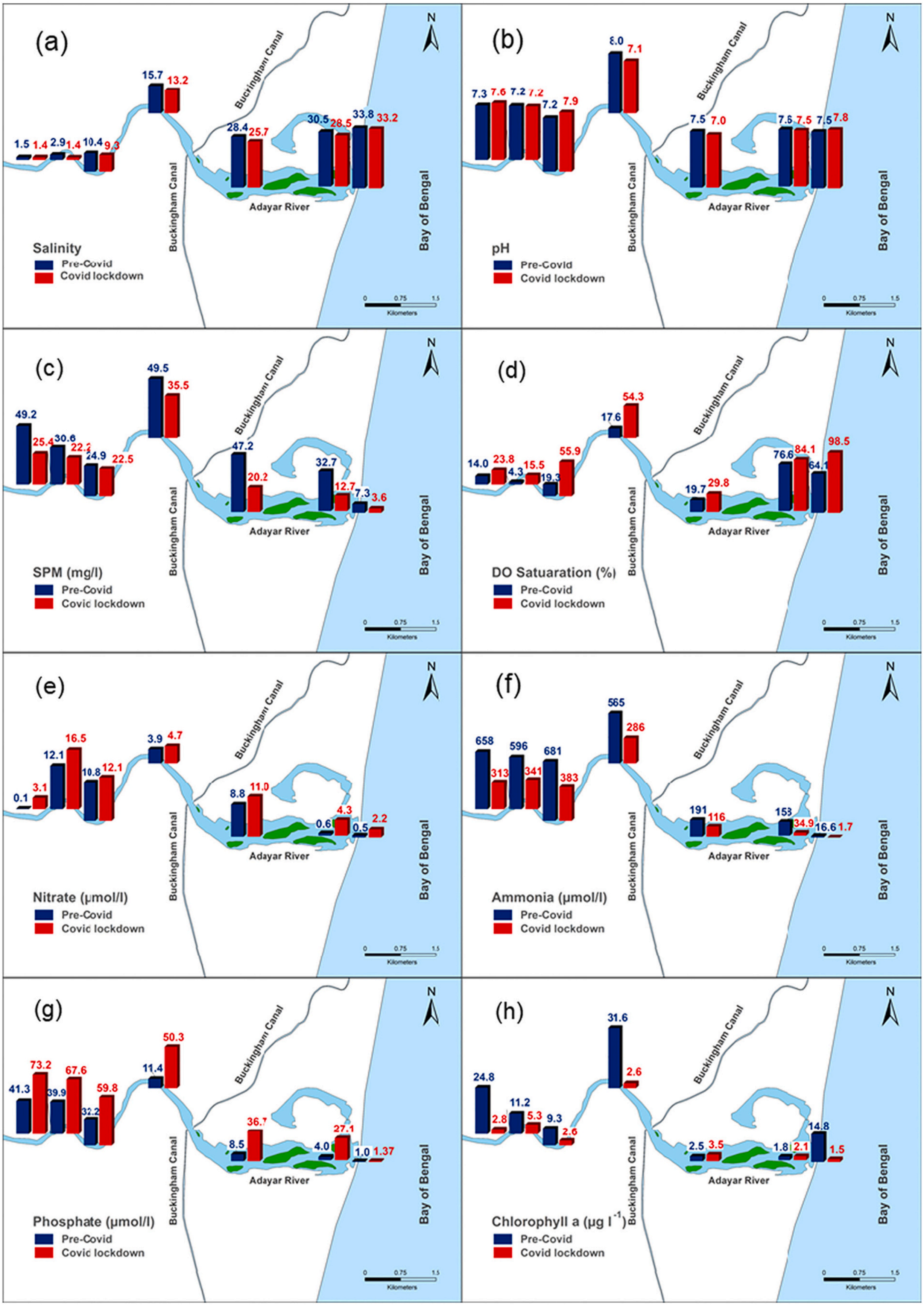

Fig. 4. Variation in physicochemical parameters such as (a) salinity (b) pH (c) SPM (d) DO saturation (e) nitrate (f) ammonium (g) phosphate and (h) chlorophyll *a* pigment concentration observed along the Adyar estuary during pre-lockdown and lockdown.

Table 4
Comparison of mean water quality parameters of Adyar River in different time scale 1995, 2006 and 2020 (pre-lockdown and COVID-19 lockdown).

Period of study	SPM (mg/l)	NH_4-N (μmol/l)	NO_3-N (μmol/l)	PO_4-P (μmol/l)	Reference
1995 (March)	212	21.4	2428.5	42.5	Gowri et al., 2008
2006 (March)	48	216.4	31.4	180	Gowri et al., 2008
Pre-lockdown (March 2020)	39	474	6.1	23.1	Present study
During lockdown (June 2020)	23	245	8.6	52.4	Present study

eutrophication and algal bloom (Ferreira et al., 2011).

Overall, it was observed that the dissolved inorganic nitrogen concentrations within both the estuary and coastal waters have been reduced significantly during the lockdown. This enhancement in surface water quality was associated with a 41% reduction in suspended particulate matter and a 48% reduction in dissolved NH_4^+-N concentrations. Improved water clarity during the lockdown in terms of reduction of SPM in the River Adyar is comparable with Vembanad Lake, west coast of India where a decrease of 15 to 35% of water column SPM was recorded along with improvement in overall lake water quality (Yunus et al., 2020). However, a marginal increase in dissolved NO_3^-N in the Adyar estuary during the lockdown phase was attributed to in-situ nitrifications resulted from the increase in DO saturation. Additionally, a significant increase (128%) in dissolved PO_4^{3-}P in the estuarine region during the later period could be associated with the increase in the domestic detergent use during COVID-19 in this highly populated city (Kumar et al., 2021). Despite a significant dip in domestic consumer growth, India's largest packaged consumer goods company has reported a 7.1% year-on-year jump in its June quarter 2020, primarily due to the pick-up in sales of detergents, soaps, and shampoos and other hygiene products (Mint, 2021). A common awareness in the urban society during the pandemic was a preference for a detergent wash of every single item (dress materials, vegetables, hand wash, bathing etc) after every single use. It is estimated that about 2.88 million tonnes of phosphate-containing detergents were used in 2015, in India, resulting in a total outflow of P of 146 thousand tonnes (Kundu et al., 2015). However, it was observed that this enrichment of PO_4^{3-}P in the estuary during the lockdown resulted in a drastic reduction in N/P ratios (six times) and chl-*a* concentrations (77%) in the surface waters of River Adyar indicate that restriction in anthropogenic activities could substantially reduce the pollution loads and improve the river and coastal water quality (Figs. S6 & S7).

Even though these improvements in estuarine and coastal water quality are considered temporary, the observations for the anthropogenically stressed river can be useful to regulate human activities as part of coastal zone management measures. The present study highlights the necessity of proper disinfection/treatment of wastewaters before its release to the river streams, surrounded by a very high population, in managing surface water pollution. The understanding gained from the observed improvement in river water quality during the lockdown can be useful to develop a systematic regulatory approach, effective in strengthening the existing wastewater management for the coastal megacity.

5. COVID-19: increase in plastics based biomedical waste

Personal protective equipment (PPE) has become one of the most important weapons to fight against the pandemic in India, the second-largest infected country in the world. The improper disposal of PPE can cause havoc to the already recognised plastic pollution in the marine environment. These wastes, in turn, will break down into microplastics and pose severe threats to marine biota (Schmidt et al., 2018; Prata et al., 2020). To understand the polymer composition of various commercially available PPE, representative samples were collected during the pandemic from Chennai city. Common PPE material, such as facemasks ($n = 50$), gloves ($n = 25$), bottles of sanitizer ($n = 20$), PPE suits ($n = 10$) and face shields ($n = 5$) were procured from commercial markets of the city during May 2020. The PPE samples were cut up into a smaller, more appropriate size using stainless steel scissors to analyse their composition using PerkinElmer FTIR-ATR. Each sample was scanned 32 times at a wavelength range from 4000 to 650 cm^{-1} and a resolution of 4 cm^{-1}. The chemical mapping of these PPE materials was carried out by comparing with reference spectra in ATR of polymer library with a threshold $\geq$80% as the value of resemblance between samples (Karthik et al., 2018; Robin et al., 2020).

A total of fourteen polymer types were identified from the collected PPE samples: Acrylonitrile butadiene styrene (ABS), Cellulose (CE), Ethylene propylene diene monomer (EPDM), Nitrile-butadiene rubber (NBR), Poly(butyl acrylate) (PBA), Polybutadiene acrylonitrile (PBAN), Polybutylene terephthalate (PBT), Polyethylene (PE), Polyester (PET), Polyethylene terephthalate glycol (PETG), Poly (1,4-cyclohexanedimethylene isosorbide terephthalate) (PICT), Polypropylene (PP), Polyvinylidene fluoride (PVDF) and Styrene-Butadiene rubber (SBR). Out of total PPE analysed, the most frequently found polymers where PP (25.4%) > PET (15.4%) > CE (10.9%) > PE (10%) > PICT (10%) (Fig. 5). Facemasks comprised of PP, PICT, CE, PET, ABS and PE while gloves comprised of NBR, SBR, PBAN, PVDF and CE. Sanitizer bottles are comprised of PP, PE, PET and PBA while gowns are comprised of PBT, PP, PET and PE. Face shield comprised of PET, PETG and EPDM (Fig. 5). The FTIR spectra of PP for the facemasks, NBR for the gloves, PE for the sanitizer bottle and PBT for the protective suits given in Fig. 6. These spectra indicated an unprecedented surge in plastic-based medical waste and their potential contribution to microplastic pollution in the marine and terrestrial environment (Fadare and Okoffo, 2020).

According to the Tamil Nadu Pollution Control Board (TNPCB), around 47 t of COVID-19 biomedical waste is generated every day (The Hindu, 2020a) during the pandemic. However, the existing common biomedical waste treatment and disposal facility (CBWTF) is constrained to manage only up to 34 t of waste per day. The existing facility in Chennai can only handle up to 72% of the total medical waste produced per day. The remaining medical waste is not properly disposed of and is mostly end up in landfills (Fig. S8). The mixing of these additional medical wastes with municipal solid waste during the pandemic has become a severe concern in recent times.

6. Effect of lockdown on coastal ecosystems

The impact of COVID-19 lockdown has led to environmental positives such as reduction in pollution (5 lakh units of industries in coastal India had been shut), improved coastal water quality (especially in coral

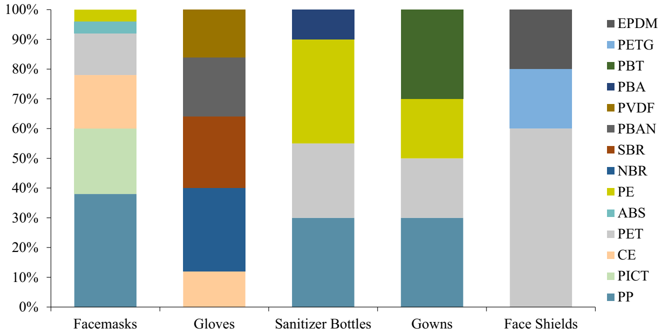

Fig. 5. Percentage composition of polymers from commercially available facemasks, gloves and other PPE.

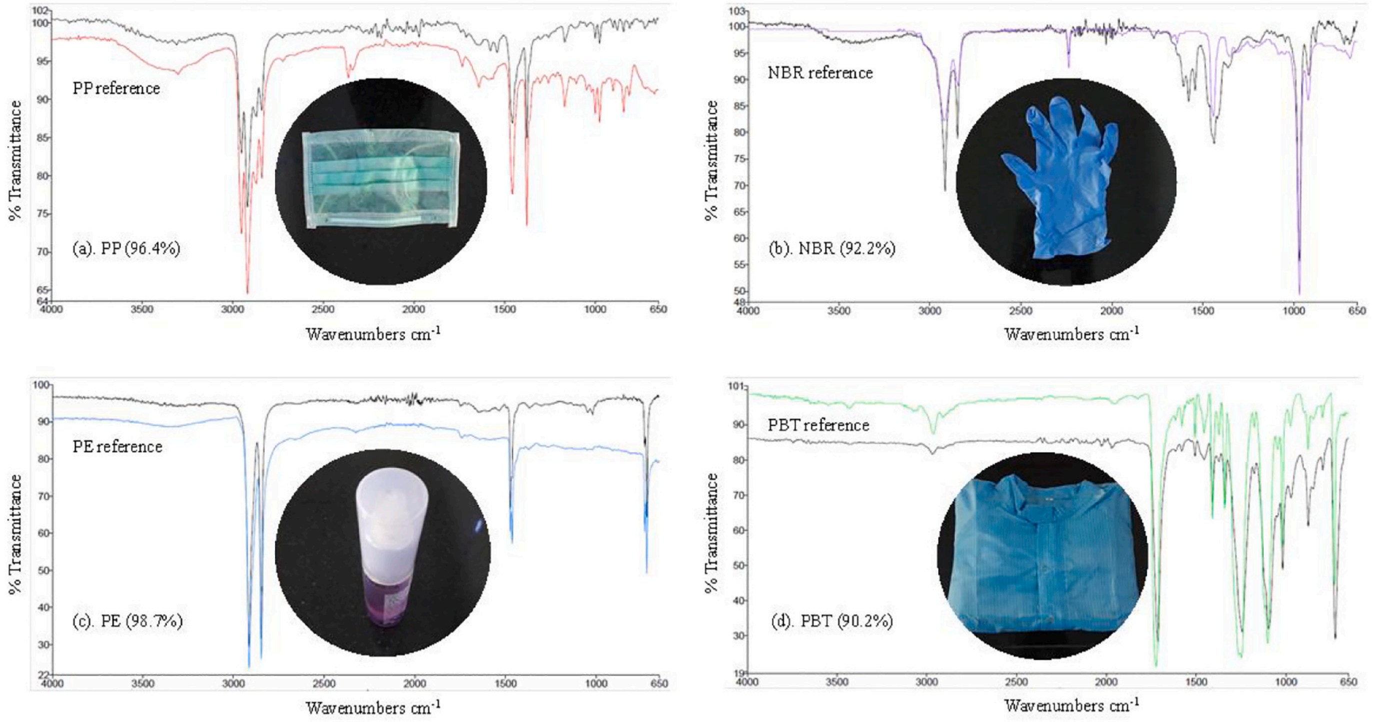

Fig. 6. FTIR spectra for the most common polymer types identified from commercially available facemasks, gloves and other PPE (Reference spectra of (a). Polypropylene (red line), (b). Nitrile-butadiene rubber (violet line), (c). Polyethylene (blue line), (d). Polybutylene terephthalate (green line) and black lines denote the sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reefs and seagrass beds, reduction in eutrophication, the occurrence of algal blooms and hypoxia). Ecologically sensitive ecosystems have also been benefited from the reduction in fishing and tourism-allied activities such as anchoring by mechanised boats, recreational diving etc. The reduction in anthropogenic operations across the coast has also resulted in daytime nesting of sea turtles (The Hindu, 2020b), return of several avifaunae (The Economic Times, 2020), sighting of dolphins in near-shore waters (Hindustan Times, 2020), increased population of ghost crabs (*Ocypode* spp.) in intertidal areas, increase in fishery stocks and undisturbed spawning activities. Reduction in tourism and the resultant decrease in littering and trampling during lockdown will be expected to have a positive impact on mangroves, dune vegetation and other coastal ecosystems (Garcés-Ordóñez et al., 2019). The lynchpin of modern beach management policies is limiting human access and to conserve ecologically sensitive areas (Scapini, 2002). Negatively, instances of poaching and illegal fishing in Protected Areas (PA) were reported. Other impacts include the cancellation or postponement of intergovernmental meetings such as the convention on biological diversity (CBD) COP 15 scheduled in Kunming, China in October 2020 and the UN Climate Change Conference COP26, planned for November 2020 in Glasgow, both of which are key meetings addressing climate change and conservation of biodiversity.

7. Impact of the pandemic on the blue economy

Two of the major sectors that were under pressure were fishing and coastal tourism, both of which are the mainstays of the blue economy in India accounting for 1.07% and 6.8% of India's GDP, respectively. Small-scale fishers and coastal communities were severely affected, due to the pandemic. Besides value chain disruption, the personal health risk of the fisher community is manifold, with livelihood loss of migrant fishers. It also leads to a rapid community spread in the fishing villages and becoming a hotspot for the pandemic. Fisherfolk was unable to sell their catch to seafood processing industries, restaurants, or corporate supply outlets due to losses in the value chain market. The culture fishery sector was affected due to the closure of inter-district borders, transport of broodstock and larval shrimps and, access to feed. A community behavioural change among the consumers in accepting seafood for fear of infection led to the stranding of fish products in the markets. International trade is also impacted in much similar way due to closed borders and strict trade regulations. For assistance in the fisheries sector to regain the disturbed supply chain, the Union Government has announced a financial package of Rs. 20,000 crores (INR).

Tourism, an important blue economy sector, came to a halt with significant downward pressure on this sector. As per the Confederation of Indian Industry (CII), 5 lakh crores of INR will be lost in this sector along with 4-5 crore jobs being cut. Concerning coastal tourism, the economic impacts affect beach stall hawkers as well as hotels, tour operators, travel agencies, and other related vendors. The coastal communities of India will be a few of the hardest hit as many have staked their livelihood on tourism-related activities (tour guides, boating operators, water sports, recreational fishing etc.) particularly in tourist hotspots in the mainland coasts and islands. The container lines have also taken massive losses due to disruptions in the global supply chain, halt in traffic and access to ports and reduced demand.

8. COVID-19 pandemic: human behaviour in response to social change

The stigma associated with social distancing due to the fear of contracting the communicable disease had led to discrimination, prejudices and negative attitudes. Social isolation of groups prompted by stigmatized behaviour results in severe mental health issues. The supply chain disruption and an urge to stay healthy have also prompted/forced people to modify their eating propensity. For example, individuals reliant on products such as seafood, which were difficult to get during the pandemic, were constrained to alter their diet. An increase in ordering food and groceries online (e-commerce) was widespread during the lockdown as the local governments allowed this to function within a specific time.

9. Causal loop diagram (CLD): COVID-19 in an Indian context

Causal loop diagram (CLD), explains the relationship between subsystems and variables, which signs the negative and positive relationships (balancing loop and reinforcing loop). CLD are tools to illustrate the casual interlinkage between components of a system and depict how changes in one component cascade changes in others and back to itself, via a feedback loop, significantly affecting the status of the entire system (Kirkwood, 1998). Systems thinking approach for COVID-19 pandemic can help policymakers to understand and control the spread of infection and its multifaceted consequences across the community since society is itself a complex adaptive system (Luke and Stamatakis, 2012; Senge, 2014). Fig. 7 presents a CLD as an important interacting component in a society that is responding to the threat of COVID-19 in the Indian context. The influential variables which cause risk of transmission are presented in black, positive benefits of COVID-19 pandemic lockdown to the environment are presented in green. The red variables suggest an open link, meaning that it has a strong impact on that variable.

The positive impact of lockdown on the environment is depicted as enhanced environmental quality, reduced greenhouse gas emissions,

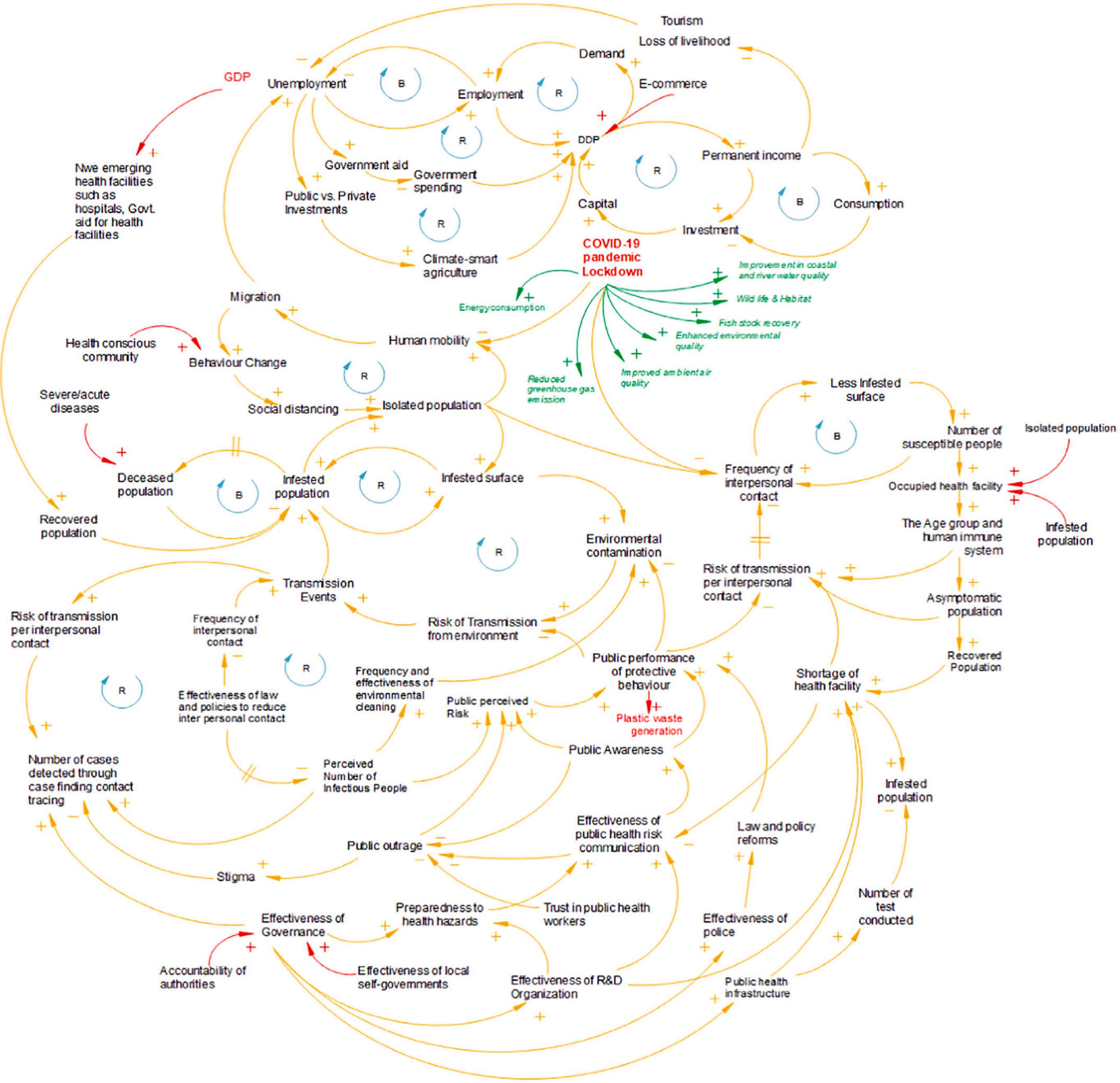

Fig. 7. Causal loop diagram illustrating some of the interacting components in a society responding to the threat of COVID-19 pandemic in an Indian context. A causal-loop diagram summarizing the casual interlinkage between components of a system, and depict how changes in one component cascade in changes in others and back to itself, via a feedback loop, significantly affecting the status of the entire system. A causal link from variable A to variable B is positive if a change in A produces a change in B in the same direction; a causal link from variable A to variable B is negative if a change in A produces a change in B in the opposite direction. Feedback loops, represented in the diagram with R or B sign surrounded by a circular arrow, can be classified as positive or negative. Positive (or reinforcing) feedback loops amplify change and are typically identified by an 'R' notation, while a negative (or balancing) counter and reduce change are identified by a 'B' notation.

improvement in the surface and coastal water quality and benefit to wildlife habitats. The incidence of interpersonal contact and environmental contamination of COVID-19 is reduced as a result of increased case detections through mass testing and contact tracking, as well as public protective behaviour. Awareness through mass media helps reduce public outrage due to prolonged lockdown and resultant mental stress. Bradley et al. (2020) emphasize policies promoting work from home, flexible or staggered working hours, increasing opportunities to prevent environmental contamination, frequency and effective environmental cleaning of public spaces. These long-term actions will result in a behavioural system shift in the population, preventing future epidemics of infectious diseases.

10. Lessons learnt and way forward

10.1. *Primary health care*

The pandemic's impact on India's economy and society is still being assessed, and the full extent of the damage may not be known for some time. With this in mind, we must learn and salvage what we can from the current circumstances. Strong policy reforms are required in various sectors, with a focus on health care. Primary health care (PHC) professionals, who deal with 80-90% of critical COVID-19 cases, require more resources, facilities, training and preparedness.

10.2. *Eco-friendly medical products*

From a long term perspective, national manufacturing units and research centres need to continue in developing indigenous diagnostic test kits, environmentally friendly personal protective equipment (Celis et al., 2021), and bio-degradable biomedical manufacturing (free of toxic chemicals released during incineration) that could help in the reduction of plastic waste generated during the pandemic and, in the face of any such future eventuality.

10.3. *Ecosystem-based urban planning*

The urban districts of India, including Chennai, have reported more than half the total COVID-19 cases in the country. Pandemic data highlights the need for sustainable, natural ecosystem-based approaches with better urban land-use planning health preparedness against such disasters. Advanced technology in the coastal megacity model could also be introduced to allow regular activities to be performed remotely and to provide vital services despite the distance (Espejo et al., 2020). In the event of future epidemic concerns, the study highly advocates smart technology to collect data on the preparedness of urban public health care facilities and vulnerable communities. This information can be used to strengthen said areas and enhance their health preparedness against such events in the future. A national database on migrant workers is important for planning current and future management needs, especially for those stranded at highway camps and those who have returned to their villages. The identification of contact sources aids in interrupting the virus's chain of transmission.

10.4. *Boosting the economy*

The Union Government has announced a package equivalent to 10% of the country's GDP to assist vulnerable low-income households, the revival of micro, small and medium enterprises (MSMEs), helping migrant workers and, provide an urban employment guarantee programme. It is possible that the consequences will not be equally distributed across the various sectors, with gaps that need to be addressed.

10.5. *The supply chain management*

Another area in need of strengthening that was highlighted during the pandemic was the supply chain networks, both global and national levels. This strengthening can be accomplished through a variety of ways, not least of which is the boosting of local and national businesses, to promote self-reliance and reduce dependency on other countries for assistance during a crisis. The consumers preferring to change to healthier food opens up the opportunity in the food sector. Reduced/ceasing the use of synthetic fertilizers (organically farmed products only), adopting the climate-smart farming (CSF) approach, zero-budget natural farming (ZBNF) farming methods are now being practised by small scale farmers. This has directly contributed to the food security of the nation.

10.6. *Waste management*

The waste management sector experienced a few challenges, especially in the marine environment during the pandemic. Domestic and hospital waste has increased during the pandemic period due to the difficulty in solid and liquid waste management. The inappropriate disposal of these wastes, particularly medical wastes, will have negative consequences on both terrestrial and aquatic biota. Improperly disposed PPE kits may lead to microplastic release, colonization of invasive species, and entanglement or ingestion by apex predators (De-la-Torre et al., 2021). New guidelines are required for PPE management (energy recovery and disposal) and protecting the coastal and marine environs is the need of the hour. Further, the high concentrations of PO_4 and its pollution potentials in the surface water of India need stringent management strategies and policy reforms on the use of phosphate in the detergents.

11. Conclusion and outlook

Improvement in ambient air and surface water quality during the lockdown highlights the need for regulated anthropic activities as part of coastal zone management measures. The result also emphasizes the importance of pollution abatement and management through ecosystem-based approaches. Regulated human activities along this region will enhance resource efficiency, ecosystem services and the wellbeing of the coastal communities.

In recent years, India is on the verge of a paradigm shift from coastal regulations to integrated coastal zone management (ICZM). Enhancing coastal and ocean resource efficiency (ENCORE) is one such national initiative proposed by the Ministry of Environment, Forest and Climate Change, Government of India and aims to strengthen coastal zone management in all coastal states and union territories under the National Coastal Mission. This program is aimed to enhance coastal resource efficiency and resilience by building collective capacity (including communities and decentralized governance) for adopting and implementing integrated coastal management approaches. ENCORE is envisioned to (i) enhance livelihood diversification and the wellbeing of coastal communities, (ii) support India's blue economy and safeguard against pollution and (iii) natural disasters including pandemics.

CRediT authorship contribution statement

R.S. Robin: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **R. Purvaja:** Conceptualization, Supervision, Resources, Project administration, Writing – review & editing. **D. Ganguly:** Writing – original draft, Investigation, Writing – review & editing. **G. Hariharan:** Investigation. **A. Paneerselvam:** Investigation. **R.T. Sundari:** Methodology, Writing – original draft. **R. Karthik:** Writing – original draft, Methodology, Formal analysis, Visualization, Writing – review & editing. **C.S. Neethu:** Writing – review & editing. **C. Saravanakumar:** Writing – review & editing. **P. Semanti:**

Formal analysis. **M.H.K. Prasad:** Formal analysis. **M. Mugilarasan:** Formal analysis. **S. Rohan:** Writing – review & editing. **K. Arumugam:** Formal analysis. **V.D. Samuel:** Writing – review & editing. **R. Ramesh:** Supervision, Project administration, Funding acquisition.

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.2021.112739.

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