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IS COVID-19 ONLY BUT A SHORT-TERM RESPITE?A CASE STUDY OF URBAN AIR QUALITY IN KOLKATA, A MEGA-CITY IN INDIA

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ABSTRACT

In this study, we take Kolkata, a mega-city in India, as case example to assess (i) if COVID-19 Lockdown (LD) helped 'healing' urban air pollution, and (ii) if the trend continued through the Un-lockdown as well (UNLD) when restrictions were lifted. Our results indicated significant reductions in $PM_{2.5}$ (significant at $p<0.01$, 56% reduction in 2020 as compared to 2019), PM_{10} ($p<0.01$; 65% reduction); NO_2 ($p<0.05$; 40% reduction); and CO ($p<0.05$; 28% reduction) through LDs. Within 2020, highest reductions since pre-Lockdown was observed for the PMs, CO, and NO_2, during LD 2-4. However, average PMs, CO and SO_2levels began soaring as restrictions were lifted. Average SO_2 ($p<0.05$) and O_3 ($p<0.01$) levels remained higher in 2020 than 2019. Computation of Enrichment Factor (EF) indicated that particulate matter (PM) levels did not comply with the World Health Organization (WHO) benchmarks. Correlation analyses revealed significant differences in patterns of interactions between air pollutants in LD as against UNLD. In the concluding section we reflect of state government's lockdown policies to probe into the observed patterns in air quality.

KEY WORDS : COVID-19 lockdown, Urban air quality, Particulate matter ($PM_{2.5}$, PM_{10}), Enrichment Factor (EF), VOC-NOx-O_3 transformation pathways

INTRODUCTION

An emerging body of literature suggests that the COVID-19 'Lockdown' events have opened up self-regenerative opportunities for Mother Nature (Cheval *et al.*, 2020; Paital, 2020). Rodriguez-Urrego and Rodriguez-Urrego (2020) observed 'ameliorative' impacts of Lockdown in 50 most polluted global capital cities.Environmental improvements have been apparent in much of Southeast Asia (Kanniah *et al*., 2020), including Wuhan, which is deemed as the epicenter of COVID-19 outbreak (Lau *et al.*, 2020). India implemented the Lockdown (LD) on March 25th continuing up to May 31st (Paital *et al*., 2020), followed bya sequence of 'Un-lockdowns' marking slow resumption ofhuman mobility and economic activities. A wealth of literature report on environmental impacts Lockdown in India (Arora *et al*., 2020) including reduction of water (Mandal and Pal, 2020) and noise pollution (Mandal and Pal, 2020); improvement in wildlife habitats (Wild Life institute of India, 2020), decline in GHG emissions (Quere *et al*., 2020) etc. Sharma *et al*. (2020) reported significant improvements in air qualityfrom several parts of India. Gautam (2020) used NASA database to demonstrate 50% reduction in air pollution levels in different parts of India. Paital *et al*. (2020) used the same database to indicate reduction in nitrogen dioxide (NO_2) and carbon dioxide (CO_2) levels. Ghosh *et al*. (2020) observed significant improvements in air quality in several Indian mega-cities.

However, most COVID-19 urban air quality studies, with the exception of Bera *et al*. (2020) and Ghosh *et al.* (2020), yet only but focused on the LD periods alone, without assessing the impacts of the UNLDs (Mahato and Ghosh, 2020; Singh and

Chauhan, 2020). However, Anjum (2020), and Zowalaty *et al*. (2020) have pointed out that as soon as the restrictions on economic activities/human mobility are lifted (e.g. initiation of Un-lockdown) and large-scale industrial and traffic operations resume on normal pace, urban/peri-urban air quality could reverse back to 'original' levels again to threaten environmental sustainability and public health. In anticipation of such 'turnaround' in post-COVID times, we undertook this study in Kolkata, a mega-city in India to deal with a growing debate among the residents, scientific community, and regulatory authorities: *Have We Already Forfeited the Environmental Gains Realized Through the COVD-19 Lockdown?* We assess temporal changes in six criteria air quality pollutants [particulate matter ($PM_{2.5}$ and PM_{10}); nitrogen dioxide (NO_2); sulfur dioxide (SO_2); carbon monoxide (CO); and ozone (O_3), obtained from government database] through 4 phases of Lockdown (LD) and 3 phases of Un-lockdown (UNLD). To that end, we structure the narrative around four interconnected questions that might guide future research and development (R & D) initiatives, and air quality management decision-making in days ahead:

(i) How did urban air quality in Kolkata fare during the Lockdown phases in 2020 against the corresponding periods in 2019?
(ii) How did air quality change since the pre-Lockdown times in 2020?
(iii) Did the ambient pollutant levels comply with regulatory standards (Indian and Global - World Health Organization) during the Lockdown periods?
(iv) Was there any difference in the interaction patterns of the pollutants during the Lockdown vis-à-vis Un-lockdown in 2020?

In the concluding section we review the state government's Lockdown/Un-lockdown strategies to reflect on potential concerns.

MATERIALS AND METOHDS

Data Acquisition

Mahato *et al.* (2020) presented detailed description of the NAMP. Briefly, it is a nation-wide campaign launched by India's Central Pollution Control Board (CPCB) to monitor primary air pollutants (SO_2, NO_2, PM_{10} and $PM_{2.5}$) levels in urban and semi-urban areas (CPCB, 2010). We obtained real-time air quality monitoring information for six criteria air quality pollutants namely, $PM_{2.5}$ and PM_{10}, NO_2, SO_2, CO, and $O_3$for the Rabindra Bharati University monitoring station (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data). This station was chosen,for being a continuous air quality monitoring station (CAAQMS) maintained by the West Bengal Pollution Control Board (WBPCB), withrelatively 'more' complete real-time air quality informationfor both 2020 and 2019 for the LD and UNLD periods, as compared to other CAAQMSs in Kolkata. Information was obtained for 24-hour period (9:00 am-9:00 am) on daily basis for each pollutant species forseven time periods:

1. March 5 – 24 : Pre-Lockdown *(Pre-LD)*
2. March 25 – April 14 : Lockdown 1 *(LD 1)*
3. April 14 – May 3 : Lockdown 2 *(LD 2)*
4. May 4 – 17 : Lockdown 3 *(LD 3)*
5. May 17 – 31 : Lockdown 4 *(LD 4)*
6. June 1 – June 30 : Un-lockdown 1 *(UNLD 1)*
7. July 1 – 31 : Un-lockdown 2 *(UNLD 2)*
8. August 1 – 31 : Un-lockdown 3 *(UNLD 3)*

Data Analyses

We conducted Welch's t-testto assess potential differences in sample means of each air quality parameter. Prior to the Welch's Test, we performed Kolmogorov-Smirnov test (K-S) to ensure normality of data distribution. For Environmental Compliance check, we used the Central Pollution Control Board's Exceedence Factor (EF). The EF has been widely used in air quality assessment in India (Haque and Singh, 2017; Thakur, 2017). With EF, air quality is categorized as below:

1. Critical Pollution (CP): $EF > 1.50$
2. High Pollution (HP): $1.00 < EF < 1.50$
3. Moderate Pollution (MP): $0.50 < EF < 1.00$
4. Low Pollution (LP): $EF < 0.50$

We performed the assessment against two regulatory benchmarks: (i) National Ambient Air Quality Standard (NAAQS) as applied in India; and (ii) World Health organization (WHO) (Table 1). We computed Pearson's correlation coefficient by pooling togetherair quality data for the LDs (Phases 1-4) and UNLDs (Phases 1-3) in 2020. The governing idea was to compare mutual interaction patterns among pollutant species, with and without the 'COVID 19 restrictions', so as to help the regulatory authorities understand process-level differences, which might be used during post-COVID times for (i) source apportionment studies and (ii) developing co-management strategies for multiple pollutants.

RESULTS AND DISCUSSION

Year-On-Year Comparison (2020 vs. 2019)

For average $PM_{2.5}$ concentrations, most significant drops ($p<0.01$) in 2020 was observed, during LDs 2-4 in 2020, as compared to corresponding values in 2019 (Figure 1a). On average, $PM_{2.5}$ levels dropped by about 56% during the LDs, while by about 16% through the UNLDs, with overall (LD 1 – UNLD 3) drop averaged around 44% in 2020, against that in 2019 (Figure 1c). Similar temporal pattern was observed for ambient PM_{10} levels as well (Figure 1b) - 65% reductions through the LDs on average, while about 14% during the UNLDs (44.5% reduction on average overall) (Figure 1c). Both the PMs displayed

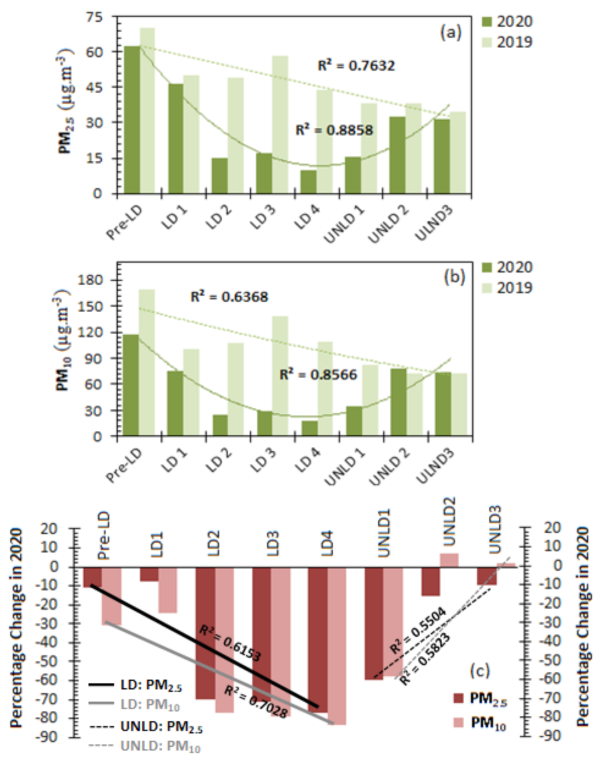

Fig. 1. Average concentration (a) $PM_{2.5}$ and (b) PM_{10} through Pre-Lockdown (Pre-LD), Lockdown (LD; periods 1-4) and Un-lockdown (UNLD; periods 1-3) in 2020 and 2019 in Kolkata, and (c) percentage differences between 2020 and 2019. In panel (a) and (b) broken line represent trend line for 2020 while solid lines for 2019. Negative values in panel (c) indicates drop in average PM concentrations in 2020 w.r.t. 2019. Light and dark green lines in panels (a, b) represent trend lines for 2019 and 2020, respectively. Blackand Grey lines in panel (c) represent trend lines for PM_{10} and $PM_{2.5}$ for the LD (solid lines)and UNLD (dotted) periods, respectively.

a polynomial pattern in 2020 – dropping from pre-LD times (March 5-25) with the imposition of Lockdown and intensifying during LD 2-4, and rising through the UNLDs, which was already apparent by polynomial trends for 2020 (Figure 1 a-b). Such 'reversal' in ambient PM levels became moreglaring from the pattern of trendlines, indicating the PM-pollution began returning to 'normalcy', endangering ambient air quality as soon as the restrictions were lifted (Figure 1c). Such trends raise a regulatory concern: Did we squander the opportunities already? Interestingly, linear drops were observed for corresponding times in 2019 for both PMs, probably due to gradual initiation of the monsoon (wind speed picking, coupled with coming of rains) that served as natural diluter to air pollutants. As opposed to that, as soon as the restrictions were lifted after the LDs in 2020, human mobility and economic activities skyrocketed to make up for opportunities lost. It is as the popular press notes, with first day of the UNLD 1, the vehicular mobility and traffic patterns in Kolkata returned to near normalcy, with thousands crowding at bus terminals (HT, 2020a).

The NO_2 levels dropped significantly ($p<0.05$) during the LDs in 2020 (Figure 2a), averaging around 40% from the 2019 values for the same period, while about 37% during the UNLDs (Figure 2c). For CO, significant ($p<0.05$) drops were observed during all through the LDs (Figure 2b), averaging around 28% (Figure 2c). However, during the UNLDs, the CO levels in 2020 became comparable with that of 2019 (no statistically significant differences), which adds to the regulators' concern. For both years, average NO_2 and CO levels displayed polynomial patterns (Figure 2 a-b).

Average SO_2 ($p<0.001$) (Figure 3a) and O_3 ($p<0.05$) (Figure 3b) levels remained significantly higher in 2020, all along the LD/UNLDs, falling in line with similar observations in India (Mahato and Ghosh, 2020; Mahato *et al.*, 2020). A likely cause for higher SO_2 levels is the operations of the thermal power plants in the city and adjoining areas (Kolaghat, Bandel, Budge-Budge, Cossipore areas) throughout the LD/UNLDs (Sarkar *et al.*, 2020). Thermal power plants in India still mostly operate on coal, leading to high SO_2 emissions. Moreover, the essential industrial operations such as food processing, pharmaceuticals, continued through the LDs, to provide citizens with basic goods and services. However, it remains unclear why the

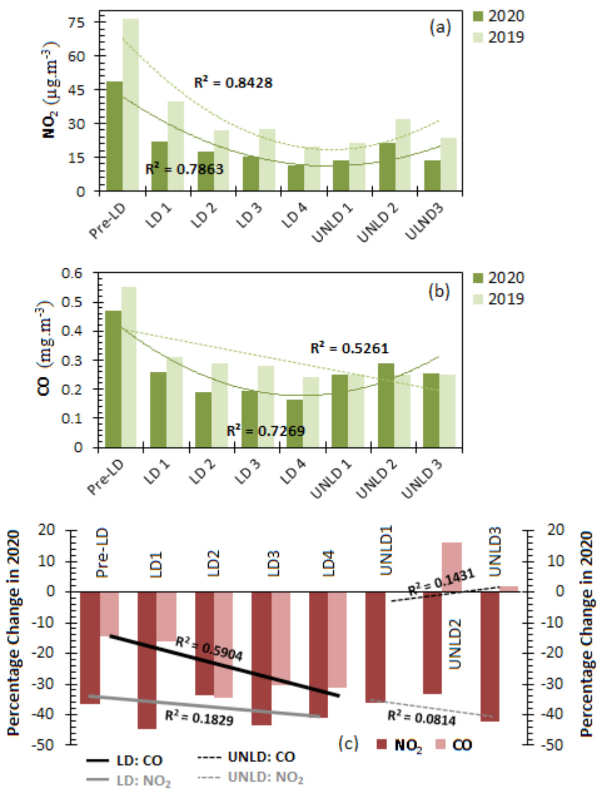

Fig. 2. Average concentration (a) NO_2 and (b) CO through Pre-Lockdown (Pre-LD), Lockdown (LD; phases 1-4) and Un-lockdown (UNLD; phases 1-3) in 2020 and 2019 in Kolkata, and (c) percentage differences between 2020 and 2019. In panel (a) and (b) broken line represent trend line for 2020 while solid lines for 2019. Negative values in panel (c) indicates drop in average concentrations in 2020 w.r.t. 2019. Light and dark green lines in panel (a) and (b) represents trend lines for 2019 and 2020, respectively. Black and Grey lines in panel (c) represent trend lines for CO and NO_2 for the LD (solid lines) and UNLD (dotted) periods, respectively.

percent difference in ambient SO_2 levels between 2020 and 2019 dropped during UNLDs (Figure 2c) and demand more in-depth research incorporating context-relevant information (e.g. ambient weather patterns and human activities in 2020 as compared to 2019).

Higher O_3 levels in Kolkata during LD-UNLD periods corroborate with studies conducted in other mega-cities, including New Delhi (Jain and Sharma, 2020), Wuhan (Xu *et al.*, 2020) Rio de Janeiro (Siciliano *et al.*, 2020), and Barcelona (Tobias *et al.*, 2020) and southern Europe (Sicard *et al.*, 2020). Higher O_3 level during LDscould partly be attributed to rise in NMHC/NOx ratios, and enhanced reactivity of VOC (volatile organic compounds), rich in aromatic compounds. The VOC could be sourced to vehicular, industrial, as well as domestic emissions (e.g. cleaning, cooking, gardening, which involve enhanced fuel usage) Wolff *et al.*, 2013). Our on-ground experience was that likelihood of domestic emission heightened during the prolonged homestay through the LDs. During the LD, the residents took to such domestic chores to keep engaged and kill growing boredom, frustration, anxiety etc

Pre-LD vs. LD/UNLD

Average concentrations in the LD took a sharp nosedive since the Pre-LD period (March 5 – 25 for our purpose) in 2020, indicating improvement in ambient air quality (Figure 4). In general, largest

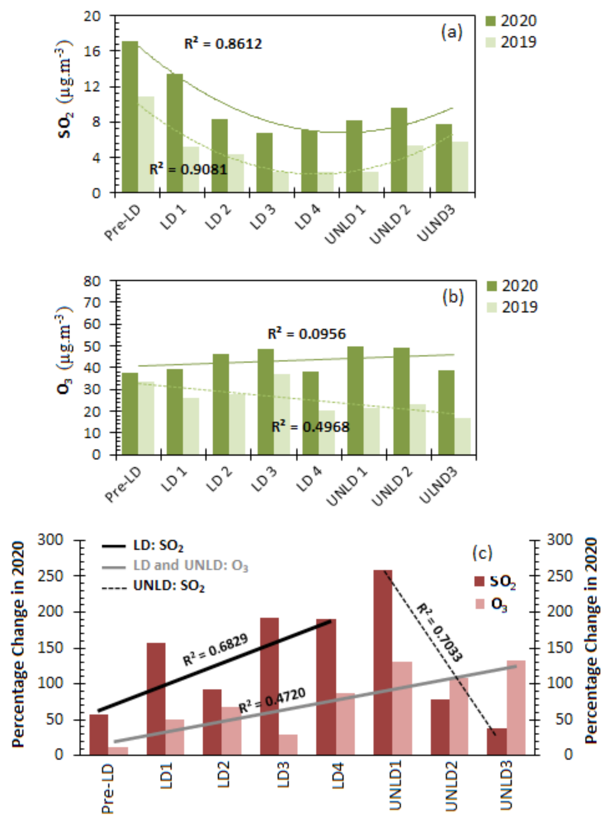

Fig. 3. Average concentrations SO_2 and O_3 through Pre-Lockdown (Pre-LD), Lockdown (LD; phases 1-4) and Un-lockdown (UNLD; phases 1-3) in 2020 and 2019 in Kolkata. Light and dark green lines in panel (a) and (b) represents trend lines for 2019 and 2020, respectively. Black and Grey lines in panel (c) represent trend lines for SO_2 and O_3 for the LD (solid lines) and UNLD (dotted) periods, respectively. For, O_3, he trend line was computed by combining LDs and UNLDs to underscore persistent rise over time since inception of LD

reductions are realized between LD 1 and UNLD 1 period, while slight *decrease* in reduction in later UNLDs. For PMs, reductions in the LDs 1 - 4 (w.r.t Pre-LD) averaged around 64.3% ($PM_{2.5}$) and 68.3% (PM_{10}) with largest drops in LD 2, which implied that 'healing touch' of the restrictions did not start taking effect until the economic activities were harshly suppressed. However, for UNLDs, reductions in particulate matter averaged around 61.9% ($PM_{2.5}$) and 51.6% (PM_{10}), indicating as soon as restrictions began to lift, pollution levels started picking up. Similar trends were observed for other species as well:

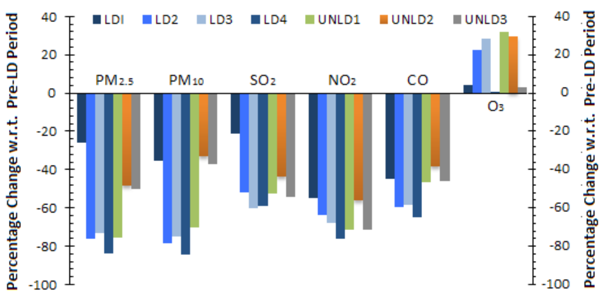

Fig. 4. Percentage changes in average pollutant concentrations during Lockdown (LD; phases 1-4) and Un-lockdown (UNLD; phases 1-3) in 2020, with respect to that in the Pre-LD period (pre March 25

- SO_2: Averaging around 57% reduction for the LDs, as compared to Pre-LD times; while about 48% between UNLD 1 and 2
- CO: Averaged around 56.9% for the LDS; about 42.1% in UNLD 1 and 2
- NO_2: 69.2% on average during the LDs; about 64% during UNLD 1-2

For the PMs and CO, concentrations dropped initially with the imposition of restrictions (LDs), while re-emerging through the UNLDs, which corroborated with earlier observations that the LDs helped 'healing' the air quality in the city only on short-term basis, while the UNLDs took away that edge. All along the study period in 2020 (LDs and UNLDs), the O_3 levels remained significantly high, as compared to the Pre-LD period. It corroborates with Siciliano *et al.* (2020), who observed increased ozone levels during the Lockdown in Rio de Janeiro, Brazil. Air quality showed slight're-improvement' in UNLD 3, probably due to two specific government policies during these times: (i) re-introduction of complete Lockdown on twice-a-week basis during which vehicular mobility and industrial operations were strictly moderated, roadside vending activities were restricted; and (ii) Embargo on air-travel to and from six mega-cities, deemed as COVID hot spots in the country. These were implemented to counter the sudden surge in COVID cases during UNLD 2. The decisions, however, elicited heavy criticisms from opposition parties.

Enrichment Factor - Environmental Compliance Test

Assessment of ambient pollutant levels against NAAQS and WHO benchmarks (Table 1) for 2019 and 2020 revealed that most PM_{10} consistently occurred in the "Critical Pollution" category (EF > 1.50) for both years (Table 2). On the other hand, improvements were observed in 2020 when EF was assessed against the NAAQS. For $PM_{2.5}$ improvements were observed for 2020, both NAAQS and WHO standards during LD phases 2-3 and UNLD 1. For the WHO standard, however, risk remains for $PM_{2.5}$ as it occurred in the "High Pollution" category (1.00 < EF < 1.50) in UNLD 2 in 2020, calling for urgent regulatory measures in post-UNLD period. SO_2, NO_2, CO and O_3, all come under "Low Pollution" category (EF < 0.50) by respective NAAQS standards for 2020, similar to 2019. By WHO standard however, SO_2 occurs in the "Medium Pollution" category (0.050 < EF < 1.00) in 2020. O3 falls in he "Low Pollution" category against the NAAQS standard for both years. However, by WHO standard, it fell in the "Medium Pollution" category in the UNLDs in 2020. Overall results indicated that though there have been improvements in ambient PM levels, yet concerns remain, especially by the WHO benchmarks. A recent assessment made by University of Chicago, involving Air Quality Life Index (AQLI), indicated

Table 1. Environmental standards (24-hour average) after the National Ambient Air Quality Standard (NAAQS) and World Health organization (WHO), and health breakpoints for different air quality parameters (expressed as ìg.m^{-3}, excepting CO measures in mg.m^{-3})

Standard	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
NAAQS	60	100	80	80	4	180
WHO (mg.m^{-3})	24	10	20	-	-	100

that *"added life-years from compliance with the WHO benchmarks for $PM_{2.5}$ could potentially raise the average life expectancy at birth from 69 to 73 years - a larger gain than from eliminating unsafe water and poor sanitation"* (https://aqli.epic.uchicago.edu/wp-content/uploads/2019/03/EPIC_IndiaFactSheet_V06-nobleeds.pdf). The study also revealed that $PM_{2.5}$ levels have doubled in Kolkata pollution between 1998 and 2016 (22 – 46 $\mu g.m^{-3}$ on average), which might translate into reduction in life expectancy of about 2.0-2.5 years in Kolkata. Particulate matter is a persistent concern to urban air quality in Kolkata (Das *et al.*, 2006). On the WHO database, 14 Indian cities appear in the top 15 global list for worst $PM_{2.5}$ pollution, including Kolkata (WHO, 2018).

Interactions Among Pollutants

From regulatory perspective, a decision-makers question could be: Did the pollutant species interact in similar fashion during the LDs and UNLDs? To delve into the matter, we computed Pearson's Correlation coefficients individually for the LDs and UNLDs. The idea was, for any urban habitat, identification of statistically significant correlations between pollutant species could yield two benefits: (i) prepare groundwork for future source apportionment studies, and (ii) developing co-management strategies for multiple pollutants. However, we also urge the regulatory authorities and scientific communities to collect more context-relevant information, and assess the biophysical environment to establish meaningful cause-effect relationships between the pollutant species, for informed policy-making in order to enforce stringent air pollution control-abatement measures.

Particulate Matter Dynamics

Strong positive correlations ($r = 0.93$; $p<0.001$) were observed between $PM_{2.5}$ and $PM_{10}$for both 2020 and 2019, which implied common sources of particulate matter in both years (Table 3). A study made by the Central Pollution Control Board showed that major PM sources in Kolkata are diesel-operated buses (accounting for about 50% of total PM in Kolkata), trucks (17%), and 3-wheelers (11%) (Figure 5a) (CPCB, 2015b). In 2019, moderately strong positive correlations ($p<0.050$ were observed between $PM_{2.5}$ and NO_2 ($r = 0.60$; $p<0.01$), CO ($r = 0.71$; $p<0.01$). However, no such associates were observed for 2020, excepting O_3 ($r = -0.41$; $p<0.05$). The PM_{10} was

Table 2. Enrichment Factor (EF) computed for different air quality parameters within the Lockdown (LD) and Un-lockdown (UNLD) phases against National Ambient Air Quality Standard (NAAQS) and World Health Organization (WHO) for 2020 and 2019 for Kolkata. EF was not computed for NO_2 and CO for the WHO. NOTE: We calculate average EF for each LD/UNLD period by taking the ratio of 24-hour time-averaged concentrations of each air pollutant and corresponding annual standards.

2020	NAAQS						WHO					
	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
Pre-LD *(March 5– March 25)*	CP	CP	MP	MP	LP	LP	HP	HP	MP	NA	NA	LP
LD 1*(March 25– April 14)*	MP	MP	LP	LP	LP	LP	CP	CP	MP	NA	NA	LP
LD 2*(April 15 – May 3)*	LP	LP	LP	LP	LP	LP	MP	CP	LP	NA	NA	LP
LD 3*(May 4 – May 17)*	LP	LP	LP	LP	LP	LP	MP	CP	LP	NA	NA	LP
LD 4*(May 18 – May 31)*	LP	LP	LP	LP	LP	LP	LP	CP	MP	NA	NA	LP
UNLD 1*(June 1 – July 1)*	LP	MP	LP	LP	LP	LP	MP	CP	MP	NA	NA	MP
UNLD 2 *(July 1 – July 31)*	MP	MP	LP	MP	LP	LP	HP	CP	MP	NA	NA	MP
UNLD 3 (*August 1 – August 31)*	MP	MP	LP	LP	LP	LP	HP	CP	MP	NA	NA	LP

2019	NAAQS						WHO					
	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
LD 1*(March 25– April 14)*	MP	CP	LP	MP	LP	LP	CP	CP	LP	NA	NA	LP
LD 2*(April 15 – May 3)*	MP	CP	LP	LP	LP	LP	CP	CP	LP	NA	NA	LP
LD 3*(May 4 – May 17)*	MP	CP	LP	LP	LP	LP	CP	CP	LP	NA	NA	LP
LD 4*(May 18 – May 31)*	MP	CP	LP	LP	LP	LP	CP	CP	LP	NA	NA	LP
UNLD 1*(June 1 – July 1)*	MP	MP	LP	LP	LP	LP	CP	CP	LP	NA	NA	LP
UNLD 2 *(July 1 – July 31)*	MP	MP	LP	LP	LP	LP	CP	CP	LP	NA	NA	LP
UNLD 3 (*August 1 – August 31)*	MP	MP	MP	LP	LP	LP	CP	CP	LP	NA	NA	LP

LP: Low Pollution (EF < 0.05); MP: Medium Pollution (0.05 < EF < 1.00); HP: High Pollution (1.00 < EF < 1.50); CP: Critical Pollution (EF > 1.50) positively associated with NO_2 (r = 0.54; *p*<0.05), CO (r = 0.41; *p*<0.01) and O_3 (r = -0.41; *p*<0.05) in 2020.

Inverse association between $PM_{2.5}$ and O_3 in 2020 was in agreement with similar studies during the Lockdown (Lokhandwala and Gautam, 2020). Aerosols could influence O_3 dynamics in urban atmosphere (Feng *et al.*, 2016) in two cyclic pathways (Zhao *et al.,* 2018):

- High O_3 levels with strong atmospheric oxidation radiation promoting secondary particle formation, enhancing ambient $PM_{2.5}$ levels
- Enhanced $PM_{2.5}$ levels reducing solar radiation in turn, which impede photolysis reactions and suppress O_3 formation

Reduction in aerosols concentrations, as was apparent in Kolkata during the LDS, favors photolysis reactions and promotes O_3 formation (Liu *et al.*, 2013). Another potential mechanism is the heterogeneity inthe surface chemical processes of $PM_{2.5}$ and aerosols that facilitates O_3-$PM_{2.5}$ interactions (Li *et al.,* 2011). The KMA should take up more strategic sampling and analyses of urban air quality in future to improve process-level understanding of particulate matter-O_3 interaction pathways, so as to devise effective co-management strategies in post-COVID times to reduce environmental health burden. A major task will be to elucidate pathways and drivers of photolysis reactions. In this regard, key biophysical factors that deserve research focus include aerosol type, aerosol size distribution, aerosol distribution in the vertical direction, relative humidity (RH), seasonality, and planetary boundary layer height (PBLH) (van Donkelaar *et al*., 2010).

NO_2-SO_2-CO-O_3

For 2019, NO_2 was positively correlated with SO_2 (r = 0.78; *p*<0.01) and CO (r = 0.79; *p*<0.01), indicating common origin, knowledge that might help the authorities set up co-management strategies in post-COVID times, although it demands more empirical research with context-relevant evidences. The NO_2 was positively correlated with SO_2 (r = 0.63; *p*<0.01) and CO (r = 0.62; *p*<0.05) in 2020 as well (Table 3). A six-city assessment by the Central Pollution Control Board (CPCB) revealed that transport sector is the prime NO_2 emitter in Kolkata with diesel-operated buses

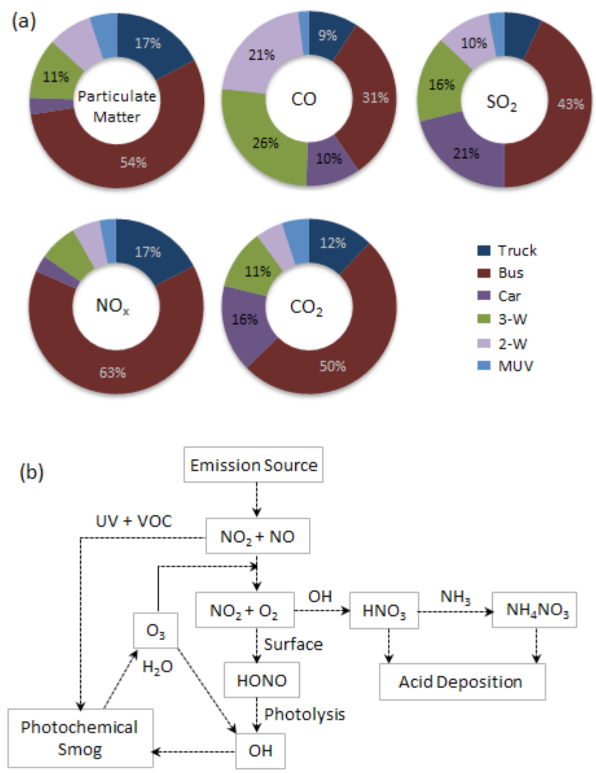

Fig. 5. (a) Percentages of different air quality pollutants in emissions of different vehicle types in Kolkata. NOTE: '3-w': three wheelers; '2-w': two-wheelers. *(Data source: Central Pollution Control Board, 2015b)*; and (b) Simplified transformation pathways involving inorganic NOx and O_3 (Ozone) in urban atmosphere. The photochemical smog is broadly composed of O_3 and secondary organic aerosols *(adopted from Allegrini and Fabe, 1995)*

Table 3. Pearson's correlation coefficient (r) computed between different pollutant species, by pooling observations during LD (lower triangle of the diagonal line) and that in the UNLD (upper triangle) in 2020.

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO	O_3
$PM_{2.5}$		0.92***	0.13	0.60**	0.71**	-0.12
PM_{10}	0.92***		0.71**	0.79**	0.83**	0.22
SO_2	0.02	0.11		0.78**	0.55*	0.74**
NO_2	0.08	0.54*	0.69**		0.79**	-0.41*
CO	0.28	0.41*	0.01	0.62*		0.13
O_3	-0.41*	-0.40*	0.51*	-0.59*	-0.39*	

*p<0.05; **p<0.01; ***p<0.001

and trucks accounting for 63% and 17% (Figure 5a) (CPCB, 2015b). In the transport sector, buses also account for about 43% of SO_2 emissions, followed by cars (21%), 3-wheelers (16%) and 2-wheelers (10%). Azimi *et al.* (2018) identified four economic factors of per capita SO_2 emission: (i) emission intensity of coal consumption; (ii) coal intensity of power generation; (iii) power intensity of GDP; and (iv) per capita GDP. The authors attributed per capita NO_x (Nitrogen Oxides, mostly NO_2 and NO) to e urban development: (i) gasoline consumption; (ii) proportion of gasoline vehicles; (iii) vehicular use rate; and (iv) growth in urbanization. Additional NO_2 and SO_2sources include residential and industrial sectors as well (Bhankar *et al.,* 2020). We urge the KMA togather more empirical evidences for source apportionment toestablishappropriate regulatory measures accordingly. Prime sources of CO in Kolkata include diesel emissions associated with buses (31% of total CO emission), 3-wheelers (26%), and 2-wheelers (21%) (Figure 5a) (CPCB, 2015b). Positive correlations were observed between SO_2 and $O_3$for both years (Table 3), although, the strength of correlation was higher in 2019 ($r = 0.74$; $p<0.01$) than 2020 ($r = 0.51$; $p<0.05$). CO is negatively correlated with O_3 in 2020 ($r = 0.39$, $p<0.05$), indicating CO consumption (converted to CO_2, Zhang *et al.,* 2019) leading to O_3 formation. It bears negative implications for urban ecosystem, exalted greenhouse gas emission and urban heat island effect.

NO_x-O_3Transformation Pathways

Sourced largely to tailpipe emissions, NO_2 occurs in multiple species assemblages within the urban atmosphere. Our analysis indicated strong inverse relationships between NO_2 and O_3 for both 2019 ($r = -0.41$; $p<0.05$) than 2020 ($r = 0.59$; $p<0.05$), which corroborated with recent studies in Kolkata (Jain and Sharma, 2020; Sarkar *et al.,* 2020) (Table 3). The nitrogen oxides (NOx) regulate ambient O_3 levels (Sarkar *et al.,* 2020;), through a complex web of transformation pathways (Zhao *et al.,* 2018) (Figure 5b). When released into the atmosphere, NO (nitrous oxide) is rapidly oxidized to NO_2(and further to nitric acid/nitrates), consuming O_3 on its way (Jain and Sharma, 2020; Xu *et al.,* 2020). In highly polluted urban conditions, this transformation is mediated by peroxy-radicals, and/or hydro-peroxy radicals (HO_2):

$$NO + O_3 \Rightarrow NO_2 + O_2$$

$$NO + RO_2 \Rightarrow NO_2 + RO$$

$$NO + HO_2 \Rightarrow NO_2 + OH$$

Oxidative transformations by radicals is rapid, which raises roadside NO_2 levels (Allegrini and Febo, 1995), especially in presence of if high levels of HNO_2 (provides OH radicals to facilitate oxidation). At daytime, in presence of sunlight (hí), NO_2 is again photolytically decomposed back to NO with formation of O_3:

$$NO_2 + hí \Rightarrow 2\ NO + O$$

$$O + O_2 \Rightarrow O_3$$

This leads to a photo-stationary state (of tentermed as 'Leighton State') where the rate of oxidation of NO is balanced by its reformation by the photolytic dissociation of NO_2 (ratio of the pollutants remains constant at a given level of solar radiation and temperature). In other words, NO-enrichment in the air leads to O_3 depletion, while NO_2 does the opposite (O_3 production). According to Guttikunda (2020), *"during the lockdowns, with little NO present in the system (shutdown of vehicular emission) to support the photo-stationary reactions, the overall O_3 production went up"*.

O_3 Formation in Urban Atmosphere: Role of VOC: NO_x Ratio

At night the oxidation of NO by O_3 proceeds to completion, i.e. until either NO or O_3 is totally depleted. However, during daytime, O_3 dynamics is largely regulated by VOCs, particularly the ratio of VOC:NOx (Pusede and Cohen, 2012), which, in presence of sunlight (200-300 nm) produces O_3 and other species (Zhao *et al.*, 2018):

$$VOC + NOx + hí \Rightarrow O_3 + (PAN, HNO_3 \ldots .etc)$$

Reduced NO_2 levels during the LDs-UNLDs has effectively raised the VOC: NOx ratio and led to O_3 formation (Sicard *et al.*, 2020). Besides O_3 accumulation, the process also involves oxidation of VOCs into oxygenated organic compounds, and formation of N-compounds. Because many of the oxygenated and N-containing organic compounds occur in condensed phase (low volatility), they are collectively termed as Secondary Organic Aerosols (SOAs) (Zhang *et al.,* 2019). The mixture composed of O_3, SOAs, and their gaseous precursors (e.g. NO_x, CO) is called *photochemical smog*.

What Went Wrong?

Our results indicated a score of rising air pollutant levels as soon as the restrictions of economic activity and human mobility were lifted during the UNLDs. The EF assessment also revealed that even during the restrictions, the ambient PM levels barely complied with the WHO regulatory benchmarks that might translate into major environmental health burden in days ahead if not addressed with stringent environmental protocols. The National Clean Air Program (NCAP), developed in 2019, already listed Kolkata among the 'non-attainment' cities that fail to meet air quality compliances (MoEFCC, 2019). Current regulatory measures for air pollution control-abatement seem highly inadequate (Majumder *et al.,* 2020). Recently, Air Quality Life Index (AQLI)[3] for India and showed that failing to meet the regulatory benchmarks for air quality could severely impact life expectancy in Kolkata in days ahead (https://aqli.epic.uchicago.edu/wp-content/uploads/2019/03/EPIC_IndiaFactSheet_V06-nobleeds.pdf). However, imposing strict protocols is difficult in Kolkata alike all Indian mega-cities, which, besides lack of finance and technology, demands public-private partnerships and a robust institutional governance and right political will. A glitch is, environmental outlook in India is politically entrenched and mainly shaped by populist electoral dynamics. For example, the state government 'relaxed' the restricts even during the LDs to maintain economic operations (FP, 2020):

- Special Economic Zones – Operations allowed for export oriented units, industrial estates and industrial townships with access control
- Manufacturing Units –Production continued for essential goods, drugs, pharmaceuticals, medical devices, their raw material and intermediaries; IT hardware; packaging material; in addition, units that demanded 'continuous' supply chains
- Agricultural operations resumed during LD 3
- Jute industry resumed with staggered shifts and social distancing
- Construction and Demolition activities were permitted with on-site workers
- Private sector began operation with 33% strength in the office quarters

The UNLDs paved ways for further human/economic mobilization: (i) economic activities were permitted every where excepting 'COVID containment zones'; (ii) the railways began operations with an envoy of 200 special trains to move the migrant workers; (iii) embargos were lifted on inter-state travel; (iv) shopping malls, religious places, hotels/restaurants, were permitted operation from June 8. What aggravates air quality crises is that, diesel accounts for the bulk of vehicular fuel in Kolkata (Thakur, 2017). Diesel emission is widely known for elevated level of CO, NO_2, SO_2, hydrocarbons and soot (particulate matter) (Jain and Sharma, 2020).

On daily basis, vehicular emissions in Kolkata contribute to about 4.6 million tons of PM on average (CPCB, 2015b), of which, nearly 45% is attributed to diesel-operated buses alone. Transitioning to clean fuel technologies has been advocated since the early 2000s (Ghosh *et al.,* 2004), but barely been implemented due to a confluence of economic/technological hardships that commonly encountered in any Indian mega-city: (i) higher fuel costs; (ii) unavailability of 'clean' fuel stations; (iii) lack of awareness; (iv) lack of governmental support; (v) lack of functional public-private partnerships to finance such projects; (vi) lack of on-ground capacity building; and (vii) right political will to influence citizens' cognizance etc. to name a few. Adding to the crises, 'fuel adulteration' is common occurrence in all Indian cities, which will continue to add tothe emission hazards in post-COVID times (Thakur, 2017). Collectively, whatever environmental gains were realized due to the restrictions, were practically obliterated as soon as restrictions were lifted.

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