

## Effect of COVID-19 lockdown on metal concentration in the water column of Asia's largest coastal lagoon

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### ABSTRACT:

A complete halt on all anthropogenic activities and human movement due to COVID-19 lockdown has provided a great opportunity to assess the impact of human activities on coastal marine ecosystems. The current study assessed the concentration of the metals in water samples of the largest brackish water lagoon of Asia; the Chilika lagoon in the state of Odisha, India between pre-COVID-19 and post-COVID-19 lockdown scenarios. Monthly water samples (n=30 stations) from 0.3 m depth were collected from three sectors of the lagoon seasonally; pre-monsoon, monsoon, and post-monsoon. In addition to various physical parameters [pH, salinity, alkalinity, (DO) dissolved oxygen, (TDS) total dissolved solids, and (EC) electrical conductivity] the collected water samples were analysed for 18 trace metals (Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, Th, Tl, U, V). Most of the physical parameters showed a significant variation between pre-and post-COVID-19 scenarios, except for pH and DO. The concentration of five metals (Be, Cd, Co, Ni, and Pb) remained below detection limits in all water samples. The impact of COVID-19 lockdown on the concentration of the metal in the water samples was noticed along with the three sectors of the lagoon. However, eight metals (Al, As, Cr, Fe, Mn, Th, U, and V) were significantly different between the COVID-19 scenarios and the remaining five metals were not statistically significant. The mean concentration of Al, As, Fe, Th, and V were higher in the pre-COVID-19 scenarios, whereas only Cr and Mn were higher in the post-COVID-19 scenarios. The mean concentration of U was similar among both COVID-19 scenarios, even though there were seasonal and sectoral differences. The seasonal influence of riverine influx was more evident on metal concentration during the monsoon season, whereas the difference between sectors was more prominent during the post-monsoon season. An increased number of correlations between physical parameters and metal concentration were observed in the post-monsoon season and post-COVID-19 scenario. This study provides evidence that the imposition of COVID-19 lockdown reduced metal influx in the water column and improved the water quality of the Chilika lagoon. Our results can be used as baseline for metal concentration in surface waters of the lagoon.

**Keywords:** Trace metals, COVID-19, Lagoon ecosystem, Anthropogenic pollution, Water quality, India

## INTRODUCTION

The spread of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2; hereafter called COVID-19) had an impact on the entire world human activities, as it spread across the globe (Cascella et al., 2020; WHO, 2021). Consequently, based on the repeated emergence, rapid transmission, and higher causality rate the WHO declared COVID-19 as a pandemic in March 2020. Following the declaration, in India, the COVID-19 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. 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. Various researchers in India used this opportunity to assess the air and water pollution status 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). As major river systems discharge various anthropogenic derived pollutants to the coastal ecosystems of India, the lockdown also led to a reduction in coastal pollution (Mishra et al., 2020; Lotliker et al., 2021; 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 both the east and the west coast of India (Vijay Prakash et al., 2021; Lotliker et al., 2021). However, these studies did not quantify the concentration of various metals in the coastal water column, which also plays an important role in maintaining water quality (Richir and Gobert, 2014). Consequently, the concentration of various trace metals was quantified in the river Ganga in India during this COVID-19 lockdown period and it was observed that due to lack of anthropogenic input there was a reduction in the input of around 50% of the metals in the water column (Shukla et al., 2021).

The coastal areas of India are dynamic ecosystems where there is a confluence of fresh and marine water. Being at the interface of land and marine systems these ecosystems receive river discharges, dredging, waste dumping, industrial effluents, domestic sewage disposal, and various other pollutants (Gopal et al., 2018; Vijay Prakash et al., 2021). This continuous input of anthropogenic pollutants exerts a significant impact on the coastal environments (Häder et al., 2020). As a result, coastal ecosystems act as a sink of contaminants including metals (Lewis and Richard, 2009). These metals play a critical role in marine ecosystem functioning (Avelar et al., 2013; Mishra et al., 2019; Morsy et al., 2020). Among these metals, some are essential micronutrients (Cu, Mn, Zn, etc.) for the primary producers, whereas others act as non-essential and toxic to organisms (As, Cd, Cr, Hg, and Pb) when the concentration of these metals exceed threshold levels (Millero et al., 2009; Stockdale et al., 2016). In recent years, the coastal waters of India are experiencing water quality deterioration as a result of increasing anthropogenic activities and influx of these materials into the coastal waters (Tripathy et al., 2014; Mishra et al., 2015). Therefore, making it essential to monitor trace metals concentrations in the coastal waters.

Chilika lagoon in the state of Odisha, India is one such important coastal ecosystem that harbours a rich diversity of plants and animals and sustains considerable anthropogenic pressure from various fishing and tourism activities (Madhusmita, 2012; Mohanty et al., 2016). Considering its ecological significance, the nodal agency for monitoring of this lagoon, i.e., Chilika Development Authority (CDA) and various other researchers have monitored the water quality of this lagoon (Panda et al., 2010; Ganguly et al., 2015; Barik et al., 2019; Nazneen et

al., 2019; and references therein). Consequently, various other studies have also monitored the metal concentration in the sediment of this lagoon (Banerjee et al., 2017; Barik et al., 2018; Nayak et al., 2004; Nazneen et al., 2019 and references therein) and fishes and crab tissues (Nayak et al., 2015; Parida et al., 2017; Panda et al., 2019). However, there is a significant lack of information on the metal concentrations in the water column of this lagoon, considering the positive impact of both riverine freshwater influx and saline water from the Bay of Bengal (Panda et al., 2015; Sahu et al., 2014).

However, there are few studies on the coastal waters of the Bay of Bengal on water quality and particulate matter (Mishra et al., 2020; Lotliker et al., 2021) which have been conducted during the lockdown period, but there are no such attempted studies to provide an overview of trace metals contamination or reduction during the COVID-19 lockdown. Secondly, the lockdown period due to COVID-19 provided an opportunity to assess this metals influx from riverine input as most of the human activities were suspended during this period. Therefore, the proposed study looks into the concentration of metals in the water samples of the Chilika lagoon, where there is an input of anthropogenic contaminants from various rivulets and agricultural activities.

The proposed study also quantifies the concentration of various metals in the surface water of the Chilika lagoon in three sectors; northern, central, southern, and three seasons; pre-monsoon, monsoon, and post-monsoon and compare the concentration of the metals between pre-COVID-19 (the year 2019-20) and post-COVID-19 (the year 2020-21) conditions. It is hypothesized that due to the implementation of lockdown and shutdown of industrial and human activities there should be a low concentration of metals in the post-COVID-19 scenarios. The study also measures the physical parameters of the lagoon and assesses the correlation between seasons, sectors, and metals concentration.

## METHODS

### *Study site:*

Chilika lagoon is Asia's largest freshwater lagoon spread across 1165 km<sup>2</sup> (CDA, 2021). This lagoon is situated on the east coast of India in the state of Odisha of India (Fig.1). The lagoon consists of various habitats such as seagrasses, salt marshes, mudflats, and island ecosystems that make it one of the biodiverse ecosystems. It supports the livelihood of millions of coastal fishermen population and acts as a feeding and breeding ground for millions of migratory birds that come through the Central Asian Flyway (CDA, 2021). The criss-cross width of the lagoon is around 32 km long and the lagoon is connected with the Bay of Bengal through an artificially opened mouth (Sahu et al., 2014; Mohanty et al., 2016; Sahoo et al., 2018). Through this mouth, there is an input of saline water which influences the water characteristics of the lagoon (Barik et al., 2020). Other than this sea mouth, a few canals such as the Palur canal bring seawater into the southern part of the lagoon (Fig.1). Other than these inputs there are silt-borne freshwater discharges from the rivulets of the Mahanadi river, which drains into the lagoon in the northern part of the lagoon. Similarly, there is drainage from degraded catchment basins from the western and southern boundaries (Nazneen et al., 2019). For the current study the lagoon is divided into three sectors; northern sector (n=8 stations), central sector (n=15 stations), and southern sector (n=7 stations).

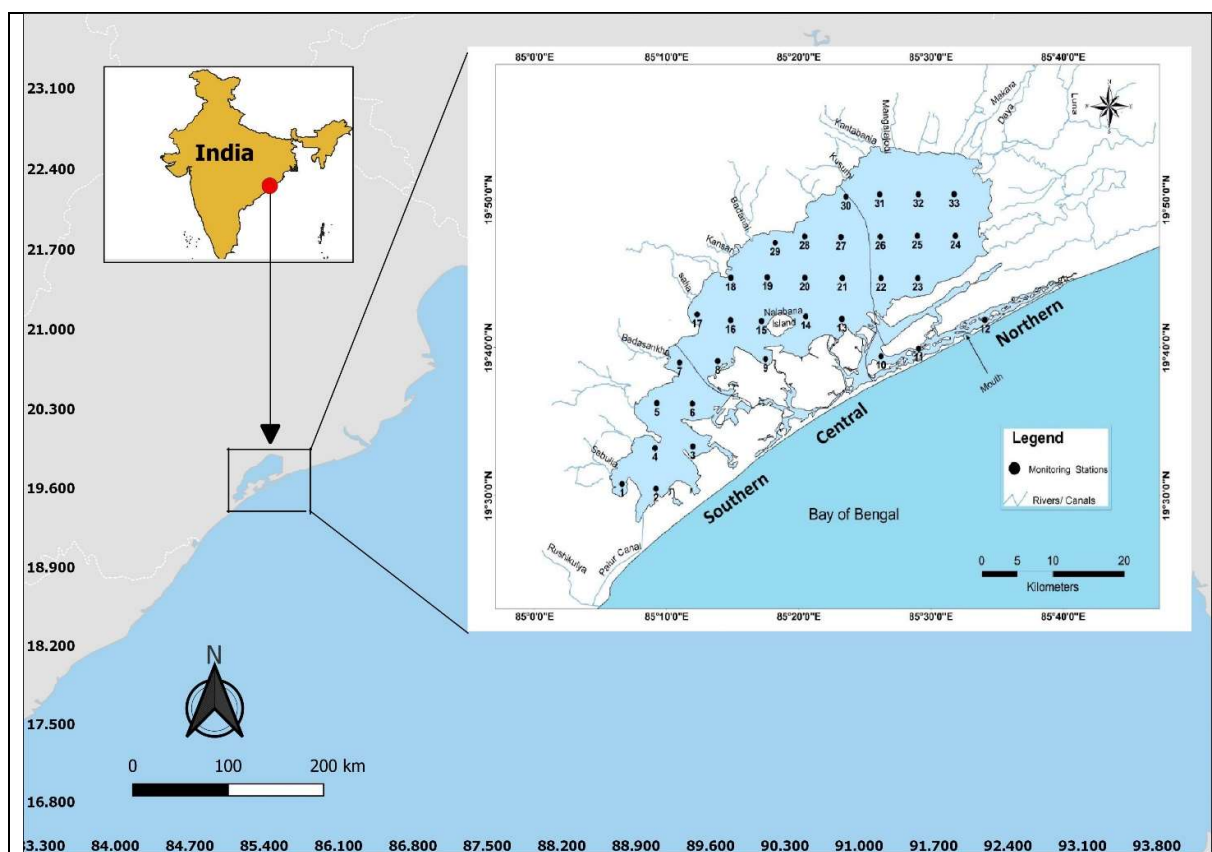


Fig.1. Map showing the sampling locations and three sectors of the Chilika lagoon, Odisha, India.

### *Sample collection and analysis*

Sampling was carried out from 30 prefixed locations by Wetland Research and Training Center (WRTC) of CDA, Odisha, which is the nodal agency for monitoring the water quality of the lagoon. Water samples were collected in May, July, September, November, and January of 2019, 2020, and 2021 and divided into pre-monsoon (May), Monsoon (July +September), and post-monsoon (November +January). Niskin sampler of 5 L was used to collect the sub-surface (0.3 m) water samples from all the 30 stations in the three seasons for the year 2019-20 and 2020-21. Physical parameters of the water samples such as pH, salinity, and electrical conductivity (EC) were measured using a water quality probe (SONDE, YSI, Model no. 6600, V2). Dissolved oxygen (DO) was quantified following the modified Winkler's method (Carpenter, 1996). Total alkalinity ( $A_T$ ) was measured following the acid titration method (APHA, 2005). All of these physical parameters were analyzed for respective parameters within 12 hours 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 30 stations. From each station  $n=3$  replicates were collected, acidified with nitric acid (0.5 mL of  $HNO_3$ , 14M Ultrapure) transported to the laboratory in dark boxes, and were stored at 4°C till further analysis. 18 trace metals (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, Th, Tl, U, and V) were analyzed using ICP-OES (5110, Agilent, Dual view). Calibration curves were prepared by analyzing the standards (Mixed Certified Calibration Verification Standard, Agilent) of known concentrations. The concentration of metals in the

water samples was determined by comparing the wavelength and intensities with reference to the calibration curve. The concentration of metals was expressed in  $\mu\text{g/l}$  or  $\mu\text{g/l}$  (parts per billion).

### *Statistics*

Data are shown as mean  $\pm$  1 standard deviation (SD) of the mean. A three-way ANOVA was used to test for significant differences in metals concentration and between physical parameters in the water samples among COVID-19 scenarios (fixed factor with 2 levels; pre- and post-COVID-19), seasons (fixed factor with 3 levels; pre-monsoon, monsoon, and post-monsoon) and sector (fixed factor with 3 levels; northern, central and southern) of the Chilika lagoon. All data were first checked for homogeneity of variances (Flinger test) and normality of distribution (Shapiro-Wilk's test). When ANOVA assumptions were not verified even after root-squared or  $\text{Log}_{10}$  transformation, the Holm-Sidak test for multiple comparisons among factors and their interactions was used. Pearson correlation coefficient was used to test the correlation between physical parameters of the water samples and the concentration of the metals. All statistical tests were conducted with a significance level of  $\alpha = 0.05$ . All statistical tests were conducted using SIGMAPLOT statistical software (ver.11.05).

## **RESULTS**

### *Physical parameters*

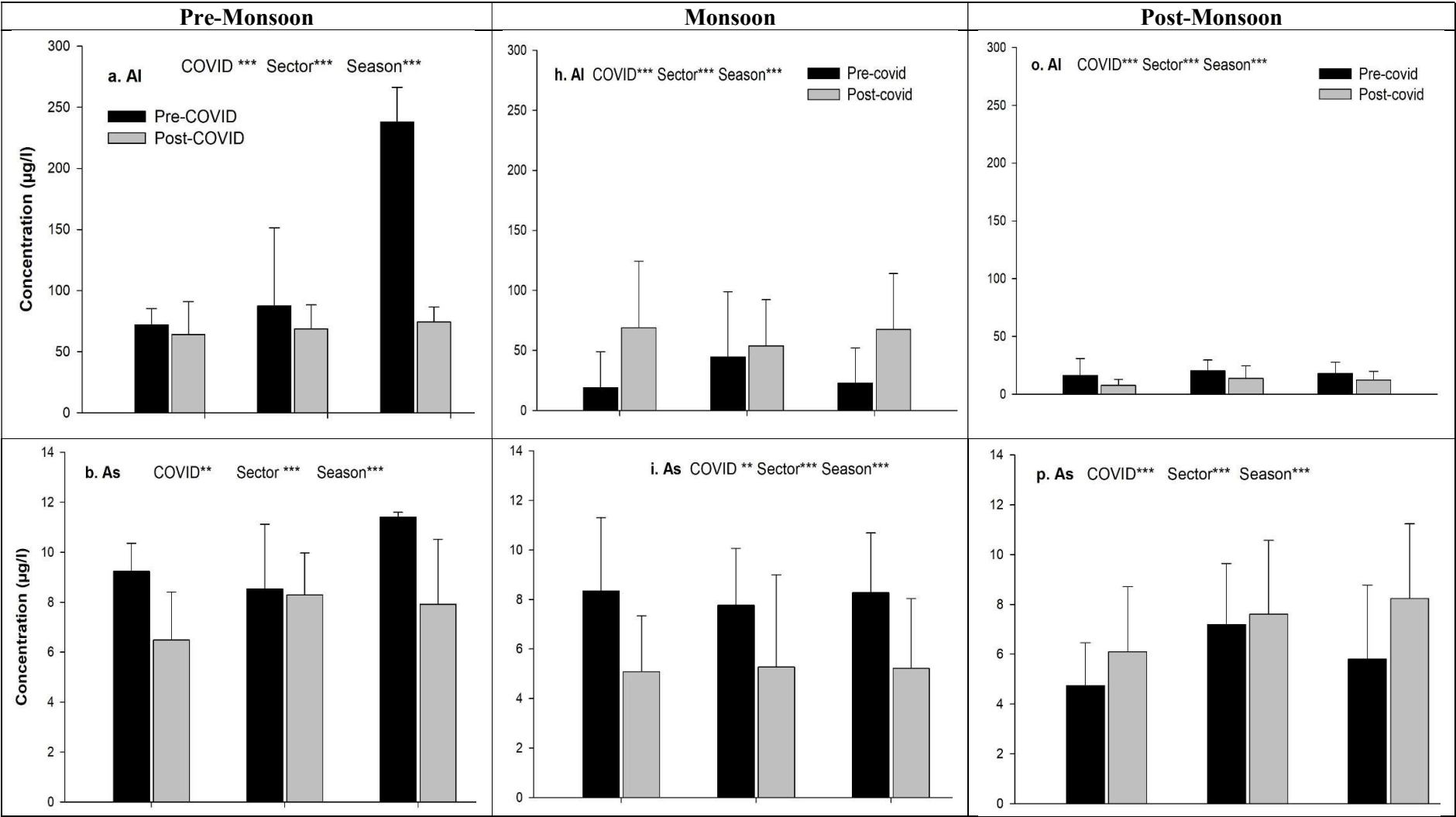
In general, the physical parameters of the Chilika lagoon varied significantly between the three sectors and seasons. The physical parameters were significant and different between the pre- and post-COVID-19 scenarios except for pH and DO (Table 1 and 2). Between the COVID-19 scenarios the average pH, salinity, and DO were similar for the entire lagoon, whereas the TDS ( $144.18 \pm 11 \text{ mg/l}$ ) and EC ( $79.57 \pm 29 \text{ mS/cm}$ ) were 11-fold and 12-fold higher in the post-COVID than the pre-COVID-19 scenarios. In the pre-monsoon season, the TDS and EC of post-COVID scenarios were 3.2-fold and 2.8-fold higher than pre-COVID-19, whereas pH,  $A_T$ , and salinity were 1-fold higher. In the monsoon season, the EC was 41-fold higher in the post-COVID than pre-COVID-19 scenario, whereas pH,  $A_T$ , and salinity were 1-fold lower in the post-COVID-19 scenarios. However, in the post-monsoon season, the EC was 16-fold higher in the post-COVID-19 scenario, whereas pH, salinity, and DO were 1-fold lower than pre-COVID-19 scenario (Table 1). In the pre-COVID-19 scenario and seasons, the southern sector of the lagoon has the highest mean values for most parameters except DO, whereas in the post-COVID-19 scenario the southern sector has higher values for pH,  $A_T$  and salinity and the northern sector for DO, TDS, and EC (Table 1).

### *Metals content in the water*

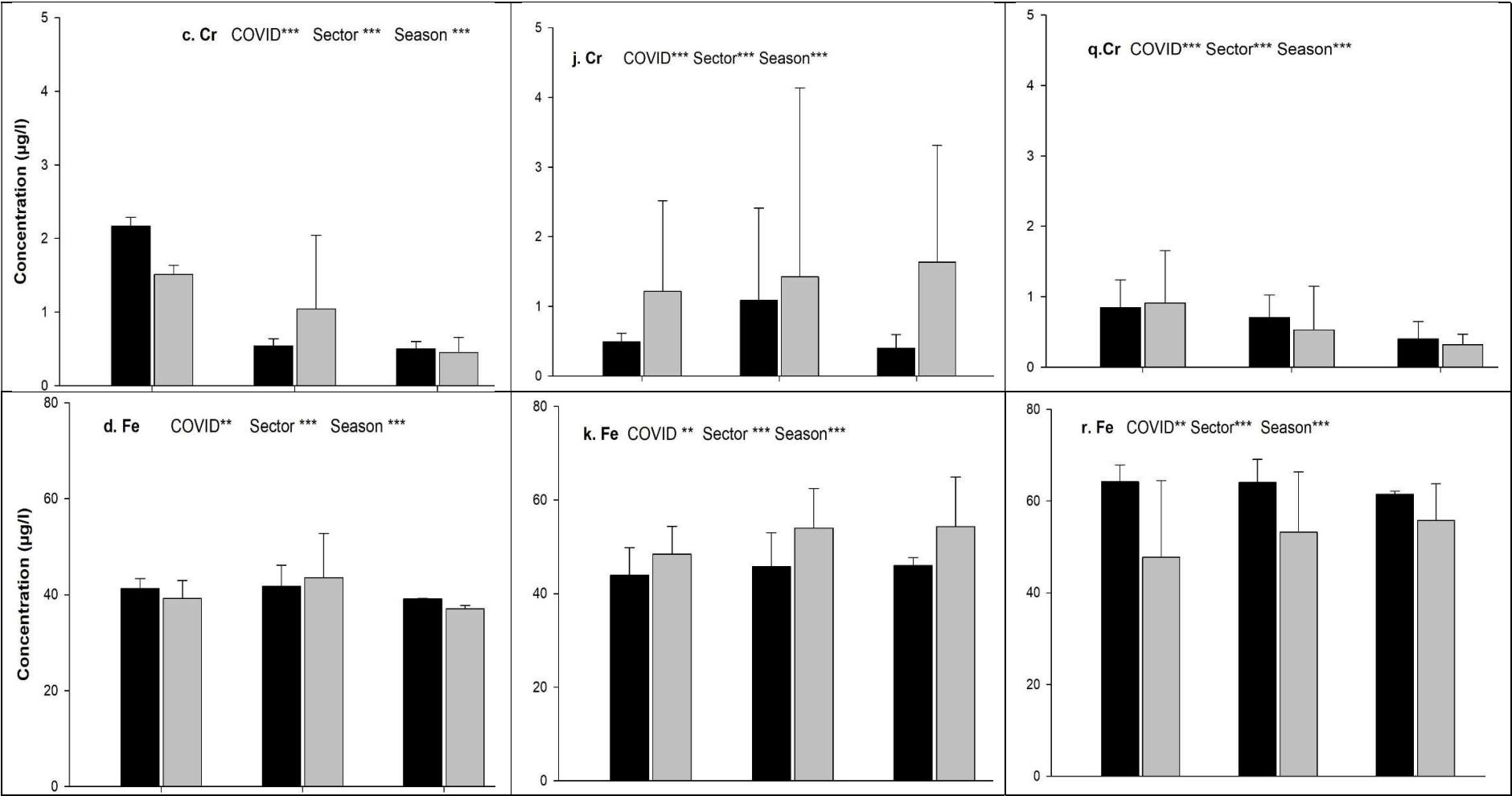
Out of the 18 trace metals analysed in the water samples, the concentration of five metals (Be, Cd, Co, Ni, and Pb) were found to be below the detection limit at the majority of the stations. Out of the remaining 13 trace metals, the concentration was significant and different for 8 metals, except for Ba, Cu, Mo, Sr, and Tl (Fig.2 and 3 and Table 3).

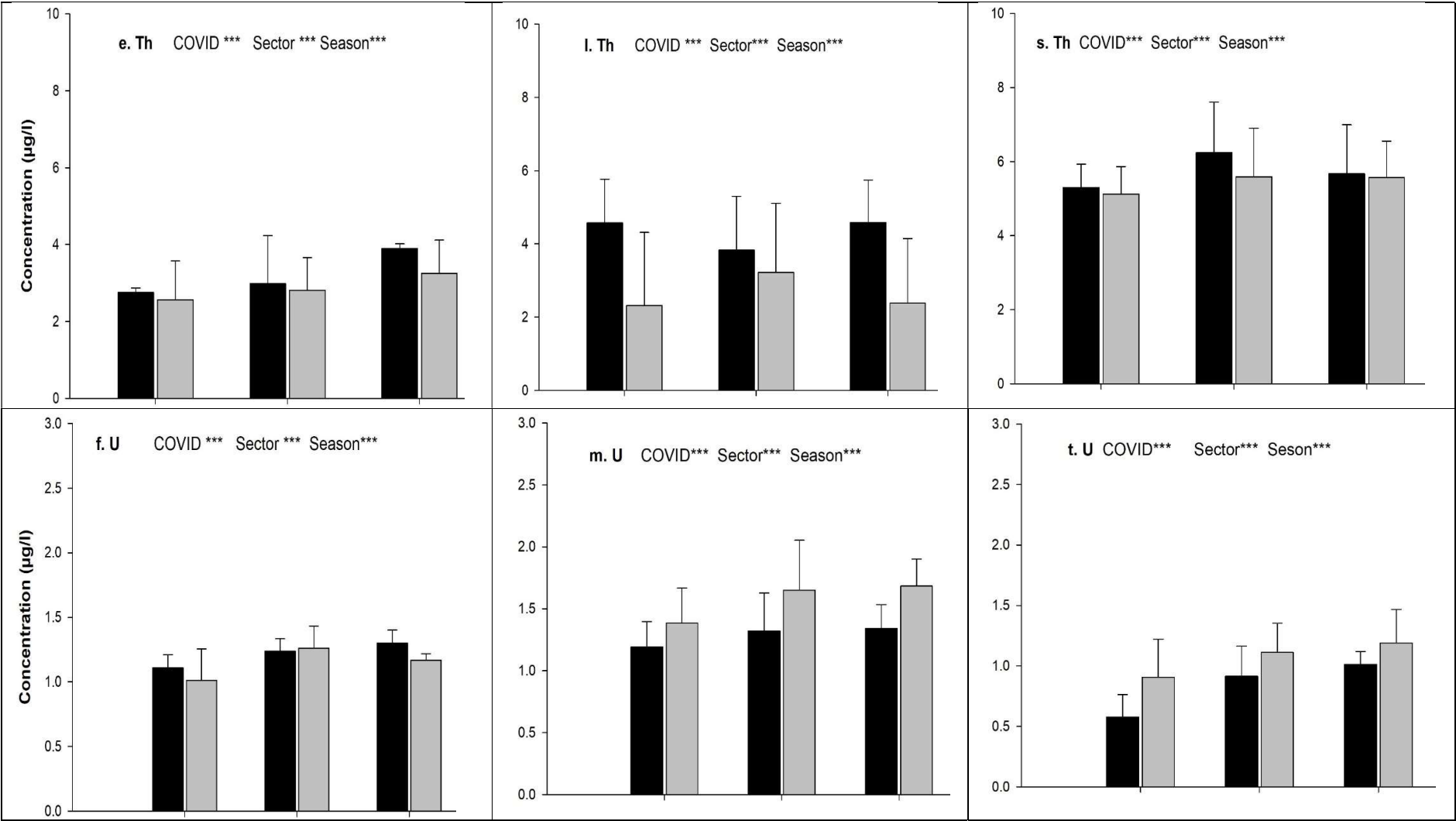
### *Pre-monsoon season*

In the pre-monsoon season, the concentration of metals such as Al, As, Fe, and Th were higher in the pre-COVID-19 scenarios than post-COVID-19, whereas the concentration of Mn was higher in post-COVID-19, and metals like Cr, U, and V were similar between both COVID-19 scenarios (Fig.2 and 3). The mean concentration of Al ( $132.53 \pm 25.63 \mu\text{g/l}$ ), As ( $9.72 \pm 1.24 \mu\text{g/l}$ ), Fe ( $40.67 \pm 2.20 \mu\text{g/l}$ ), and Th ( $3.21 \pm 0.46 \mu\text{g/l}$ ) in the pre-COVID-19 were 2-fold, 1.2-fold, 1-fold and 1-fold higher than the post-COVID-19 scenario respectively (Fig. 4a and b).











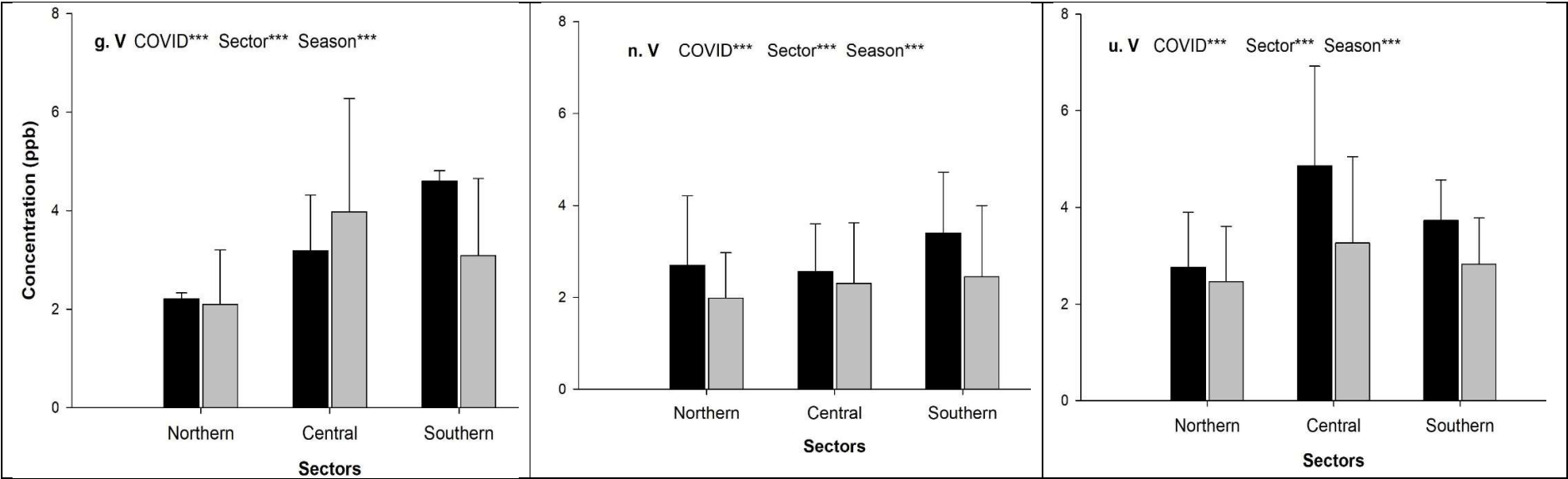


Fig.2. Metal concentration (mean  $\pm$  SD) in the surface water of the Chilika lagoon within three sectors and seasons in pre- and post-COVID scenarios. Common elements with statistical significance between the three factors (COVID, sectors and seasons) derived from three-way ANOVA analysis are presented. Significance level ( $p < 0.001^{***}$ ,  $p < 0.01^{**}$ ,  $p < 0.05^{*}$ ).

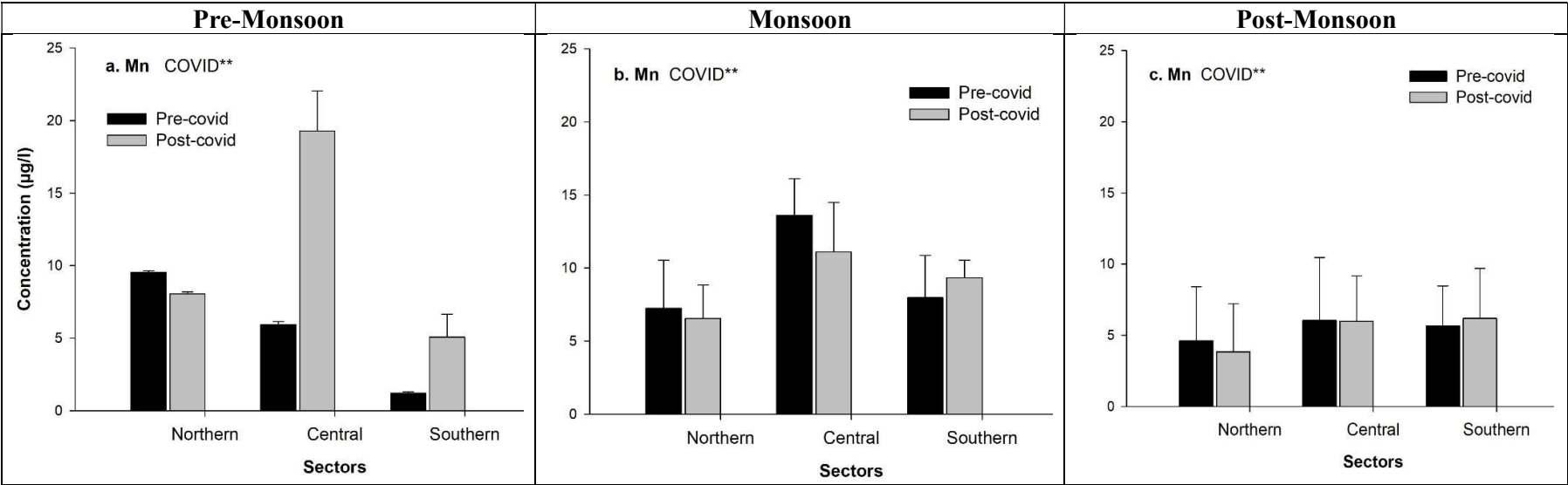


Fig.3. Metal concentration (mean  $\pm$  SD) in the surface water of the Chilika lagoon within three sectors and seasons in pre- and post-COVID scenarios. Common elements with statistical significance between the COVID scenarios and not within seasons or sectors derived from three-way ANOVA analysis are presented. Significance level ( $p < 0.001$ \*\*\*,  $p < 0.01$ \*\*,  $p < 0.05$ \*).

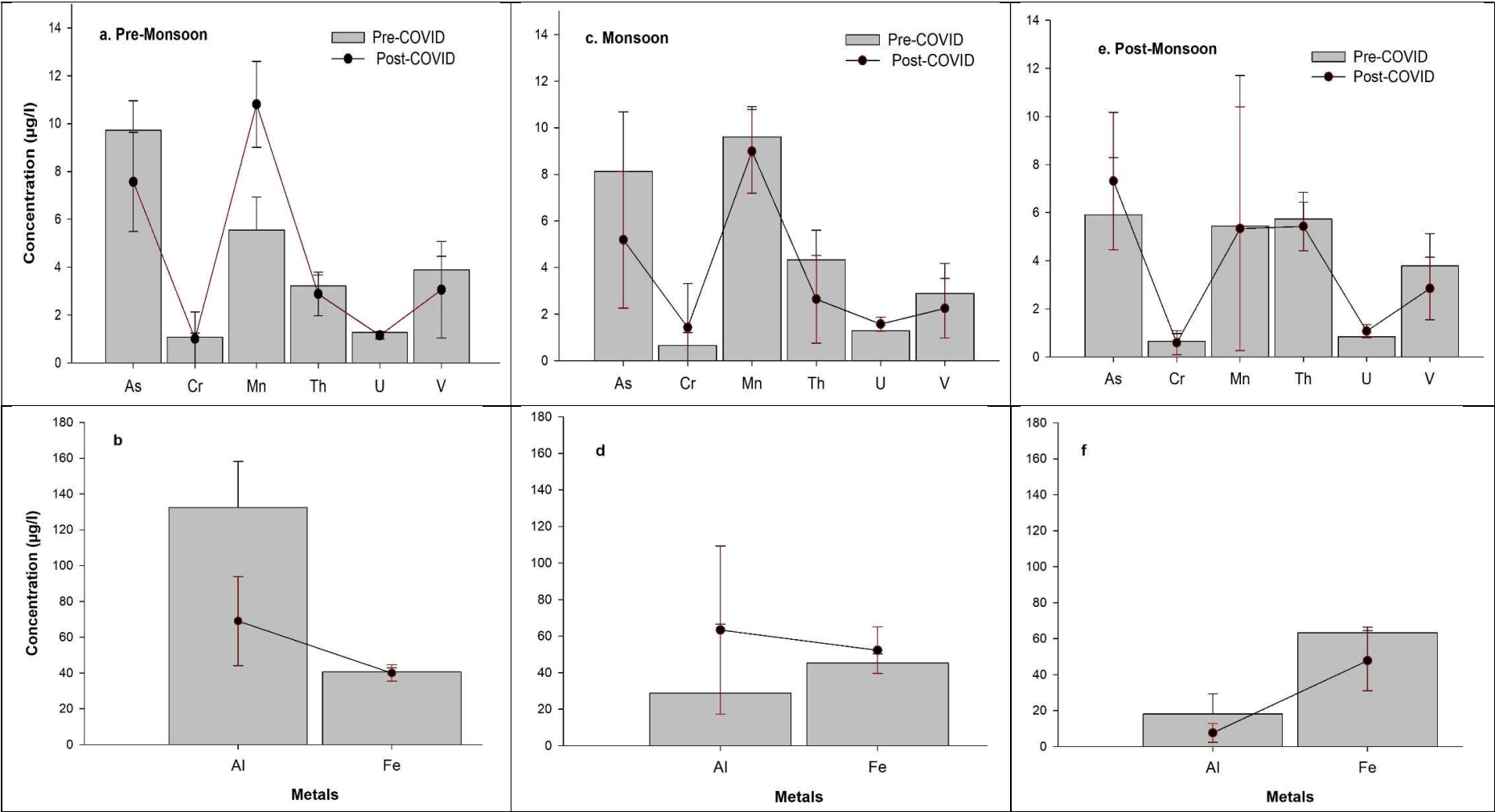


Fig.4 Mean metal concentration ± standard deviation of statistically significant elements (Al, As, Cr, Fe, Mn, Th, U and V) in post-COVID scenarios between sectors and seasons are plotted against pre-COVID scenarios. Elements such as Al and Fe are separated due to their high concentration than other elements for better representation. Pre-monsoon (a and b), monsoon (c and d) and post-monsoon (e and f).

Table 1. Physical parameters of the water samples of the Chilika lagoon. pH (Total Scale units, TS), alkalinity ( $A_T$ , mg/l), Dissolved oxygen (DO, ppm), Total dissolved solids (TDS, mg/l), Electrical conductivity (EC, milli Siemens/cm).

		Pre-COVID			Post-COVID		
		Sectors			Sectors		
Seasons		Northern	Central	Southern	Northern	Central	Southern
Pre-Monsoon	pH (TS)	7.71±0.38	8.11±0.27	8.13± 0.38	8.47±0.57	8.48 ± 0.56	8.78± 0.24
	$A_T$ (mg/l)	109.25± 17.4	128.64 ±18.87	141.71± 16.58	116±21.6	163 ± 30.25	182.85± 22.9
	Salinity	4.76±4.14	16.49 ±5.20	11.85 ± 0.51	4.28±4.01	11.07± 9.54	8.32± 0.97
	DO (ppm)	7.56±1.22	7.38 ±1.28	6.38± 1.67	7.74±1.57	6.64± 1.93	7.60± 1.42
	TDS (mg/l)	6.55±5.58	20.76 ± 6.65	15.78 ± 0.54	123.45±21.5	10.95±6.88	6.98± 0.75
	EC (mS/cm)	9.63±8.20	30.56 ± 9.80	23.20± 0.77	141±39.4	22.35± 14.05	14.24±1.53
Monsoon	pH (TS)	7.82±0.39	8.10±0.17	8.22 ± 0.15	7.81±0.31	7.90±0.27	8.03±0.45
	$A_T$ (mg/l)	1.49±1.55	6.89±2.71	11.47±1.28	0.66±0.78	6.51±3.66	9.37±0.34
	Salinity	123±14.68	133±19.73	156 ± 13.24	110±27.38	130.3±19.5	141.42±9.3
	DO (ppm)	8.51±1.31	7.81±1.40	6.59±0.66	8.11±1.09	8.09±0.77	7.94±1.15
	TDS (mg/l)	0.11±0.04	1.86±2.08	7.69±1.61	137±125.8	120.3±16.6	7.81 ± 0.26
	EC (mS/cm)	0.24±0.10	3.72±4.02	15.67±3.36	434±44.4	361±52.1	15.94±0.54
Post-Monsoon	pH (TS)	8.05±0.31	8.49±0.32	8.37±0.17	7.59±0.20	8.18±0.31	8.36±0.21
	$A_T$ (mg/l)	124±15.31	150±15.56	166 ± 7.07	142±5.87	182±18.42	201±19.64
	Salinity	0.41±0.18	3.99±1.80	6.73±0.46	0.54±0.43	3.80±1.44	6.49±0.70
	DO (ppm)	9.70±0.95	9.24±0.74	8.52±0.48	8.72±1.25	7.82±0.93	7.79±1.11
	TDS (mg/l)	0.35±0.16	3.37±1.41	5.75±0.36	232±104	70.48±138	5.51±0.50
	EC (mS/cm)	0.73±0.35	6.41±3.13	11.77±0.69	162±53	135±265	11.25±1.02

Table 2. Significant difference of various physical parameters of the water samples between pre- and post-COVID scenarios, seasons and within the three sectors of the Chilika lagoon derived from three-way ANOVA analysis at significance level ( $p < 0.05$ ) are presented. Significant  $p$  values are highlighted in bold. Pre-monsoon (Pre-M), Monsoon (M), Post-Monsoon (Post-M), Southern (S), Central (C), Northern (N).

	COVID	Season ( $p$ value)	Within Season ( $p$ values)			Sectors ( $p$ value)	Within sector ( $p$ values)		
Variables	Pre vs Post		Pre-M vs M	Post-M vs M	Pre- vs Post-M		S vs N	C vs N	S vs C
pH	0.314	<0.001	0.001	0.005	0.149	<0.001	<0.001	<0.001	0.068
Alkalinity	<0.001	<0.001	0.056	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Salinity	0.014	<0.001	0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.118
DO	0.613	<0.001	0.021	0.002	<0.001	0.003	<0.001	0.026	0.085
TDS	<0.001	0.256	0.834	0.236	0.112	<0.001	<0.001	<0.007	0.041
EC	0.001	0.023	0.011	0.031	0.683	0.034	0.013	0.482	0.033

Table 3. Significant difference between element concentration in the water samples between pre- and post-COVID scenarios, seasons and within the three sectors of the Chilika lagoon derived from three-way ANOVA analysis at significance level ( $p < 0.05$ ) are presented. Significant  $p$  values are highlighted in bold. Pre-monsoon (Pre-M), Monsoon (M), Post-Monsoon (Post-M), Southern (S), Central (C), Northern (N).

	COVID	Season ( $p$ value)	Within Season ( $p$ values)			Sectors ( $p$ value)	Within sector ( $p$ values)		
Element	Pre vs Post		Pre-M vs M	Post-M vs M	Pre- vs Post-M		S vs N	C vs N	S vs C
Al	<b>0.002</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>
As	<b>0.023</b>	<b>0.003</b>	<b>&lt;0.001</b>	0.023	0.265	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.319
Ba	0.324	<b>&lt;0.001</b>	0.394	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.079
Cr	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.438	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.485
Cu	0.094	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.179	<b>0.019</b>	0.424	0.250	0.265	0.984
Fe	<b>0.038</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.022</b>
Mn	<b>0.015</b>	0.488	0.249	0.393	0.760	0.176	0.065	0.260	0.463
Mo	0.155	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.747	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.864
Sr	0.508	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.973
Th	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.832	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.979
Tl	0.372	<b>&lt;0.001</b>	<b>0.002</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.018</b>	0.060
U	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.002</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.326
V	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>0.003</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	0.843

The mean concentration of Mn ( $10.81 \pm 1.8 \mu\text{g/l}$ ) in the post-COVID-19 scenario was 2-fold higher than pre-COVID-19 (Fig.4). The concentration of Al and As in the pre-monsoon season of pre-COVID-19 was highest among seasons and sectors (Fig.4a and b). In the pre-monsoon season, between sectors and COVID-19 scenarios, the concentration of various metals did not follow a similar pattern of increase or decrease (Table 4). The concentration of Al and Th between sectors followed a similar pattern of increase in both COVID-19 scenarios. Whereas metals like As, U, and V followed a similar pattern in the pre-COVID-19 and a different pattern in the post-COVID-19 scenarios (Table 4).

Table 4. Mean concentration  $\pm$  standard deviation of statistically significant elements in pre- and post-COVID scenarios between sectors and seasons. The pattern of increase or decrease of element concentration is presented. Bold letters indicate the pattern is same in pre- and post-COVID scenarios. Southern (S) Central (C) and Northern (N)

Season	Elements	Pre-COVID	Post-COVID
Pre-Monsoon	Al	<b>S&gt;C&gt;N</b>	<b>S&gt;C&gt;N</b>
	As	<i>S&gt;C&gt;N*</i>	<i>C&gt;S&gt;N*</i>
	Cr	N>S=C	N>C>S#
	Fe	C=N>S#	C>N>S#
	Mn	N>C>S	C>N>S#
	Th	<b>S&gt;C&gt;N</b>	<b>S&gt;C&gt;N</b>
	U	S>C>N	C<S>N*
	V	S>C>N	C<S>N*
Monsoon	Al	C>S>N	N>S>C
	As	S=N>C#	C=S>N
	Cr	C>N>S	S>C>N#
	Fe	<b>C=S&gt;N</b>	<b>C=S&gt;N</b>
	Mn	<b>C&gt;S&gt;N</b>	<b>C&gt;S&gt;N</b>
	Th	S=N>C#	C>S=N
	U	<b>C=S&gt;N</b>	<b>C=S&gt;N</b>
	V	S>N>C	C=S>N#
Post-Monsoon	Al	<b>C&gt;S&gt;N</b>	<b>C&gt;S&gt;N</b>
	As	C>S>N	S>C>N#
	Cr	<b>N&gt;C&gt;S</b>	<b>N&gt;C&gt;S#</b>
	Fe	C=N>S#	S>C>N#
	Mn	C>S>N	S>C>N#
	Th	<b>C&gt;S&gt;N</b>	<b>C&gt;S&gt;N</b>
	U	<b>S&gt;C&gt;N</b>	<b>S&gt;C&gt;N</b>
	V	<b>C&gt;S&gt;N</b>	<b>C&gt;S&gt;N</b>

(\*) indicate the patterns are different between pre- and post-COVID, but similar patterns are observed for different elements.

(#) indicates similar pattern for an element between seasons or COVID scenarios.



### *Monsoon season*

The mean concentration of metals like Al ( $63.31 \pm 46.84 \mu\text{g/l}$ ), Cr ( $1.42 \pm 1.89 \mu\text{g/l}$ ), Fe ( $52.21 \pm 12.71$ ), and U ( $1.57 \pm 0.30 \mu\text{g/l}$ ) were 2-fold, 2.1-fold and 1-fold and 1.2-fold higher in the monsoon season for post-COVID-19 than pre-COVID-19 scenarios respectively (Fig.2, 3 and 4c and d). Whereas the concentration of metals like As ( $8.13 \pm 2.56 \mu\text{g/l}$ ), Mn ( $9.61 \pm 1.3 \mu\text{g/l}$ ), Th ( $4.33 \pm 1.28 \mu\text{g/l}$ ), and V ( $2.89 \pm 1.29 \mu\text{g/l}$ ) was 1.5-fold, 1-fold, 1.6-fold, and 1.2-fold higher in pre-COVID-19 scenarios respectively (Fig.2, 3 and 4). For the monsoon season, the concentration of Cr and U in the post-COVID-19 scenarios were the highest among seasons and sectors (Fig.4c and d). The concentration of metals like Fe, Mn, and U in the monsoon season between COVID-19 scenarios followed a similar pattern of increase, whereas As and Th followed a similar pattern of increase in pre-COVID-19 scenarios, and Cr and V followed a similar pattern in post-COVID-19 scenarios (Table 4).

### *Post-monsoon season*

In the post-monsoon season, the mean concentration of As ( $7.31 \pm 2.60 \mu\text{g/l}$ ) and U ( $1.07 \pm 0.31 \mu\text{g/l}$ ) were 1.2-fold higher in post-COVID-19 than in the pre-COVID-19 scenarios (Fig.2 and 4). However, the concentration of Al ( $18.14 \pm 11.17 \mu\text{g/l}$ ), Cr ( $0.64 \pm 0.32 \mu\text{g/l}$ ), Fe ( $63.25 \pm 3.12 \mu\text{g/l}$ ), Mn ( $5.44 \pm 6.26 \mu\text{g/l}$ ), Th ( $5.78 \pm 1.10 \mu\text{g/l}$ ), and V ( $3.78 \pm 1.34 \mu\text{g/l}$ ) were 1.6-fold, 1.1-fold, 1.2-fold, 1-fold, 1-fold and 1.3-fold higher than post-COVID-19 scenario respectively (Fig.2 and 4e and f). Most of the metals (Al, Cr, Th, U, and V) followed the same pattern on increase between both COVID-19 scenarios, exception was As, Fe, and Mn (Table 4). The highest concentration of As, Fe, and Mn followed a similar pattern of distribution in post-COVID-19 than pre-COVID-19 scenarios (Table 4).

### *Correlation*

The correlation between physical parameters and metals concentration in the water column was significant only for a few metals and parameters for the COVID-19 scenarios (Table 5). In the pre-monsoon season, a higher number of correlations between physical parameters and metals were observed in pre-COVID-19 than post-COVID-19 scenarios (Table 5). In the pre-COVID-19 scenario pH was observed with a negative correlation with Ba, Mo, and U, and in post-COVID-19 with Ba (Table 5). For  $A_T$ , there were positive correlations with Th and V in pre-COVID-19 scenarios and no correlation in the post-COVID-19. Salinity was positively correlated with Mo and U in pre-COVID-19, Al, and Mn in the post-COVID-19. Though there were positive and negative correlations between TDS and EC with Mn and Mo in pre-COVID-19, no such interactions were observed for the post-COVID-19 (Table 5).

For the monsoon season, only U and V were observed with a positive correlation with most physical parameters in pre-and post-COVID-19 scenarios (Table 5). There were no correlations in the pre-COVID-19 scenario with pH, except for U, whereas in post-COVID-19 only Cr was positively correlated with pH. The metals As and Mo were positively correlated with salinity only in the post-COVID-19 scenario, whereas U is positively correlated with salinity in both COVID-19 scenarios. DO was only positively correlated with Tl in the pre-COVID-19, whereas there were no correlations with DO and EC in the post-COVID-19 scenario.  $A_T$  was positively correlated with Th and U in pre-COVID-19 and with only U in post-COVID-19. With TDS, U was positively correlated in pre-COVID-19 and negatively correlated in post-COVID-19 (Table 5).

Table 5. Correlation between physical parameters and element concentration in the water samples among seasons and COVID scenarios of the Chilika lagoon. Pearson correlation co-efficient and *p* values are presented (in bold) which showed a significant positive or negative correlation. Alkalinity (A<sub>T</sub>), Dissolved oxygen (DO), Total dissolved solids (TDS), Electrical conductivity (EC), Salinity (S)

Season	Elements	Pre-COVID						Post-COVID				
		pH	A <sub>T</sub>	S	DO	TDS	EC	pH	A <sub>T</sub>	S	TDS	EC
Pre-Monsoon	Al	-	-	-	-	-	-	-	-	0.469, <b>0.01</b>	-	-
	Ba	-0.622, <b>0.003</b>	-	-	-	-	-	-0.534, <b>0.002</b>	-	-	-	-
	Mn	-	-	-	-	0.801, <b>0.003</b>	-	-	-	0.451, <b>0.01</b>	-	-
	Mo	-0.414, <b>0.02</b>	-	0.432, <b>0.02</b>	-	-0.403, <b>0.03</b>	-0.391, <b>0.003</b>	-	-	-	-	-
	Th	-	0.394, <b>0.03</b>	-	-	-	-	-	-	-	-	-
	U	-0.497, <b>0.006</b>	-	0.444, <b>0.01</b>	-	-	-	-	-	-	-	-
	V	-	0.544, <b>0.002</b>	-	-0.407, <b>0.02</b>	-	-	-	-	-	-	-
Monsoon	As	-	-	-	-	-	-	-	-	0.402, <b>0.02</b>	-	-
	Ba	-	-	-	-	0.426, <b>0.02</b>	0.421, <b>0.01</b>	-	-	-	-	-
	Cr	-	-	-	-	-	-	0.437, <b>0.01</b>	-	-	-	-
	Cu	-	-	-	-	0.362, <b>0.04</b>	0.384, <b>0.03</b>	-	-	-	-	-
	Fe	-	-	0.386, <b>0.03</b>	-	-	-	-	-	-	-	-
	Mo	-	-	-	-	-	-	-	-	0.408, <b>0.002</b>	-	-
	Th	-	0.459, <b>0.01</b>	-	-	-	-	-	-	-	-	-

Post-Monsoon	Tl	-	-	-	0.426, <b>0.01</b>	-	-	-	-	-	0.396, <b>0.03</b>	-
	U	0.496, <b>0.005</b>	0.461, <b>0.001</b>	0.714, <b>0.0009</b>	-	0.551, <b>0.001</b>	0.534, <b>0.002</b>	-	0.404, <b>0.02</b>	0.681, <b>0.005</b>	-0.407, <b>0.02</b>	-
	V	-	-	-	-	-	0.414, <b>0.02</b>	-	0.521, <b>0.02</b>	-	-	-
	Al	-	-	-	-	-	-	-	-	-	-	0.457, <b>0.01</b>
	As	-	-	0.412, <b>0.02</b>	-	-	-	-	-	-	-	-
	Ba	0.451, <b>0.01</b>	0.532, <b>0.002</b>	0.604, <b>0.005</b>	-0.495, <b>0.006</b>	0.669, <b>0.007</b>	0.624, <b>0.003</b>	0.571, <b>0.001</b>	0.794, <b>0.002</b>	0.798, <b>0.002</b>	-0.618, <b>0.003</b>	-
	Cr	-	-	-0.577, <b>0.001</b>	-	-0.480, <b>0.008</b>	-0.503, <b>0.005</b>	-0.697, <b>0.002</b>	-0.730, <b>0.006</b>	-0.769, <b>0.001</b>	0.630, <b>0.002</b>	-
	Cu	-	-	-	-	-	-	0.508, <b>0.004</b>	-	-	-	-
	Fe	-	-	-	-	-	-	0.555, <b>0.001</b>	0.663, <b>0.009</b>	0.800, <b>0.001</b>	-0.726, <b>0.008</b>	-
	Mn	-	-	-	-	-	-	-0.638, <b>0.001</b>	-0.657, <b>0.001</b>	-0.651, <b>0.001</b>	0.525, <b>0.003</b>	-
	Mo		0.595, <b>0.006</b>	0.744, <b>0.003</b>		0.736, <b>0.007</b>	0.732, <b>0.006</b>	-	-	0.402, <b>0.02</b>	-	-
	Th	-	-	-	-	-	-	-0.525, <b>0.003</b>	-0.594, <b>0.006</b>	-0.616, <b>0.003</b>	0.511, <b>0.004</b>	-
	Tl	-	-	-	-	-	-	-	-0.491, <b>0.006</b>	-0.381, <b>0.04</b>	0.489, <b>0.006</b>	-
	U	0.507, <b>0.005</b>	0.645, <b>0.001</b>	0.825, <b>0.003</b>	-0.533, <b>0.001</b>	0.811, <b>0.009</b>	0.828, <b>0.002</b>	-0.458, <b>0.01</b>	-0.398, <b>0.03</b>	-0.433, <b>0.01</b>	-	-
	V			0.512, <b>0.02</b>			0.375, <b>0.04</b>	0.522, <b>0.003</b>		0.434, <b>0.01</b>	-0.555, <b>0.001</b>	

Most of the metals of post-COVID-19 were correlated with physical parameters in the post-monsoon season (Table 5). However, an increased number of correlations between metals and physical parameters were observed in post-COVID-19 than in the pre-COVID-19 scenarios. The metals like Ba and U were positively correlated with physical parameters except DO in the pre-COVID-19 scenario. Consequently, Ba was positively correlated with pH,  $A_T$ , salinity and negatively correlated with TDS. Whereas U was negatively correlated with pH,  $A_T$  and salinity in post-COVID-19. Similarly, Mn was negatively correlated with pH,  $A_T$  and salinity and positively correlated with TDS. On the other hand, Fe was positively correlated with pH,  $A_T$  and salinity and negatively correlated with TDS in the post-COVID-19 scenarios (Table 5)

## DISCUSSION

Coastal ecosystems receive a large influx of anthropogenic contaminants through riverine input and these contaminants are reflected in the water, sediment, and associated biodiversity of these ecosystems (Nazneen et al., 2019; Vijay Prakash et al., 2021; Lotliker et al., 2021). Our results suggest a similar phenomenon, where the COVID-19 induced lockdown has halted various industries and human activities and resulted in the reduction of various metals in the water samples of the Chilika lagoon. The Chilika lagoon has a high influence of the seasonal influx of freshwater during the monsoon season, which also brings a large quantity of dissolved organic materials, which can also influence the metal content in the water column (Panda et al., 2010; Sahu et al., 2014; Barik et al., 2018). This seasonal influx of materials and mixing with saline water also influences the physical parameters of the lagoon between the three sectors, which are evident in the results irrespective of the COVID-19 scenarios.

The lockdown induced due to COVID-19 was a blessing in disguise, where human-derived impacts were reduced through the shutdown of industrial activities (Muhammad et al., 2020). One of the major rivers that supply water to the Chilika lagoon is the river Mahanadi (61% inflow), which passes through Indian states of Chhattisgarh and Odisha (Mishra and Dwibedy, 2015; Hussain et al., 2020). In general, this river along with 53 more small river tributaries brings the majority of the influx of various contaminants from the small scales industries, agricultural and mining fields into the Chilika lagoon ecosystem (Sundaray et al., 2012; Mohanty and Samanta, 2016; Hussain et al., 2020). As a result, most of the metals like Al, As, Fe, Th, U, and V were higher in the pre-COVID-19 scenarios (Fig.4). Even though the metals like Ba, Mo, Sr, and Tl that were not statistically significant were also higher in pre-COVID-19 scenarios along with metals Be, Cd, and Ni which were observed in below detection limit in more than one sector (See Supplementary Table 1 and Fig.1). However, certain metals like Cr, Cu, Mn, and Pb were only 1-fold higher in the post-COVID-19 scenario than the pre-COVID-19, which suggests that these metals were incorporated into the water column through the natural, seasonal and biogeochemical processes of the system which remained the same, even during shutdown of industrial inputs (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 permeable sector between fresh and saline water (Panigrahi et al., 2007; Rajawat et al., 2007; Sahu et al., 2014; Barik et al., 2018). The Indian monsoon arrived in the state of Odisha on June 11 and 12 for the years 2019 and 2020 respectively (IMD, 2019, 2020) suggesting that the influence of the onset of monsoon season on the variation of metal content was minimum. Further, the water influx during both monsoon periods was not different and had very low variability between both years (IMD, 2020), probably diminishing the effect of monsoon on metal concentration. However, it has been

observed that most of the metal concentrations remains higher either in pre-monsoon or post-monsoon seasons, except for few metals like Mn and U in pre-COVID-19 scenarios and Cr, Fe, and U in post-COVID-19 scenarios (Fig.4). Mostly in the monsoon season, the standard deviation of metals concentration was significantly higher compared to the pre-monsoon and post-monsoon seasons. This was particularly due to the dilution effect as the freshwater in high quantities enters into the lagoon during the monsoon period. Secondly, higher standard deviation between the sampling stations of individual sector reflects the internal dynamics of the lagoon, i.e., distance from the landward or seaward influence, local macrophytes, and fishing activities (Amir et al., 2019; Nazneen et al., 2019a).

Consequently, there is a significant variation in salinity,  $A_T$ , TDS, and EC along with the three sectors of the lagoon, which was also evident in our results (Table 1 and 2). Even though the variation in pH and DO were not statistically different between COVID-19 scenarios, there were significant variations between seasons and sectors. The positive correlation between these physical parameters and metals indicates the effect of change in physical parameters in controlling the metal concentration (Nazneen et al., 2019). These results also indicate that, the seasonal influence was more relevant in the post-monsoon seasons in both COVID-19 scenarios, with an increasingly higher number of correlations of physical parameters with metal concentrations (Table 5). The high values of TDS in the water samples of the lagoon in the post-COVID-19 scenario could be the reason for the high concentration of Cr and Mn. Consequently, these two metals also had a positive correlation with TDS in the post-COVID-19 scenarios (Table 5).

Other than the seasons and sectoral differences during COVID-19 scenarios, the three sectors of the lagoon were dominant 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 and metal cycling (Sanz-Lázaro et al., 2012; Bonanno et al., 2017). The role of these macrophytes in sector-wise productivity that leads to variation in metal accumulation, cycling, and release of sediment-bound metals has also been observed in the Chilika lagoon (Amir et al., 2019).

## Conclusion

COVID-19 is declared as a pandemic across the globe during which most of the industrial and human-derived activities were restricted under the lockdown period. This provided an opportunity to assess the effects of this lockdown on various natural ecosystems, which otherwise would have been impossible to replicate. In the present study, the metal concentration in the water column of the Chilika lagoon in pre-and post-COVID-19 scenarios were compared. Lower concentrations of various metals have been observed in the post-COVID-19 scenarios than in pre-COVID-19 conditions. This led to conclude that halt of industrial and mining activities in the catchment area has resulted in lowering the concentration of these metals in the lagoon ecosystem. Consequently, certain metals like Cr and Mn concentration have shown 1-fold higher concentrations in the post-COVID-19 scenario, suggesting the complex internal dynamics of the lagoon, which is mainly driven by salinity and macrophytes. The results of this study can be used as a baseline for metal concentrations in the surface water of this lagoon system. This study also suggests that, the lockdown induced due to COVID-19 reduced the metal concentrations to some extent, but the natural biogeochemical process and seasonal influence of monsoon on the lagoon are more evident in the variation of metals in the three sectors than COVID-19 scenarios.

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