Non-uniform effect of COVID-19 lockdown on the air quality in different local climate zones of the urban region of Kochi, India

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Abstract
Deterioration of ambient air quality associated with urbanisation is a serious concern in many parts of the world. In India, air pollution, primarily due to particulate matter, has increased exponentially in the last few decades due to rapid urbanization, industrialization and population growth. This study investigates the non-uniform influence of COVID-19 lockdown on the ambient air quality of three distinct local climate zones (LCZs) within the urban region of Kochi (Kerala, India). The analysis of the air pollutant data of the ambient air quality monitoring stations during the pre-lockdown (PRLD), lockdown (LD) and post-lockdown (PTLD) periods of 2021 implies the significance of lockdown measures in the improvement of urban air quality. The air quality index (AQI) exhibits characteristic variability in different LCZs and contrasting behaviour between the LD period of 2020 and 2021, primarily due to the differences in the lockdown restrictions and strategies as well as the influence of local climatic factors. This study highlights the need for multiple monitoring stations in the urban regions with respect to different LCZs to identify the urban air quality hot spots.

Keywords Air Quality · COVID-19 · Local climate zones · Urban areas

1 Introduction
Air quality is one of the primary concerns for environmental health and air pollution due to anthropogenic activities is a major public health hazard across the world. In recent decades, air quality in India has deteriorated significantly due to rapid urbanization, industrial growth and population expansion, and is expected to worsen irrespective of the mitigation policies that have been implemented [1]. The particles smaller than 2.5 and 10 µm in aerodynamic diameter (PM$_{2.5}$ and PM$_{10}$), nitrogen dioxide (NO$_2$), carbon monoxide (CO) and ozone (O$_3$) are the significant pollutants that influence air quality in major cities of India [2, 3, 4]. More than 90% of the global population lives in locations where the PM$_{2.5}$ levels exceed the WHO thresholds.

Although exposure to PM$_{2.5}$ substantially varies across space and time, the annual PM$_{2.5}$ exposure in India in 2017 was remarkably higher (91 µg/m$^3$) than in most countries worldwide [5]. Long-term exposure to particulate matter causes respiratory and cardiovascular disorders, including asthma, bronchitis and lung cancer [6, 7, 8]. Air pollution caused nearly 1.1 million premature deaths in India in 2015 and was responsible for almost 18% of all deaths in the country in 2019 [5]. Vehicular exhaust, emissions from large-scale industries, bi-products of small-scale industries, such as brick kilns, open waste burning, suspended dust on the roads and nearby premises due to traffic and construction activities, combustion of various fuels for cooking and in-situ power generation are the primary sources of air pollution in the major cities of India.

The physical distancing measures and movement restrictions (commonly referred to as lockdowns) to restrict and slow down the transmission of the COVID-19 pandemic positively influenced the natural environment, particularly in ambient air quality across the world [9, 10, 11, 12]. During the early stages of the COVID-19 pandemic, India witnessed a nationwide lockdown from 25 to 2020, which was extended until 31 May 2020 with staggered phases of relaxation. The nationwide lockdown was effective to curtail the
COVID-19 transmission rates and reduce contaminations [13]. A year later, with a surge in the COVID-19 cases, India implemented another lockdown during 08–31 May 2021 encouraged by the effectiveness of the lockdown to contain the pandemic in 2020. However, the lockdown in 2021 was less stringent than that of 2020 and offered fewer restrictions on different sectors.

Numerous studies have addressed the improvement in ambient air quality in the urban region across India during the COVID-19 lockdown [14, 15, 16, 17]. Given that the air quality index (AQI) shows remarkable spatial variation while considering data from multiple monitoring stations within an urban area [18], many such studies in the Indian context used ambient air quality data of a single monitoring station within the region. In comparison with the planned European cities with well-segregated residential, commercial, industrial, and green space zones, most Indian cities have emerged from tiny urban sprawls. Hence, the AQI may exhibit significant spatial variation within an urban area due to the heterogeneous topographic and surface morphology, meteorological factors and diverse local sources. Thus, the present study sought to address the non-uniform effect of the COVID-19 lockdown on the ambient air quality in three different Local Climate Zones (LCZs) of Kochi - an urban region of Kerala (India) - during the pre-lockdown, lockdown and post-lockdown periods of 2020 and 2021. The current assessment of the effect of COVID-19 lockdowns, with differing degrees of restrictions, on ambient air quality provides important lessons for the management of such pandemics in different strategic conditions.

2 Materials and methods

2.1 Study area

Kochi is located in the Ernakulam district of Kerala State (India) and the study area extends between 09 50’ N and 10 10’ N latitudes and 76 10’ E and 76 25’ E longitudes (Fig. 1). The region is one of the fast-growing urban centres located on the southwest coast of India. The urban agglomeration of Kochi primarily belongs to the Kochi Municipal Corporation and nearby Municipalities and Grama Panchayaths and has a population of 2.2 million [19]. The region is connected to other parts of the country by all major modes of transport such as road, rail, air and water. The majority of the commercial traffic in the region occurs via different national highways (e.g., NH 66, NH 85, NH 544, NH 966 A, and NH 966B) and major district roads of Kerala. The study area is home to one of the major international airports and seaports in southern India. The urban region supports one of the largest international container trans-shipment terminals in India and is an important mobility hub in Kerala. Kochi is one of the largest agglomerations and the hub of commercial and retail activities in Kerala. It is also an important chemical industrial and manufacturing centre with numerous large, medium and small scale industries and an emerging information technology centre in Kerala. Different industrial campuses, such as Info-Park and Cochin Special Economic Zone, established in the region support economic growth.

The physiography of the region is gently undulating and a large portion of the region lies at nearly sea level. The
average altitude of the region increases gradually towards the east. The study area is interlaced with numerous canals and waterbodies connecting to the Vembanad lagoon. The study area receives an annual rainfall of about 3000 mm in roughly 120–140 days and the majority of the annual rainfall is contributed by the Indian summer monsoon season (June-September). Kochi experiences a humid tropical climate (Am of Koppen climate classification), with an annual variation of temperature between 20 and 35 °C. The region is characterized by moderate to high humidity due to its proximity to the Arabian Sea and the Vembanad backwaters.

**2.2 Local climate zone classification of the study area**

The LCZs are classified based on the mean height of buildings, street width, vegetative fraction, the proportion of sky hemisphere visible from the ground (known as sky view factor), anthropogenic heat flux, etc. [20]. Based on the variability of these factors, Stewart and Oke classified the urban-rural built up into a hierarchy of ten LCZs, namely, compact high-rise (CHR), compact mid-rise (CMR), compact low-rise (CLR), open high-rise (OHR), open mid-rise (OMR), open low-rise (OLR), large low-rise (LLR), lightweight low-rise (LWLR), heavy industry (HI), and sparsely built (SB), and land cover types to dense trees, scattered trees, bush, scrub, low plants, bare rock and paved, bare soil and sand, etc. Large, open water bodies, such as seas and lakes, and small water bodies, such as rivers, reservoirs, and lagoons are also included within the land cover system. In this study, we used ambient air quality data from three air quality monitoring stations (i.e., City Centre, CC; Mobility Hub, MH and Industrial Area, IA), representing three different LCZs of Kochi.

**2.2.1 City Centre (CC)**

The ambient air quality station at CC (Fig. 1) is installed at Kacheripady, which represents an area of commercial and retail activities. The region is characterized by a dense urban centre, with low buildings and a uniform surface pattern, and is classified as CMR. The CMR zone covers an area of 1.62 km² and has dense traffic primarily during the daytime. The average surface albedo around the ambient air quality monitoring station is 0.17.

**2.2.2 Mobility hub (MH)**

The MH at Vytilla is an integrated transit terminal located in the eastern part of the urban region. The MH facilitates the convergence of different forms of public transportation. The

| Period     | Data Collected       | 2021       | 2020       |
|------------|----------------------|------------|------------|
| PRLD       | 1 March – 31 July (68)* | 26 January – 31 July | 26 January - 23 March (58)* |
| LD         | 8 May – 31 May (24)*  | 24 March – 31 May (69)*  |
| PTLD       | 1 June – 31 July (61)* | 1 June – 31 July (61)*  |

*Number of days in parentheses

MH station (Fig. 1) represents the region with compact low-rise densely packed buildings separated by narrow streets and alleys. The LCZ of the MH station falls under the CLR class and covers an area of 1.49 km². The average surface albedo around the ambient air quality monitoring station is 0.17 to 0.19.

**2.2.3 Industrial Area (IA)**

The industrial region of the Kochi is primarily extended across Elloor and supports about 250 chemical industries for manufacturing all forms of chemicals and fertilizers. The IA station (Fig. 1) describes a highly irregular mix of industrial structures with hard-packed surfaces and belongs to the HI class of LCZ classification. The HI zone covers an area of 11.0 km² and the average surface albedo varies from 0.16 to 0.18.

**2.3 Data collection and analysis**

The air pollutant concentration data (Pollution Control Board, Government of Kerala) from three different LCZs of the urban region of Kochi was used for this study. The ambient air quality monitoring stations were chosen to represent three distinct LCZs: CC in CMR, MH in CLR and IA in HI. In this study, we considered eight air pollutants, including particulate matter (PM$_{2.5}$ and PM$_{10}$), nitrogen oxides (NO and NO$_2$), ammonia (NH$_3$), sulphur dioxide (SO$_2$), ozone (O$_3$), and carbon monoxide (CO). The AQI has been assessed using the daily concentration of the atmospheric air pollutants during the pre-lockdown (PRLD), lockdown (LD) and post-lockdown (PTLD) period of 2021 and compared with the PRLD, LD and PTLD phases of 2020 (Table 1).

The AQI was determined using the approach suggested by the Central Pollution Control Board, Government of India 4, 21. Estimation of AQI requires PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, O$_3$, NH$_3$, and CO concentrations (up to a 24-hour averaging period), with a minimum of three pollutants (at least one of them being PM$_{2.5}$ or PM$_{10}$) [21]
The AQI of the different ambient air quality monitoring stations (CC, MH and IA) of the urban region of Kochi shows significant variability between the stations and different phases (i.e., PRLD, LD and PTLD) of 2021 (Table 2). The temporal variability of the AQI of the CC station exhibits an improvement in the AQI during the LD period (median = 30; range = 23–54) compared to the PRLD (57; 33–112) and PTLD (48; 29–81) periods. The AQI of the majority of the total days during the LD period was good (95%), whereas the rest of the days were characterized by satisfactory AQI levels (Fig. 2). During the PRLD, the AQI of the majority of the days (77%) was satisfactory, followed by good (18%) levels, while during the PTLD, the AQI of more than 60% of the total days was good and showed satisfactory levels for the rest of the period. The temporal pattern and the AQI statistics show a declining trend in the AQI values at CC due to the lockdown restrictions compared to the PRLD period. However, relaxation in the lockdown measures in the PTLD phase facilitated a partial reversal of the trend in AQI to reach the AQI values during the PRLD period. Among the different air pollutants at CC, PM$_{10}$ (58% days), PM$_{2.5}$ (23% days) and CO (19% days) were dominant during the PRLD, whereas CO was the prominent pollutant on 85% of days during LD and PTLD periods followed by PM$_{10}$.

The temporal variability of the AQI of the MH station also shows remarkable improvement in the ambient air quality during the LD (median = 43; range = 33–53) period compared to the PTLD (48; 29–81) and PRLD (79; 45–119) periods (Table 2). The AQI of MH was mostly at the satisfactory level in the PRLD period (88% days), whereas the AQI during the LD period was at the good level for 95% of the total days (Fig. 3).

The air quality levels during the PTLD period varied between good (76% of the total days) and satisfactory (24%) levels. Although the PTLD period shows enhanced AQI levels compared to the LD period, the AQI values did not elevate to the level of the PRLD period. The prominent pollutant that influenced the AQI during the PRLD period (more than 90% of the total days) was particulate matter (PM$_{10}$ and PM$_{2.5}$), while it was CO during the LD (89% of the total days) and PTLD (67% of the total days) periods (Fig. 3).

The air quality levels during the PTLD period varied between good (76% of the total days) and satisfactory (24%) levels. Although the PTLD period shows enhanced AQI levels compared to the LD period, the AQI values did not elevate to the level of the PRLD period. The prominent pollutant that influenced the AQI during the PRLD period (more than 90% of the total days) was particulate matter (PM$_{10}$ and PM$_{2.5}$), while it was CO during the LD (89% of the total days) and PTLD (67% of the total days) periods (Fig. 3).

3.2 Variability of air pollutants

The temporal variability of the different air pollutants recorded at the ambient air quality stations of different
LCZs is given in Table 3. The daily time series (1 March 2021–31 July 2021) of the concentration of different air
pollutants measured at CC, MH, and IA is shown in Fig. 5. The concentration of all the air pollutants (except SO$_2$) at CC showed a significant reduction during the LD period in 2021. The concentration of PM$_{2.5}$, PM$_{10}$, NO, NO$_2$, NH$_3$ and CO were lowered by 69%, 59%, 8%, 44%, 21%, and 14%, respectively compared to their concentration during the PRLD period. However, SO$_2$ increased by 33% during the same period. During the PTLD period, the air pollutants except SO$_2$ showed an increase in their concentration: PM$_{2.5}$ by 18%, PM$_{10}$ by 45%, NO by 20%, NO$_2$ by 11%, NH$_3$ by 8% and CO by 50% (Table 3). It may be noted that the PM$_{2.5}$, PM$_{10}$, NO, NO$_2$, NH$_3$ and SO$_2$ concentrations at CC during the PTLD period were lower than the PRLD period by 63%, 40%, 38%, 15% and 21%, respectively, which implies that the air pollutant concentrations did not return to the level during the PRLD even after the slurring staggerings in the lockdown measures. On the other hand, NO and CO concentrations increased (11% and 29%, respectively) in the PTLD period compared to the PRLD (Fig. 5c-h).

The concentration of all pollutants at MH showed a marginal decrease (except for NH$_3$ and O$_3$) during the LD period of 2021 compared to the PRLD period (Table 3). For instance, PM$_{2.5}$, PM$_{10}$, NO, NO$_2$, SO$_2$ and CO showed a reduction by 69%, 72%, 9%, 27%, 67% and 20%, respectively. On the other hand, the concentration of NH$_3$ and O$_3$ increased by 9% and 138%, respectively. The particulate matter (PM$_{2.5}$ by 55% and PM$_{10}$ by 77%), SO$_2$ (74%) and CO (13%) during the PTLD period showed an increase compared to the LD period of 2021. However, while comparing with the PRLD period, all the pollutant levels at MH (except O$_3$) during the PTLD period, showed a reduction of 52%, 50%, 12%, 27%, 3%, 43%, and 10% for PM$_{2.5}$, PM$_{10}$, NO, NO$_2$, NH$_3$, SO$_2$ and CO, respectively. The concentration of O$_3$ increased by 8% during the PTLD compared to the PRLD period (Fig. 5g).

The concentration of all the air pollutants at IA is apparently different from the other two stations (CC and MH) in the urban region during the LD period of 2021 (Table 3). The concentration of most of the air pollutants increased in the LD period compared to the PRLD period. For example, the concentration of NO, NO$_2$, NH$_3$, CO and O$_3$ was increased by 25%, 10%, 124%, 22%, and 11%, respectively during the LD period. However, the concentration of PM$_{2.5}$, PM$_{10}$ and SO$_2$ decreased by 19%, 35% and 29%, respectively during the same period. The PTLD witnessed a significant increase in the NO$_2$ (55%), SO$_2$ (23%) and CO (36%) levels compared to the LD period, whereas NH$_3$ showed a decrease of 27% (Table 3). The concentration of NO (21%), NO$_2$ (70%), NH$_3$ (63%), CO (67%) and O$_3$ (10%) in the PTLD period was relatively higher than in the PRLD period also. But PM$_{2.5}$, PM$_{10}$ and SO$_2$ concentrations were reduced by 21%, 34%, and 13%, respectively than the PRLD period.

### 4 Discussion

The results of this study indicate significant spatial variability in the reduction of the concentration of prominent pollutants and improvement in the ambient air quality of the urban region of Kochi during the LD period of 2021. The ambient air quality at the monitoring stations (CC, MH, and IA) representing different LCZs (CMR, CLR, and HI) responded differently to the lockdown measures. A comparison of the air pollutant levels during the LD phases of 2020 and 2021 indicates that the lockdown measures were significant in the improvement of the ambient air quality in the urban region of Kochi. In general, the LD period in 2020 recorded a significant reduction in most of the air pollutants at CC (except NH$_3$ and CO), MH (except NH$_3$) and IA (Table 3). However, in 2021, the reduction of the air pollutant levels was notable at CC and MH, whereas most of the pollutants at IA showed a significant increase in the LD period compared to the PRLD period. During the LD period of 2021, the AQI values at CC and MH stations exhibited a reduction of about 50%, indicating a significant improvement in the air quality during the LD phase. However, hardly any changes were recorded at the IA station. The lockdown during 2020 exerted a reduction of 53% of the AQI values at MH and 41% at IA but the AQI of the CC showed only a nominal decrease (~5%).

Another notable difference between 2020 and 2021 is the change in the air quality during the PTLD period compared to the LD period (Table 3). In 2020, most of the air pollutants continued to decrease during the PTLD period and recorded lower levels than during the LD period. However, the AQI values showed an increase in the PTLD period (33% at CC and 50% at MH) compared to the LD phase during 2020, which is primarily due to the increase in any of the prominent pollutants contributing to the AQI. Contrastingly, the AQI during the PTLD period of 2020 at IA showed a reduction in the AQI values by 26%. In 2021, most of the air pollutants at CC, MH, and IA stations showed an increase in the PTLD compared to the LD period. The AQI values of the PTLD period in 2021 also registered an increase in AQI values by 60% at CC, 12% at MH, and 56% at IA.

During the lockdown in 2021, the AQI at CC recorded a significant reduction in the concentration of all the prominent pollutants (PM$_{10}$, PM$_{2.5}$, and CO) (Table 3). Although PM$_{10}$ and PM$_{2.5}$ levels at CC were significantly lower in the LD (17.3 and 37.3 µg/m$^3$) and PTLD (9.8 and 24.0 µg/m$^3$) periods of 2020 compared to the PRLD period (40.0 and 70.6 µg/m$^3$), CO levels remained high during the LD (1.6 mg/m$^3$) and PTLD (2.2 mg/m$^3$) phases than the PRLD (1.4 mg/m$^3$). Similar variability was observed for CO during the PTLD period in 2021 also. The natural emissions from biogenic sources, biomass burning and enhancement
in agricultural activities could be the major sources of the higher levels of CO in the region. A similar increase in the concentration of CO during 2020 was also reported in four South Indian cities [4]. The LD period of 2021 witnessed an increase in the O$_3$ concentration in MH as well as IA stations (Table 3). It is worthy to note that the concentration of O$_3$ at MH increased by 138% during LD compared to the PRLD period. The primary sink for atmospheric O$_3$ is the titration in the presence of a high concentration of NO in the atmosphere [22]. The concentration of NO and NO$_2$ at MH declined by 9% and 27% respectively, during the LD period of 2021, which could be a potential reason for the higher levels of O$_3$. However, such a relationship was not apparent in 2020, instead, a decrease in O$_3$ levels was recorded during the LD period of 2020.

The dominant pollutants at CC and MH during the PRLD period were PM$_{10}$ and PM$_{2.5}$. The dominant sources of particulate matter are traffic emissions and construction activities. Apart from these sources, the Arabian Sea is also a significant source of particulate matter as sea spray and ship/oceanic emissions [23]. The concentration of various gaseous pollutants recorded slightly higher values during
the LD period even though the anthropogenic emissions got reduced. It is reported that the natural processes dominated the concentration level during the LD period compared to the PRLD period [24]. However, the role of these sources in the temporal variability would be small compared to anthropogenic contributions. MH is one of the busiest transportation hubs in Kerala. The petrochemical industries of the Ambalamugal industrial region (near MH) could also be a major source of particulate matter at MH. Construction activities (for the Kochi Metro) could have a significant role in the particulate matter levels at CC and MH. The lockdown during 2020 as well as 2021 limited the construction activities in the region, which might have influenced particulate matter levels during the LD phases. It may be noted that the particulate matter at CC and MH during the LD phases (of 2020 and 2021) was reduced by more than 50% during the PRLD period (Table 3). Even after the relaxations in the lockdown measures, PM$_{10}$ and PM$_{2.5}$ exhibited a notable reduction in concentration compared to the PRLD period, which is mainly due to the effect of increased humidity and monsoon rainfall.

The temporal variability of AQI at IA in 2021 indicates hardly any improvement in the ambient air quality. On the contrary, air quality showed significant improvement during the LD phase of 2020 (Table 3). Although the particulate matter at IA showed a decrease in its concentration during the LD period of 2021, CO levels remained slightly higher during the LD and PTLD periods. In 2021, CO levels regulated the AQI at IA throughout the LD and PTLD periods, whereas the CO levels were influential for only one-third of the PRLD period. However, the prominent pollutant controlling the AQI during 2020 was particulate matter (PM$_{10}$), and the significant reduction of PM$_{10}$ during the LD period contributed to the reduction in the AQI values. Emission from a large number of industrial units is attributed to the increased CO levels at IA. The lockdown during 2020 resulted in the reduction of CO levels (~40%) in the LD and PTLD periods compared to the PRLD period (Table 3). However, in 2021, the lockdown measures did not restrict the operation of industrial units completely, which might have led to higher CO levels even during the LD phase. The AQI values at all the stations in 2021 were significantly lower (compared to 2020) implying better air quality than in 2020, where seasonal rainfall might also have played a significant role. The amount of rainfall received in 2021 was relatively higher compared to the same period in 2020 [25]. The removal of air pollutants from the atmosphere by precipitation and improvement in air quality has been reported by many researchers [26, 27, 28]. In general, the rainy days are fewer during the PRLD period compared to the LD and PTLD periods [25], and hence, the influence

| Station | Pollutant | PRLD | LD | PTLD | 2021 | 2020 | 2021 | 2020 | 2021 |
|---------|-----------|------|----|------|------|------|------|------|------|
| CC*     | PM$_{2.5}$| 30.2 | 40 | 9.5  | 17.3 | 11.2 | 9.8  |
|         | PM$_{10}$ | 60.2 | 70.6 | 24.9 | 37.3 | 36.2 | 24   |
|         | NO       | 15.1 | 39  | 13.9 | 6.6  | 16.7 | 9.3  |
|         | NO$_{2}$ | 5    | 4.8 | 2.8  | 2.4  | 3.1  | 5.5  |
|         | NH$_{3}$ | 4.7  | 16.2 | 3.7  | 16.9 | 4    | 14   |
|         | SO$_{2}$ | 6.7  | 3.6 | 8.9  | 3    | 5.3  | 2.4  |
|         | CO (mg/m$^3$) | 0.7 | 1.4 | 0.6  | 1.6  | 0.9  | 2.2  |
| MH      | PM$_{2.5}$| 36.5 | 51.3 | 11.2 | 19.4 | 17.4 | 16.6 |
|         | PM$_{10}$ | 72.5 | 119.5 | 20.5 | 36.4 | 36.3 | 28.6 |
|         | NO       | 33.7 | 82.8 | 30.8 | 72.8 | 29.8 | 31.3 |
|         | NO$_{2}$ | 4.4  | 18.7 | 3.2  | 10.5 | 3.2  | 6.9  |
|         | NH$_{3}$ | 3.4  | 6.9 | 3.7  | 7.4  | 3.3  | 6.2  |
|         | SO$_{2}$ | 9.4  | 19  | 3.1  | 16   | 5.4  | 20.4 |
|         | CO (mg/m$^3$) | 1  | 1.3 | 0.8  | 1.1  | 0.9  | 1.6  |
|         | O$_{3}$  | 4.8  | 7.8 | 11.4 | 1.3  | 5.2  | 1.3  |
| IA      | PM$_{2.5}$| 22.9 | 16.8 | 18.6 | 9.3  | 18.2 | 10.2 |
|         | PM$_{10}$ | 43.8 | 95.1 | 28.4 | 55.1 | 29.1 | 43   |
|         | NO       | 7.5  | 12.8 | 9.4  | 8.2  | 9.1  | 8.9  |
|         | NO$_{2}$ | 12   | 14.8 | 13.2 | 6.1  | 20.4 | 3.8  |
|         | NH$_{3}$ | 4.9  | 17.4 | 11   | 6.1  | 8    | 5.2  |
|         | SO$_{2}$ | 11.2 | 6.2 | 8    | 5.6  | 9.8  | 5.5  |
|         | CO (mg/m$^3$) | 0.9 | 0.5 | 1.1  | 0.3  | 1.5  | 0.3  |
|         | O$_{3}$  | 42.5 | 31.4 | 47.3 | 22.7 | 46.9 | 10.1 |

Units: µg/m$^3$ unless mentioned otherwise * O$_{3}$ is not available at CC

Table 3: Concentration of pollutants during PRLD, LD, and PTLD periods of 2020 and 2021


of rainfall on the concentration of pollutants was minimal during the PRLD period.

The three LCZs considered in this study are characterized by a low pervious fraction compared to other LCZs of the region. Although vegetation plays a major role in the dispersion and deposition of air pollutants, mostly particulate matter [29, 30], vegetation cover is highly dispersed in the region due to compact buildings and impervious surfaces in the urban region. The variability of building and surface morphological parameters of the three monitoring stations is shown in Table 4. The natural surface fraction is less than 30% in all the LCZs, where the MH and IA stations have a relatively higher vegetation fraction (~30%) compared to CC (<20%).

The results of this study infer that the variability in the improvement of air quality between the various periods of 2021 and 2020 could be the result of the differences in the intensity of the lockdown restrictions during the LD phases as well as the difference in the public response to the relaxation of the lockdown measures. Since variation in the air quality is also linked to the local meteorological factors, the differences in the changes in the air quality could also be the result of the variability of the regional meteorology (though not analyzed in this study) between the periods. The effect of seasonality on the ambient air quality of Kerala was demonstrated by Thomas and coauthors31, who observed a significant declining trend in the concentration of various air pollutants in Kerala between PRLD and LD periods. The results of this study also signify the intra-urban variation of AQI in three LCZs within the Kochi and call for measurements from a dense network of observation stations to understand the air quality behaviour of cities that have emerged from tiny urban sprawls.

Table 4  Building and surface morphological parameters of three monitoring stations

| Stations | Mean Building Height | Canon or Building Aspect Ratio (H/W) | Sky View Factor | Building Surface Fraction | Impervious Surface Fraction | Pervious Surface Fraction |
|----------|----------------------|-------------------------------------|-----------------|---------------------------|-----------------------------|--------------------------|
| CC       | 9–24 m               | 0.8–2.5                             | 0.3–0.6         | 40–70%                    | 30–50%                      | <20%                     |
| MH       | 3–9 m                | 0.6–0.9                             | 0.2–0.6         | 40–60%                    | 20–50%                      | <30%                     |
| IA       | 6–10 m               | 0.3–0.5                             | 0.6–0.9         | 30–50%                    | 20–40%                      | <30%                     |

5 Conclusion

The effect of COVID-19 lockdown measures on the ambient air quality of the Kochi urban region has been investigated in this study. The AQI calculated at the different ambient air quality monitoring stations (CC, MH and IA) representing different LCZs (CMR, CLR and HI) of Kochi showed significant spatio-temporal variability between the PRLD, LD and PTLD periods in 2020 and 2021. We observed a significant reduction in the concentration of the air pollutants and an improvement in the ambient air quality (manifested as a reduction of AQI by 50%) at CC and MH stations during the LD period of 2021, whereas hardly any changes at IA. On the other hand, the LD period of 2020 witnessed a reduction of 53% of the AQI values at MH and 41% at IA, but no significant changes at CC (~5%). This study also reports a significant difference in the changes in the air pollutant levels between the LD and PTLD periods of 2020 and 2021. While most of the air pollutants continued to decrease in the PTLD period and recorded lower levels than the LD period in 2020, most of the air pollutants at CC, MH and IA stations showed an increase in the PTLD than the LD period in 2021. The differences in the improvement of ambient air quality of different LCZs between the various periods of 2021 and 2020 could be a result of the following factors: (1) varying levels of lockdown restrictions and public response to the staggered phases of relaxation, and (2) variability in the regional meteorological factors. The study highlights the intra-urban variation of AQI with respect to local climate and calls for measurements from a dense network of observation stations to understand the air quality behaviour of cities for better air quality management.

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Data Availability The Daily CPCB AQI data for more than 200 Indian stations is available open-source at https://app.cpcbccr.com/ccr/#/caaqm-dashb oard-all/caaqm-landing.

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Declarations

Conflict of 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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