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COVID-19 induced lockdown reduced metal concentration in the surface water and bottom sediment of Asia's largest lagoon

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ABSTRACT

COVID-19 (hereafter COVID) induced lockdown provided a unique opportunity to evaluate the effects of human activities on coastal ecosystems. This study quantified the seasonal variations in concentrations of nine metals (Al, Cr, Cd, Co, Cu, Fe, Mn, Ni, and Pb) in surface water and sediment samples of the largest brackish water lagoon in Asia (i.e., Chilika Lagoon), comparing pre-and post-COVID scenarios. The COVID lockdown resulted in a wide variation in metals concentrations, with surface water showing 1 to 8.6-fold reduction in metals such as Al, Cr, Cu, Fe, Mn, and Pb, while sediment displayed a more modest reduction of 1 to 1.3-fold. Metals like Cd, Co and Ni were below detection limit in post-COVID water samples with a slight decrease (1-fold) in the sediments. COVID lockdown did not show any significant correlation with metal concentrations in water or sediment. This study provides baseline data for metal contamination in the surface water and sediment of the Chilika Lagoon.

1. Introduction

The spread of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2; hereafter called COVID) had an impact on the entire world human activities, as it spread across the globe (Cascella et al., 2020; World Health Organization, 2020). Consequently, based on the repeated emergence, rapid transmission, and higher causality rate the WHO declared COVID as a pandemic in March 2020. Following the declaration, in India, the COVID led to a nationwide lockdown and shut down in mid-March 2020. This lockdown (March–October 2020) led to the suspension of almost all industrial and agricultural activities across the country, other than the essential services industry which was not closed. Under this lockdown period, industrial and human activities were significantly reduced (Patterson Edward et al., 2021; Selvam et al., 2020a). This period provided a window of opportunity to study the natural ecosystems under the lack of human-induced disturbances, which would otherwise not be possible. In India, various researchers used this unique opportunity to assess the pollution status of air (e.g., atmospheric pollution) and water (e.g., river and oceans) under the influence of the imposed lockdown and observed a reduction in various pollutants in the natural ecosystems (Garg et al., 2020; Lokhandwala and Gautam, 2020; Mishra et al., 2020; Patel et al., 2020). A reduction in environmental pollution was also observed in coastal ecosystems that are connected to India's major river systems that discharge various anthropogenic derived pollutants into the coastal ecosystems (Acharya et al., 2022b; Panja et al., 2022; Patterson Edward et al., 2021; Prasood et al., 2023; Selvam et al., 2020a; Vijay Prakash et al., 2021). However, this lockdown resulted in a decline of phytoplankton biomass in the Bay of Bengal due to reduced input of nutrients (Mishra et al., 2020), whereas reduction in pollutants improved the surface water quality along India's east and the west coast (Lotliker et al., 2021; Panja et al., 2022; Prasood et al., 2023; Selvam et al., 2020b; Vijay Prakash et al., 2021). This improved water quality increased coral reef-associated fish populations (Patterson Edward et al., 2021). Similarly, another study observed a reduction in metal concentrations such as lead (Pb) and iron (Fe) in sub-surface groundwater in the coastal district of South India (Selvam et al., 2020a, 2020b). Additionally other studies quantified the concentration of various metals in the river Ganga in India during COVID lockdown period and observed a significant reduction (50 %) in the input of various metals in the water column (Shukla et al., 2021).

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However, none of the research on the impacts of COVID lockdown assessed the concentration of metals in surface water and sediment of coastal ecosystems of India.

India's coastal ecosystems are highly dynamic as they receive significant influx of riverine discharges, and face extensive dredging activities (Mishra et al., 2022; Mishra and Farooq, 2022a). Additionally, these ecosystems also receive untreated sewage and industrial effluents, delivered both through the riverine input and direct disposal of various other pollutants (Gopal et al., 2018; Vijay Prakash et al., 2021). The continuous influx of anthropogenic pollutants exerts significant pressure on these coastal ecosystems (Acharya et al., 2022b; Häder et al., 2020). As a result, these ecosystems act as a sink of contaminants including metals (Lewis and Richard, 2009; Mishra et al., 2022; Mishra and Farooq, 2022a; Nazneen et al., 2022). Despite, these metals playing a critical role in marine ecosystem functioning (e.g., copper (Cu), manganese (Mn), and zinc (Zn) as essential micronutrients and arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) as non-essential to primary producers) (Avelar et al., 2013; Mishra et al., 2019; Morsy and Mishra, 2020), can exert toxic effects on the marine biodiversity once their concentration exceed threshold levels (Millero et al., 2009; Stockdale et al., 2016). In recent years, the quality of India's coastal waters has deteriorated significantly due to the increased influx of these contaminants driven by various anthropogenic activities (Tripathy et al., 2014; Mishra et al., 2015). Therefore, there is an urgent need for continuous monitoring of trace metal concentrations in the coastal waters to safeguard these vital ecosystems and ensure their sustainability.

Chilika Lagoon in the state of Odisha, India, is a Ramsar site and the largest brackish water lagoon in Asia (Acharya et al., 2022b; Nazneen et al., 2022; Panigrahi et al., 2007). This lagoon is a unique and important ecosystem that harbours a rich biodiversity and sustains considerable anthropogenic pressure from various fishing and tourism activities (Madhusmita, 2012; Mohanty et al., 2016; Mohapatra et al., 2022). Considering its ecological significance, the Chilika Development Authority (CDA) which is nodal agency for monitoring this lagoon, along with various other researchers have been actively monitoring the water quality of this lagoon (Panda et al., 2010; Barik et al., 2019; Nazneen et al., 2019; and references therein). Additionally, a few studies have also monitored the metal concentration in the sediment and plant biomass (Banerjee et al., 2017; Barik et al., 2018; Nayak et al., 2004; Nazneen et al., 2022; Nazneen et al., 2019), and in the tissues of fishes and crab within the lagoon (Parida et al., 2017; Panda et al., 2019; Acharya et al., 2022b). However, there is a significant lack of baseline information regarding the seasonal variations in metal concentrations in both the water column and sediment of this lagoon, which have been highlighted by various researchers (Panda et al., 2015; Sahu et al., 2014).

To addressed this knowledge gap, our study quantified seasonal (i.e., pre-monsoon, monsoon and post-monsoon) metal concentrations in the top 30 cm of surface water (up to 30 cm depth) and bottom sediments of the lagoon in both pre-COVID and post-COVID scenarios. The unique circumstances during the COVID-19 pandemic provided a window of opportunity to assess the influence of reduced anthropogenic activities on the metal influx into the lagoon through riverine inputs. This study hypothesizes that the reduction in anthropogenic input during post COVID scenario would correlate with lower metal concentration in both surface water and sediment. Additionally, the study measured the physical parameters of surface water in Chilika Lagoon and establishes a relationship between seasonal variations in these parameters and metal concentrations in water and sediment samples across COVID scenarios.

2. Materials and methods

2.1. Study site

Chilika Lagoon, located in Odisha, India, spreads across an area of 1165 km^2 (CDA, 2021). This lagoon is situated along the eastern coast of India (Fig. 1) and is recognised as Ramsar Site. The lagoon characterized by its diverse habitats, including seagrasses, salt marshes, mudflats, and island ecosystems (Behera et al., 2023; Mishra and Farooq, 2022b; Mishra and Apte, 2021; Stankovic et al., 2023). These habitats contribute to the lagoon's rich biodiversity which supports the livelihood of millions of coastal fishermen and serves as a critical feeding and breeding ground for millions of migratory birds that come through the Central Asian Flyway (CDA, 2021). The lagoon, with a width of approximately 32 km at its widest point connects to the Bay of Bengal through an artificially opened mouth (Sahu et al., 2014; Mohanty et al., 2016; Sahoo et al., 2018). This connection allows the influx of saline water which influences the water characteristics of the lagoon (Barik et al., 2020a, 2020b). In addition to this saline water inputs, the lagoon receives silt-laden freshwater discharges from the tributaries of the Mahanadi River in the north, as well as drainage from the degraded catchment basins along the western and southern boundaries (Nazneen et al., 2022). For the current study, nine stations across the lagoon were selected for sampling purposes (Fig. 1).

2.2. Water and sediment sample collection and analysis

Sampling was conducted at nine pre-selected locations by the Wetland Research and Training Centre (WRTC) of CDA, Odisha, which is the nodal agency for monitoring (i.e., water and sediment) the ecosystem quality of the lagoon. Water and sediment samples were collected in May, July, September, November, and January of 2019, 2020, and 2021. These months corresponds to pre-monsoon (May), monsoon (July and September), and post-monsoon (November and January) seasons, including both pre-COVID and post-COVID scenarios. Sub-surface water samples (30 cm) were collected using a water sampler from all nine stations during the three seasons over the year 2019–20 and 2020–21. Physical parameters of the water, including pH, salinity, and electrical conductivity (EC) were measured in-situ using a water quality probe (SONDE, YSI, Model no. 6600, V2). Dissolved oxygen (DO) was determined following the modified Winkler's method (Carpenter, 1965) and total alkalinity (A_T) was measured via the acid titration method (APHA, 2005). All of these parameters were analysed within 12 h of sampling in the laboratory of WRTC, CDA, Odisha.

Nitric acid-washed 100 mL polyethylene bottles were used for the collection of water samples from the nine stations. From each station three replicates were collected, acidified with 0.5 mL of 14 M Ultrapure nitric acid (HNO_3,), transported to the laboratory in dark boxes, and stored at 4 °C until further analysis. Nine metals (Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, and Pb,) were analysed using ICP-OES (5110, Agilent, Dual-view). Calibration curves were prepared by analysing the certified standards (Mixed Certified Calibration Verification Standard, Agilent) of known concentrations. Metals concentrations in water samples were determined by comparing the wavelengths and intensities with reference to the calibration curves. For precise measurements, the analysis was carried out in triplicate, and the analytical accuracy was checked by analysing the known certified multi-element standard solutions after every twenty samples. The accuracy and precision of the data were found to be within 95 % with a standard deviation of ±5 %. The metal concentrations are reported in mg L^{-1}.

2.3. Sediment sampling and analysis

Bottom sediment samples ($n = 3$ per station) were collected from the Chilika Lagoon using a sediment grab sampler, stored in plastic zip-lock bags, stored in dark boxes and brought to the laboratory. In the laboratory, the samples were oven-dried at 60 °C for 48 h. The dried sediment samples were then digested in a microwave digestion system (Multiwave Pro, Anton Paar) using high purity acids. Each batch (8 samples per batch) included 0.25 mg of sediment samples, a Certified Reference Material (CRM; HISS-1) and blank. The sediment samples

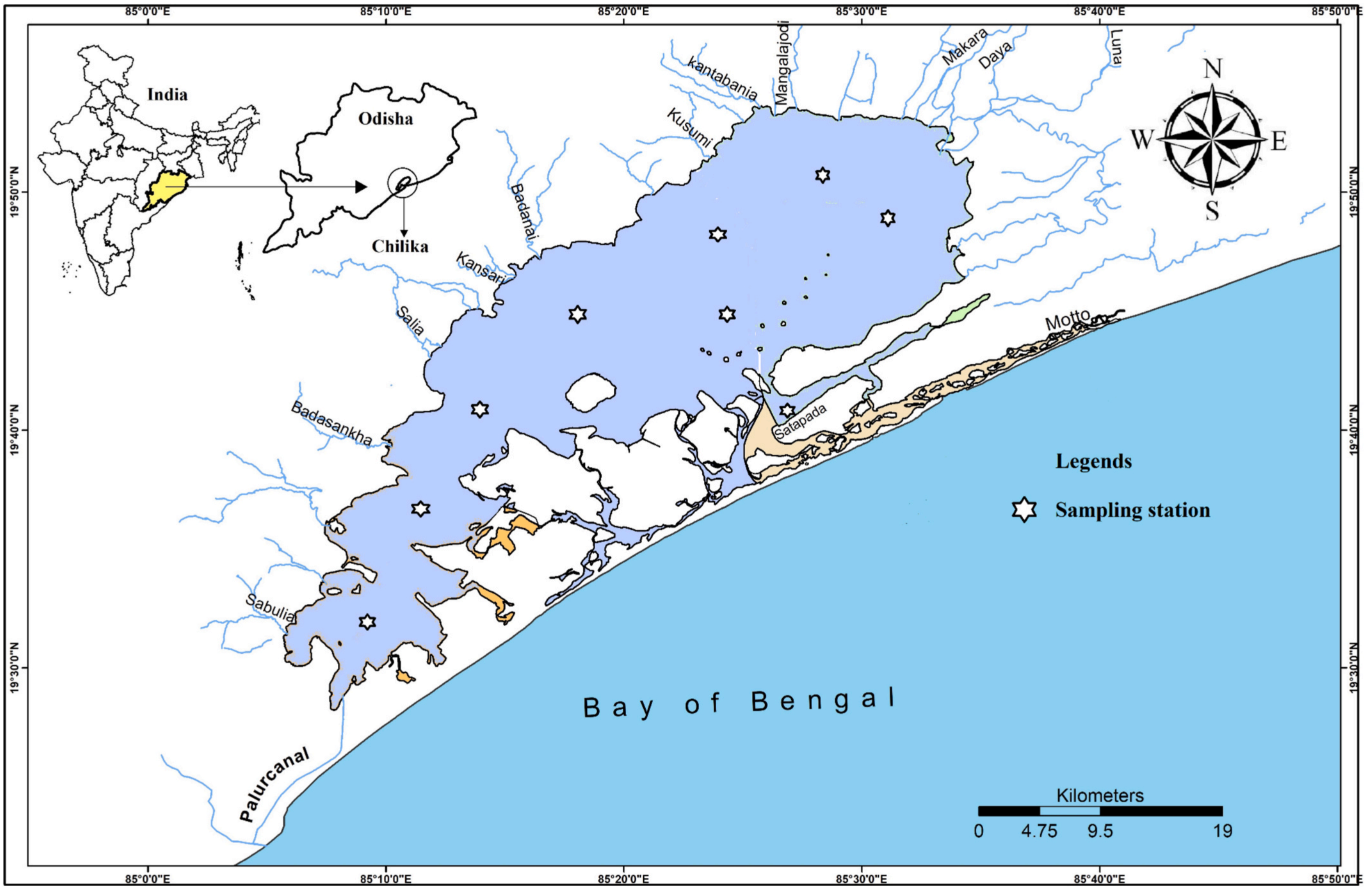

Fig. 1. Map showing the sampling locations of the Chilika Lagoon, Odisha, India.

were treated with 4.5 mL Hydrochloric acid (HCl) and 4.5 mL Nitric acid (HNO_3) of ultra-pure grade before being digested in the digestion system. Microwave assisted digestion was conducted at a power setting of 1300 watts, with a 20-min ramp time and a 60-min hold time. After microwave digestion, the digested solution was transferred from the PTFE (Polytetraflouroethylene) digestion vial to a 50 mL graduated volumetric flask. To ensure complete transfer of the sample, the PTFE vial was rinsed three times with 10 mL of distilled water, and the rinse water was combined with the solution in the volumetric flask. The final volume was then adjusted to 50 mL by adding distilled water directly to the volumetric flask. Following this, the entire 50 mL solution was filtered using a 0.45-μm polycarbonate filter to remove any particulate matter that might have been introduced during the transfer and rinsing process. This has ensured that the final solution used for analysis was free of any solid particles that could interfere with subsequent measurements. The solutions were analysed by the dual-view ICP-OES. Data accuracy was checked with CRM and the recovery was found to be within 95 % with a standard deviation of ±5 %. The metal concentration in the sediments is reported in mg Kg^{-1}.

Enrichment Factor:

The Enrichment Factor (EF) was utilized as an indicator to assess the variation in the influx of anthropogenic metal inputs during the COVID scenarios (Barbieri, 2016). The EF was calculated using Eq. (1)

$$EF = \left(\frac{\text{Metal}}{\text{RE}}\right)\text{sediment} \Big/ \left(\frac{\text{Metal}}{\text{RE}}\right)\text{background} \tag{1}$$

Where RE is the value of metal adopted as Reference Element (RE), which in this study, is iron (Fe). The EF value between 0.5 and 1.5 indicates that the trace metal concentration may come entirely from natural weathering processes (Zhang and Liu, 2002). However, an EF value >1 indicates that a significant portion of the metals may have been delivered from non-crust materials, delivered by point or non-point anthropogenic sources or a combination of both (Zhang and Liu, 2002; Yongming et al., 2006). The sediment quality associated with various EF values are presented in Table 1.

2.4. Statistics

A three-way ANOVA (Analysis of Variance) was conducted to test for significant differences in metal concentrations in the water and sediment samples, using three fixed factors, i) COVID scenarios (pre-and post-COVID), ii) seasons (pre-monsoon, monsoon, and post-monsoon), and iii) variables (water and sediment) of the Chilika Lagoon. For physical parameters of the surface water, a two-way ANOVA analysis was performed using seasons and COVID scenarios as fixed factors. Before performing for ANOVA, all data were checked for homogeneity of variances using Flinger test and for normality of distribution using Shapiro-Wilk test. When ANOVA assumptions were not met, Tukey's multiple comparison test was used for multiple comparisons among the factors and their interactions. The Pearson correlation coefficient was used to examine the relationship between the physical parameters of the water

Table 1
Enrichment Factor (EF) and the associated sediment quality.

Value	Sediment Quality
EF < 2	Deficiency to minimal enrichment
2 < EF <5	Moderate enrichment
5 < EF < 20	Significant enrichment
20 < EF <40	Very high enrichment
EF > 40	Extremely high enrichment

samples and the metal concentrations in surface water and sediment samples. All statistical analyses were conducted with a significance level of $\alpha = 0.05$ using GraphPad PRISM (ver.10.3.2) statistical software. Data is presented as mean ± standard devation (SD) unless mentioned otherwise.

3. Results

3.1. Physico-chemical parameters

In general, the physico-chemical parameters of the surface water of the Chilika Lagoon varied significantly between the seasons than in COVID scenarios, except for alkalinity and Total Dissolved Solids (TDS, Fig. 2). The alkalinity of the surface water was significantly different between seasons (two-way ANOVA; $F_{2,48} = 3.40$, $p = 0.04$) and COVID scenarios ($F_{1,48} = 8.52$, $p = 0.005$) (Fig. 2a). The alkalinity of the water in post-COVID (163.97 ± 32.09 mg L^{-1}) was 1.2-fold higher than pre-COVID levels (Fig. 2a). Seasonally, the alkalinity of the surface water in pre-monsoon (171.83 ± 43.98 mg L^{-1}) and post-monsoon (184 ± 38.19 mg L^{-1}) periods was 1.3-fold and 1.2-fold higher in the post-COVID than in pre-COVID scenario, and no significant differences was observed during the monsoon season between COVID scenarios (Fig. 2a). Similarly, the TDS also varied significantly across seasons ($F_{2,48} = 10.57$, p = 0.04) and COVID scenarios ($F_{2,48} = 11.76$, $p = 0.01$). The highest TDS was observed in pre-monsoon season (15.98 ± 10.90 mg L^{-1}) in pre-COVID scenario, which was 5-fold higher than the lowest TDS observed in post-monsoon season in pre-COVID scenario (Fig. 2b).

Other parameters of water column such as pH ($F_{2,48} = 7.34$, p = 0.01), salinity ($F_{2,48} = 7.42$, $p = 0.001$), DO ($F_{2,48} = 4.64$, p = 0.01) and EC ($F_{2,48} = 4.78$, p = 0.01showed significant seasonal variations (Fig. 2, Supplementary Table, S1). In post-COVID conditions, the highest pH (8.57 ± 0.07) was observed in pre-monsoon season, which was 1-fold higher than the lowest pH (8.02 ± 0.04) observed during the pre-monsoon season of pre-COVID scenario (Fig. 2c). The highest salinity was observed in pre-monsoon season (12.66 ± 10.81) and the lowest in the post-monsoon season (3.97 ± 2.87) of post-COVID scenario (Fig. 2d). Contrastingly, the highest DO (9.46 ± 1.18 ppm) was observed in post-monsoon season in pre-COVID, which was 1.6-fold higher than the lowest DO (5.94 ± 1.65 ppm) observed in pre-monsoon season in post-COVID (Fig. 2e). Similarly, the highest EC observed in pre-monsoon season (23.49 ± 16. 04 mS) of pre-COVID was 3.3-fold higher than the EC (7.05 ± 5.46 mS) in post-monsoon season of pre-COVID (Fig. 2f).

3.2. Metals content in the water and sediment

The metals concentration in both the water and sediment samples varied significantly primarily across COVID scenarios (Figs. 3, 4 and Supplementary Table, S2). Significant variation in the concentration of Al ($F_{1,96} = 148.3$, $p < 0.0001$), Cr ($F_{1,96} = 221.7$, p < 0.0001) and Cu ($F_{1,96} = 125$, p < 0.0001) were observed in water and sediment samples across COVID scenarios (Fig. 3, Supplementary Figure, S3). In the surface water, the mean concentration of Al (0.057 ± 0.05 mg L^{-1}) and Cr (0.001 ± 0.00 mg L^{-1}) decreased by 1-fold and 8.6-fold in post-COVID, respectively, compared to pre-COVID levels (Al 0.058 ± 0.02 mg L^{-1}; Cr 0.009 ± 0.01 mg L^{-1}) (Fig. 3a, c). Contrastingly, the mean concentration of Cu (0.013 ± 0.01 mg L^{-1}) increased by 1.7-fold in post-COVID, compared to pre-COVID levels (0.007 ± 0.008 mg L^{-1}) (Fig. 3e). Similarly, in the sediments, the mean concentration of Al (52,956.88 ±

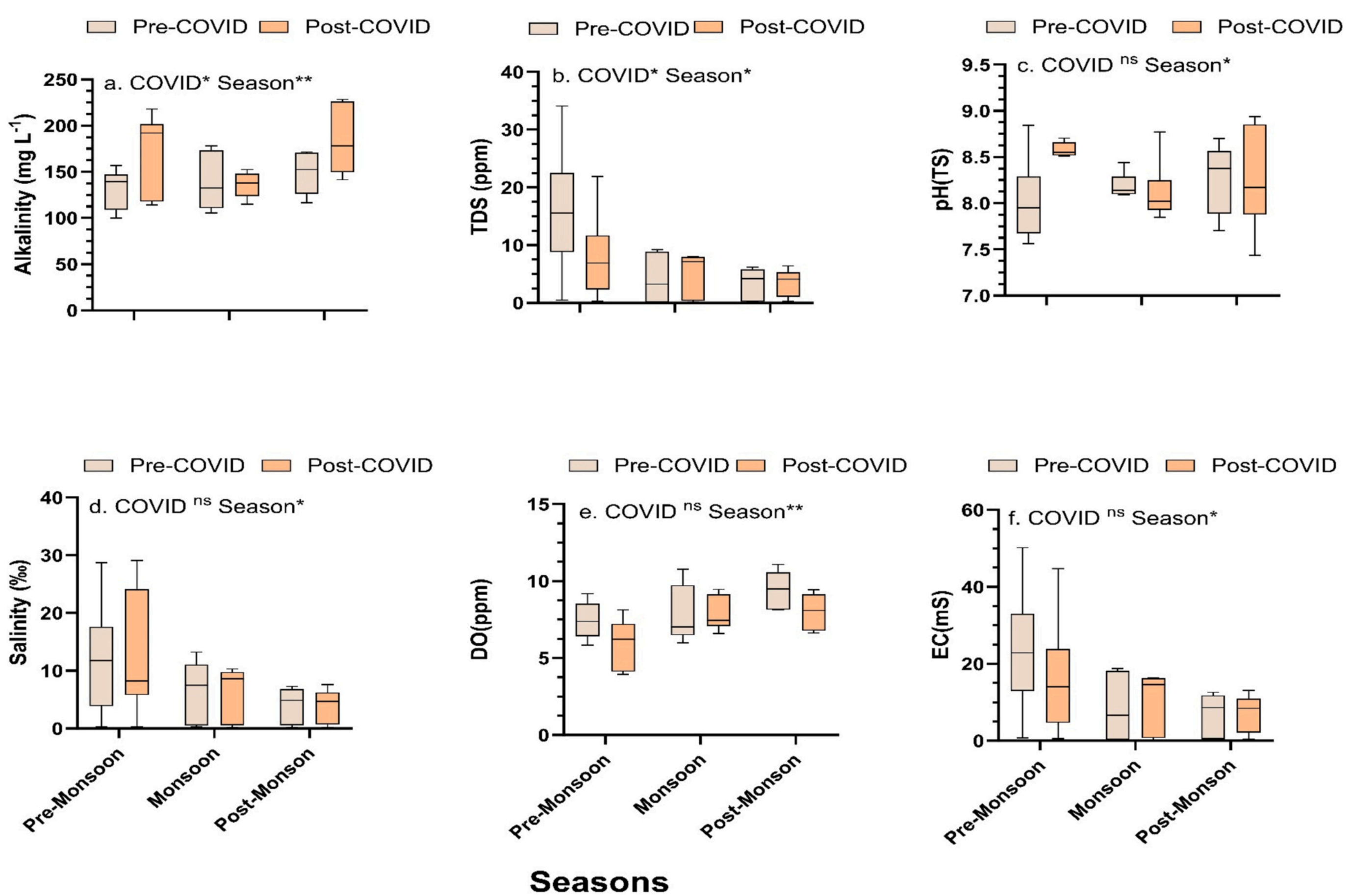

Fig. 2. Physical parameter values of the water column in pre-COVID and post-COVID scenarios from the Chilika Lagoon. Statistical significance was derived from two-way ANOVA analysis using COVID scenarios and seasons as fixed factors. ($p < 0.001$**, $p < 0.05$*, not significant ^{ns}).

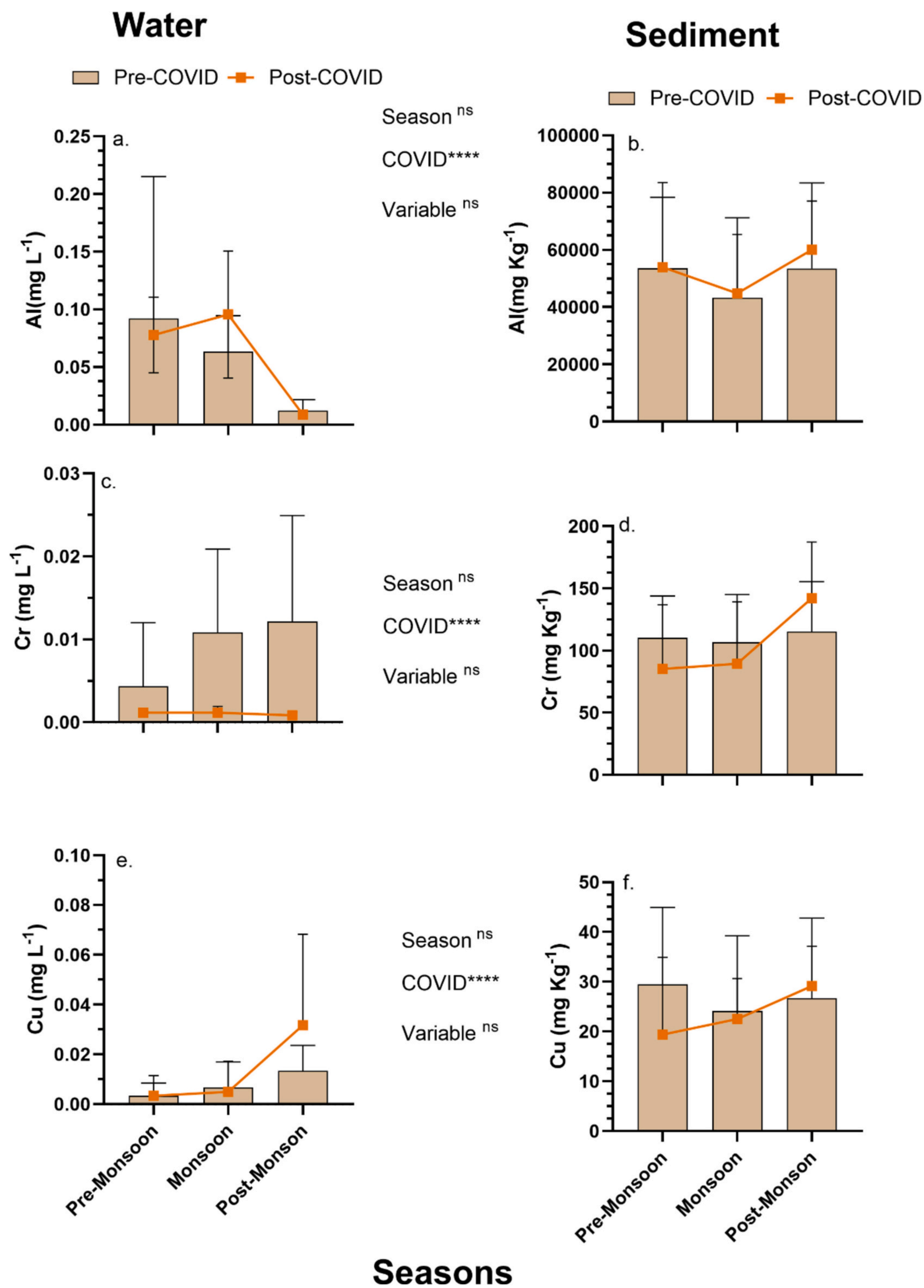

Fig. 3. Metal (Al, Cr, Cu) concentration (mean ± SD) in the surface water (mg L^{-1}) and sediment (mg Kg^{-1}) of the Chilika Lagoon across COVID scenarios. Significant differences were derived from three-way ANOVA analysis using COVID, seasons and variables (sediment and water) as fixed factors. ($p < 0.0001$****, $p < 0.001$***, not significant ns).

22,377 mg Kg^{-1}) increased 1-fold in post-COVID, compared to pre-COVID levels (50,148.92 ± 27,511 mg Kg^{-1}) (Fig. 3b). However, the mean concentration of Cr (105.61 ± 8.83 mg Kg^{-1}) and Cu (23.67 ± 10.53 mg Kg-1) in post-COVID scenario were decreased by 1-fold compared to pre-COVID levels (Cr:110.73 ± 37.41 mg Kg^{-1}; Cu: 26.74 ± 16.04 mg Kg-1) (Fig. 3d & f).

Similarly, significant differences in concentration of Fe ($F_{1,\ 96}$ = 165.6, $p < 0.0001$), Mn ($F_{1,96}$ = 52.88, $p < 0.0001$) and Pb ($F_{1,\ 96}$ = 110, $p < 0.0001$) were observed in water and sediment across COVID scenarios (Fig. 4, Supplementary Table, S2). In surface water, the mean concentration of Fe (0.055 ± 0.01 mg L^{-1}) in post-COVID increased by 1.3-fold compared to pre-COVID (0.042 ± 0.01 mg L^{-1}) scenario (Fig. 4a), however, the mean Mn concentration in surface water remained stable between scenarios (Fig. 4c). The mean Pb concentration

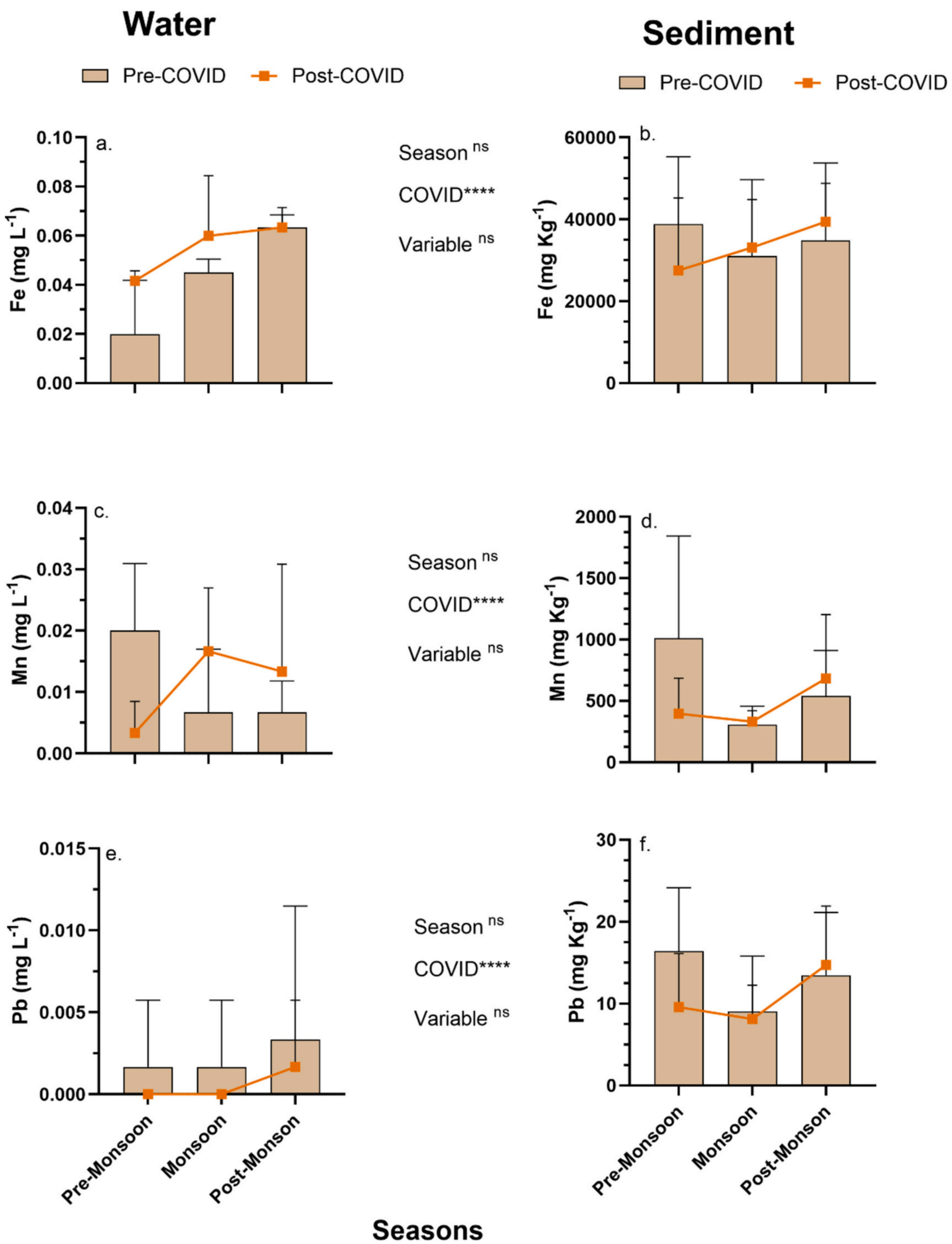

Fig. 4. Metal (Fe, Mn, Pb) concentration (mean ± SD) in the surface water and sediment of the Chilika Lagoon across COVID scenarios. Significant differences were derived from three-way ANOVA analysis using COVID scenarios, seasons and variables (sediment and water) as fixed factors. ($p < 0.0001$****, $p < 0.001$***, not significant ^{ns}).

(0.0005 ± 0.001 mg L^{-1}) in surface water was reduced by 4-fold in post-COVID compared to pre-COVID concentration of Pb (0.0022 ± 0.001 mg L^{-1}) (Fig. 4c). In the sediment, the mean concentration of Fe (33,351.39 ± 1293 mg Kg^{-1}), Mn (469.89 ± 299 mg Kg^{-1}) and Pb (10.78 ± 5.95 mg Kg^{-1}) was decreased by 1-fold, 1.3-fold and 1.2-fold than their respective [Fe (34,884.60 ± 18,044 mg Kg^{-1}), Mn (619.70 ± 450.07 mg Kg^{-1}) and Pb (12.95 ± 7.40 mg Kg^{-1})] concentrations in pre-COVID scenario (Fig. 4b, d, & f).

Out of the nine metals analysed, Cd, Co and Ni in water samples were below detection limits at least in one of the three seasons in either pre- or post-COVID scenarios, with significant differences observed in sediment metal concentrations only across COVID scenarios (Supplementary Figure, S3). In general, post-COVID mean sediment concentrations of Cd (0.50 ± 0.37 mg Kg^{-1}), Co (53.21 ± 5.40 mg Kg^{-1}) and Ni (48.70 ± 18.44 mg Kg^{-1}) were 1-fold lower compared to pre-COVID levels (Cd: 0.56 ± 0.35 mg Kg^{-1}; Co:55.24 ± 51.49 mg Kg^{-1}; and Ni: 50.02 ± 26.16 mg Kg^{-1}) (Supplementary Figure, S3). The EF analysis indicated a cumulative reduction in metals enrichment of 4.2-fold in water and 1-fold in sediment in post-COVID compared to pre-COVID scenarios (Fig. 5)

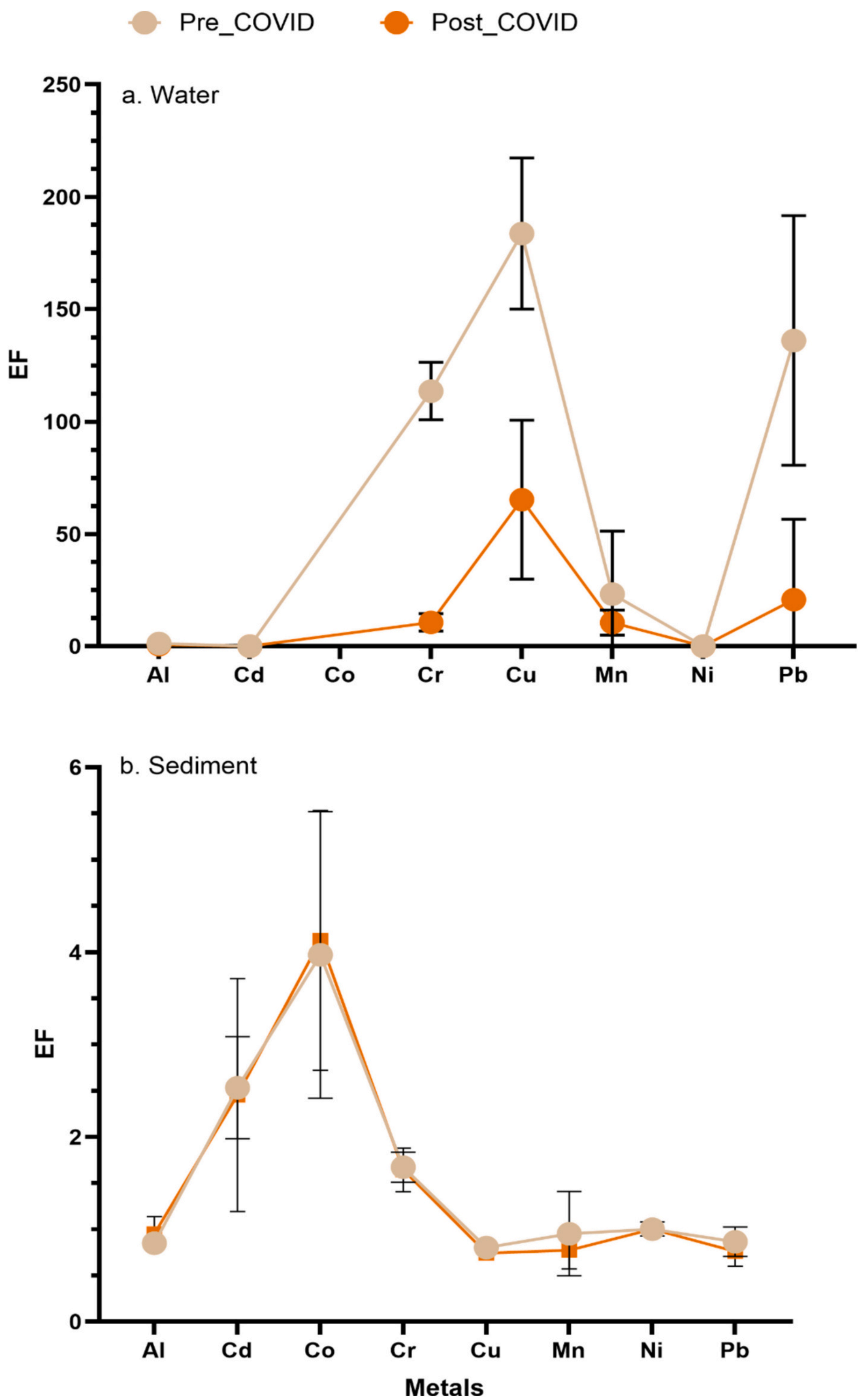

Fig. 5. Enrichment Factor for all metals in a) water and b) sediment across seasons in pre-and post-COVID scenarios. Iron (Fe) was used as a reference element for calculation of EF, as a result is not represented in the graph (please see methods for more details).

3.3. Correlation between physical parameters and metals

Significant correlations were observed between physical parameters and metals concentrations in surface water for five metals including Al, Cr, Cu, Fe, and Mn between the COVID scenarios (Table 2). Between the seasons and COVID scenarios, an increased number of correlations between metal concentration in surface water and physical parameters were observed in post-COVID scenarios (Table 2). Interestingly, an increased number of correlations were observed in post-monsoon season and post-COVID scenario. The concentration of Cr showed a negative correlation with salinity, TDS and EC in both pre-and post-COVID scenarios. Similarly, Cu, and Fe concentrations showed positive correlations with all physical parameters, except DO, whereas Mn displayed negative correlations with all water quality parameters (Table 2. In sediments, all nine metal concentrations (Al, Cd, Co, Cr, Fe, Mn, Ni, Pb) showed significant correlations with selected water quality parameters

Table 2
Correlation between physical parameters and element concentration in the water and sediment samples among seasons and COVID scenarios of the Chilika Lagoon. Pearson correlation co-efficient and statistical significance p values are presented (in bold) which showed a significant positive or negative correlation. The elements with no correlation with any of the physical parameters are excluded. Alkalinity (A_T), Dissolved oxygen (DO), Total dissolved solids (TDS), Electrical conductivity (EC), Salinity (S).

Season	Variable	Element	Pre-COVID						Post-COVID				
			pH	A_T	S	DO	TDS	EC	pH	A_T	S	TDS	EC
Pre-Monsoon	Water	Al	–	–	–	–	–	–	–	–	0.469, **(0.01)**	–	–
		Mn	–	–	–	–	–	–	–	–	0.451, **(0.01)**	–	–
Monsoon		Cr	–	–	–	–	–	–	0.437, **(0.01)**	–	–	–	–
		Cu	–	–	–		0.362, **(0.04)**	0.384, **(0.03)**		–	–	–	–
		Fe	–	–	0.386, **(0.03)**	–	–	–	–	–	–	–	–
Post-Monsoon		Cr	–	–	−0.577, **(0.001)**	–	−0.522, **(0.003)**	−0.604, **(0.005)**	−0.697, **(0.002)**	−0.730, **(0.006)**	−0.769, **(0.001)**	−0.804, **(0.0001)**	−0.795, **(0.002)**
		Cu	–	–	–	–	–	–	0.508, **(0.004)**	–	–	–	–
		Fe	–	–	–	–	–	–	0.555, **(0.001)**	0.663, **(0.009)**	0.800, **(0.001)**	0.836, **(0.0001)**	0.833, **(0.0002)**
		Mn	–	–	–	–	–	–	−0.638, **(0.001)**	−0.657, **(0.001)**	−0.651, **(0.001)**	−0.738, **(0.0004)**	−0.728 **(0.007)**
Pre-Monsoon	Sediment	Al	–	–	−0.782, **(0.056)**	–	–	–	–	−0.842, **(0.035)**	–	–	–
		Cd	–	–	–	–	–	–	–	–	−0.809, **(0.051)**	–	–
		Co	0.828, **(0.042)**	–	–	–	–	–	0.957, **(0.002)**	–	–	–	–
		Cr	–	–	−0.784, **(0.054)**	–	–	–	–	−0.881, **(0.020)**	–	–	–
		Fe	–	–	–	–	–	–	−0.802, **(0.04)**	−0.837, **(0.037)**	–	–	–
		Ni	–	–	−0.781, **(0.056)**	–	–	–	−0.714, **(0.04)**	−0.825, **(0.043)**	–	–	–
		Pb	–	–	–	–	–	–	−0.914, **(0.01)**	−0.800, **(0.045)**	–	–	–
Monsoon		Mn	–	–	–	–	–	–	−0.949, **(0.003)**	–	–	–	–
Post-Monsoon		Mn	–	–	–	–	–	–	–	–	–	−0.793, **(0.040)**	−0.792, **(0.030)**

between seasons and COVID scenarios. Except for the positive correlation between Co and surface water pH in both COVID scenarios, all other metals showed negative correlations with water quality parameters such as salinity, pH, alkalinity, TDS and EC (Table 2).

4. Discussion

Coastal ecosystems receive a large influx of anthropogenic contaminants through riverine input. These contaminants are often reflected in the water, sediment, and associated biodiversity of these ecosystems (Acharya et al., 2023; Barik et al., 2020a, 2020b; Nazneen et al., 2022; Pati et al., 2022). Understanding the correlation between physical parameters of the water column, sediment composition and seasonality is important for assessing the accumulation of these contaminants in the ecosystem and their trophic transfer to the associated biodiversity (Acharya et al., 2023; Barik et al., 2020a, 2020b; Mishra and Farooq, 2022a; Pati et al., 2022). The present study quantified the seasonal variation in metal concentrations (Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, and Pb) in surface water and sediment samples from the Chilika Lagoon. comparing pre-and post-COVID scenarios. The findings indicate that the COVID-19 lockdown had a positive effect and reduced the metal concentrations in both water and sediment samples (Figs. 3, 4 & Supplementary Figure, S3). The COVID induced lockdown was described as a 'blessing in disguise', which curtailed industrial and human activities (Muhammad et al., 2020; Yunus et al., 2020) and resulted in a reduced influx of various metals influx into the waters of the Chilika Lagoon.

The influx of metals into the Chilika Lagoon is also highly influenced by the seasonal freshwater input mostly during the monsoon season, which introduces large quantities of dissolved organic matter that influences the metal content in the water column (Panda et al., 2010; Sahu et al., 2014; Barik et al., 2018). The present study observed that most metals (except for Cd, Co and Ni) exhibits higher concentrations and subsequent enrichment in the pre-COVID scenario, suggesting a reduction in anthropogenic activities during the lockdown period. This decrease in anthropogenic activities also resulted in the reduction of other anthropogenic contaminants such as petroleum hydrocarbons, as has been observed in the Chilika Lagoon (Acharya et al., 2023). Similar reduction in metal concentrations in the surface water were also reported from other coastal areas of India (Chakraborty et al., 2021; Selvam et al., 2020b; Vijay Prakash et al., 2021) and globally (Buzzi et al., 2022; Hartiningsih and Diana, 2024; Yunus et al., 2020).

The Chilika Lagoon is a unique system, due to the influence of high riverine input from the Mahanadi River, which accounts for 61 % of the inflow into the lagoon through its northern sector, along with seawater input from the Bay of Bengal (Mishra and Dwibedy, 2015; Hussain et al., 2020). The Mahanadi River, along with 53 other small tributaries, transports a significant load of contaminants from small scales industries, agricultural and mining into the lagoon (Sundaray et al., 2012; Mohanty and Samanta, 2016; Hussain et al., 2020). As a result, metals such as Al, Cr, Cu, Fe, Pb and Ni were found in higher concentrations in the sediment during the pre-COVID period (Figs. 3 & 4). The effect of COVID lockdown was clearly visible in the surface water metal concentrations of the Chilika Lagoon, suggesting that the COVID lockdown had a more substantial effect on metal concentrations than the natural seasonal variations (Banerjee et al., 2017; Barik et al., 2018; Barik et al., 2020a, 2020b; Sahoo et al., 2018). Similar reductions in metal concentrations in the surface water were observed along the coast of Tamil Nadu during COVID-19 lockdown (Selvam et al., 2020b). Moreover, reductions in metal concentrations have also been reported in riverine sediment and soil samples associated with groundwater in India in post-COVID scenario (Chakraborty et al., 2021; Lotliker et al., 2021; Prasood et al., 2023; Shukla et al., 2021). This study is among the first to provide information on post-COVID sediment metal concentration from Indian coastal ecosystem. The observed post-COVID higher metal concentrations of Fe and Mn in sediment suggest that these essential metals were incorporated into the water column through natural, seasonal and biogeochemical processes which remained unaffected, even during the industrial shutdown (Barik et al., 2018; Nazneen et al., 2019).

Seasonal and sectoral influence is predominant in this lagoon ecosystem, where the northern sectors receive the highest influx of freshwater and the southern sector the lowest, whereas the central sector of the lagoon acts as a transition zone between fresh and saline water (Panigrahi et al., 2007; Rajawat et al., 2007; Sahu et al., 2014; Barik et al., 2018). The timing of onset of monsoon in the state of Odisha in 2019 and 2020 (June 11 and 12, respectively) (IMD, 2019-2020) suggests minimal influence of the onset of monsoon on variability of metal content. Furthermore, the water influx during both monsoon periods exhibited low variability between the years (IMD, 2019-2020), probably diminishing the effect of monsoon on metal concentration. This is particularly due to the dilution effect during the monsoon, where high quantities of freshwater enter into the lagoon and reduces the metal concentrations in water and sediment decrease followed by an increase in the post-monsoon season as the dissolved organic matter settles down and the biogeochemical cycling processes takes over in this lagoon ecosystem (Mishra et al., 2023).

Consequently, there is a significant variation in alkalinity and TDS between COVID scenarios, whereas other water parameters varied primarily only across seasons (Fig. 2). Similar trends in surface water alkalinity and TDS have also been observed at other locations along the Indian coast (Panja et al., 2022; Selvam et al., 2020b). This indicates that these parameters are influenced by industrial and human activities, which were curtailed during COVID lockdown. The observed increase in alkalinity may be a result of increased primary productivity combined with productivity of the marine macrophytes (e.g., seagrass, seaweeds etc.,) under lack of various human induced disturbances such as damage due to boats, fishing activities and release of total petroleum hydrocarbons (TPHC) (Acharya et al., 2022a). With reduced TPHC input, there was minimal microbial degradation of hydrocarbons, which typically produces acidic by-products. As a result, the buffering capacity of the lagoon remained intact, allowing for the maintenance of high alkalinity (Gupta et al., 2008). Furthermore, the lockdown reduced sediment disturbance from boat traffic, preventing the release of hydrocarbons stored in the sediments into the water. This reduced the potential for acidification and helped sustain higher alkalinity levels (Naithani et al., 2007). According to Acharya et al. (2023), the lockdown led to a significant improvement in water quality, including higher alkalinity, as the bicarbonates and carbonates in the water continued to buffer pH effectively in the absence of comparatively higher TPHC levels before COVID-19 (Fengqing et al., 2008). Furthermore, this high productivity can be supported by the decomposition of organic matter and biogeochemical cycling of nutrients in the lagoon (Mishra et al., 2021). Additionally, the natural seasonal input of nutrients and decrease of pollution inputs may also contribute to the high primary productivity, increase in dissolved carbon dioxide consumption and the subsequent increase in pH, resulting in increased alkalinity (Gupta et al., 2008) as observed in this study; post-monsoon>pre-monsoon >monsoon. Similarly, the TDS levels, which decreased 2-fold during the initial stages of the COVID lockdown in pre-monsoon season, normalized once monsoon and its associated river discharges arrived. Despite the influence of COVID lockdown on alkalinity and TDS, these parameters did not significantly affect the metal concentrations in the water and sediment samples of the Chilika Lagoon (Table 2). Though there was a lack of input from anthropogenic activities, the natural biogeochemical process and metal cycling continued during the lockdown period, as a result, other water quality parameters that were not affected by COVID, played a prominent role in regulating the metal concentrations (Nazneen et al., 2022; Panda et al., 2019; Pati et al., 2022). Other than the effect of COVID lockdown and seasons, the lagoon is inhabited by different macrophytes and macroalgae, such as seagrass are dominant in the southern sector, the central sector is dominant by macroalgae, and the northern sector by freshwater macroalgae and saltmarsh plants, which also play an important role in bioaccumulation of these metals, their cycling and release of sediment bound metals (Mohapatra et al., 2022; Nazneen et al., 2022). The role of these macrophytes in sector-wise productivity is crucial in understanding the variation in metal dynamics in the Chilika Lagoon (Amir et al., 2019; Mishra et al., 2023).

5. Conclusion

The COVID-19 pandemic led to global lockdown during which most of the industrial and human-derived activities were restricted. This unique situation provided an opportunity to assess the effects of “no human influence” on various natural ecosystems (including coastal ecosystems), which would otherwise be impossible to replicate. In the present study, a significant reduction in metal concentrations was observed in the water column and sediment samples of the Chilika Lagoon following the COVID lockdown. These findings suggest that the reduction in influx of metals due to halt of industrial and other anthropogenic activities resulted in lowering the metal concentrations in both the surface water and sediment samples, with marked differences between pre-and post-COVID scenarios. However, sediment metal concentrations showed less variation across COVID scenarios compared to surface water, indicating that the sediment metal sink capacity do not significantly affect by short-term halt of anthropogenic activities. The ongoing seasonal metal recycling in the sediment driven by macrophytes and microbes mediated biogeochemical processes remained active during the lockdown. The results of this study provided a valuable baseline for metal concentrations in the surface water and sediment samples of Chilika Lagoon system. This study also suggests that while the COVID induced lockdown reduced the metal concentrations to some extent temporary, natural biogeochemical processes and seasonal variations played a more important role in the metal's dynamics in the lagoon than the short-term effects of human activity cessation.

CRediT authorship contribution statement

Amrit Kumar Mishra: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization. **Anjalis Mishra:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Sandip Kumar Mohakud:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Prasannajit Acharya:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Pradipta Ranjan Muduli:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Syed Hilal Farooq:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.2024.117127.

Data availability

Data will be made available on request.

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