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Regulated Traffic Emission Influence on Urban Air Quality - A Coherent Analysis using Sequential Covid-19 Pandemic Lockdown Episodes in Lucknow, India

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Air quality deterioration has been a major concern due to the increased road transportation and other urban activities to fulfill the requirements of the growing population in the cities. A relative difference between the impact of stationary sources and road traffic on urban air quality was rarely addressed. Further, dispersion extent of traffic emissions during the regulated road vehicular density and movement was underexplored. The study quantitatively assessed the influence of regulated road traffic emissions on atmospheric particle pollution using the episodic COVID-19 traffic restrictions in Lucknow, India. Concurrent VKT emissions and near-road measurements of PM_{10} were evaluated for 9 sampling sites covering residential, commercial, and industrial areas in the city. An incremental trend is observed in ambient PM_{10} by 1.9 and 1.7 times with the sequentially increased load of vehicular emission from the complete lockdown to partial lockdown and the following partial lockdown to unlock phases of COVID-19, respectively, in the city. USEPA AERMOD-model predictions concerning traffic emission alone provided the impact of air dispersion ranging from 0.2 km to 1.5 km distance from the city roads to nearby surrounding areas. Predictions and observations of PM_{10} differed maximally during the complete lockdown, and by the unlock phase of COVID-19, the difference was reduced, which indicates the significant influence of stationary and non-stationary sources in the city. Further, the variations between the predictions and observations of PM_{10} for residential, commercial, and industrial sites in the city give a comprehensive understanding of emission source distribution impact under urban land use settings in Lucknow.

Keywords: COVID-19 lockdowns, Dispersion modelling, Particle pollution, Traffic volume, Vehicular emission

Introduction

The quality of ambient air is directly influenced by the activities of industrialization, urbanization, and infrastructure development. The air quality deterioration leads to adverse health of the exposed public. Dispersion and concentration of air pollutants in the atmosphere strongly depend on three key factors such as strength of the emission sources, terrain status, and local meteorological conditions of a region.[1] Numerous studies highlighted vehicular emissions as the prime factor of poor air quality particularly in the urban atmosphere.[2,3] Further, recent source apportionment studies of megacities in India under NCAP (National Clean Air Programme) also emphasized traffic emissions as a major contributor followed by the other local and regional level fugitives.[4–7] However, it is difficult to confirm the quantification of the relative impact of vehicular emissions alone on urban air pollution unless using a comparison study between the traffic emission contributions of controlled and uncontrolled episodic events like stringent restrictions on vehicular movements, and road traffic density during the business-as-usual periods. Such a situation was aroused around the globe with the restrictions on public movements to control the Novel Coronavirus disease (COVID-19) pandemic of December 2019.

Air quality studies identified a significant association between COVID-19 pandemic records from hospitals and the concentration of atmospheric aerosol as effective transmitting virus carriers in most metropolitan cities.[8,9] Kumar *et al.* also found there was a positive connection between the air pollution exceedances with the number of hospital admissions due to COVID-19 infections along with the increase in the death rate of confirmed COVID-19 cases.[10] Therefore, strict lockdown measures were applied everywhere, including the cities in India, to control

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the aerosol-transmitted pandemic and protect the health of the public. The government of India enforced complete national lockdown restrictions from March to April 2020 by suspending all rail, air, and road transportation services except emergency local services. In the subsequent year 2021 of the same period also implemented a partial lockdown to control the COVID-19 pandemic, where conditional relaxation was applied by opening up some government, industrial, and economic sectors. Prohibition on traffic and public movements was also continued, particularly for quarantine and busy market zones in various cities in India. Complete relaxation from the COVID-19 lockdowns was decided for most cities in India since 2022. The initial strict lockdowns controlled the road traffic movement by almost 70% (as allowed emergency vehicles and ambulances) and subsequent relaxed lockdowns also restricted the on-road vehicular movement almost by ~50% (as blocked some road routes near quarantine zones) in comparison to the strict lockdowns and unlock phase traffic (business-as-usual period).[11–13]

Throughout the world, sudden reductions in air pollution levels were reported during the COVID-19 pandemic lockdowns and the sequential extension of lockdown to partial lockdown periods.[14,15] For the cities in India, air pollution reduction was also visually observed in COVID-19 lockdowns from 35% to 54%.[15–17] Gulia *et al*. reported a substantial decline in $PM_{2.5}$ concentrations, with reductions of ~16-32% across 46 Indian cities and about 30% in Lucknow, underscoring the dominant role of anthropogenic activities in urban air quality.[18] Mahato *et al*. reported that PM_{10} and $PM_{2.5}$ concentrations experienced a maximum reduction exceeding 50% compared to the pre-lockdown period in Delhi.[17] Kumari *et al.* observed maximum decreases of 58% in PM_{10} and 57% in $PM_{2.5}$ across 39 Indian cities during the 2020 lockdown, compared to the previous year.[19] Further, local weather patterns also significantly influenced the corona-virus's spread and remain highly correlated to the number of deaths as micro-meteorology plays a key role in dispersion, transportation, and react of air pollutants in the atmosphere.[20] A decrease in COVID-19 instances was observed in numerous studies when temperatures increased.[21] Likewise, there is no discernible correlation between humidity and the frequency of COVID-19 cases, suggesting that humidity has no effect on transmission in some areas.[22] Rainfall also does not seem to be directly related to the number of cases, although wind speed has a positive correlation with COVID-19 instances, most likely because it helps virus particles spread through the particle pollution in the atmosphere.[23] Singh *et al.* pointed out that the high Air Quality Index (AQI) reduced the natural healing rate of the atmosphere against uninterrupted anthropogenic activities.[24] However, the sudden pause of human disruption and activity during the COVID-19 lockdowns resulted in a reversal situation as the atmosphere's natural rate of healing outpaced the rate of pollution and turned into clean air atmosphere and decreased AQI rankings.

Beginning from the stringent restrictions to the relaxation of lockdowns of COVID-19, a drastic change was observed in the vehicular density and traffic flow in each various city, however, their relative emission influence on the corresponding urban air quality was rarely assessed quantitatively.[25–27] Besides, sources other than traffic flow were also restricted parallelly in most cities to control the public movement and pandemic incidents of COVID-19. Little research only addressed the actual impact of stationary sources along with the controlled vehicle emissions on ambient air quality using sequential episodic COVID-19 lockdowns.[28,29] Further, studies on the atmospheric dispersion of traffic emissions alone and the relative contribution of different types of vehicles to ambient particle pollution are under-explored, which has the possibility to apply the episodic situation like COVID-19 pandemic restrictions on urban traffic movement.

Given the above rationale, the relative impact of changes in road traffic density and type of vehicle movement, and their emission strength on atmospheric PM_{10} (i.e., particulate matter size $\leq$ 10 micrometres) is quantified in the present study. The study also addressed the emission inventory of different types of vehicles, trends of particle pollution, and comparison between atmospheric air dispersion simulations outputs by AERMOD (AMS/EPA Regulatory Model) with ground-level measurements of PM_{10} during COVID-19 sequential lockdown, partial lockdown, and unlock phase for an urban region of Lucknow, India. Further, the study emphasized the novel evidence on how the change in vehicular density and urban landscape patterns affects the air quality of a major city. The study results assist with scientifically validated information to the policymakers in preparing better air quality management plans by targeting not only vehicular sources but also paying attention to other diversified local fugitives.

Materials and Methods

Study Area and Sampling Network

Lucknow is the capital city of the Uttar Pradesh state, India, and a plethora of new road construction plans have been enforced for more convenient vehicular movement in the city. The study area is laid out between the latitudes: 26°46’30” N to 26°54’16” N and longitudes: 80°49’12” E to 81°40’ E, covering the entire city area of 461.55 sq. km. The road network in the city has become dense, and many residential, commercial, and industrial areas are encircled by the traffic roads due to the rapid development of the city. Ambient PM_{10} sampling was carried out at 9 different functional zones in the city during the sequential COVID-19 pandemic lockdowns (i.e., complete lockdown in 2020 and partial lockdown in 2021) and also subsequent unlock phase of year 2022. The sampling sites covered four residential sites (L1-Aliganj, L2-Vikas Nagar, L3-Indira Nagar, and L4-Gomati Nagar), four commercial sites (L5-Charbagh, L6-Alambagh, L7-Aminabad, and L8-Chowk), and one industrial area (L9-Amausi), which covers the different land-use types of the city. The collection of PM_{10} samples was carried out approximately 100 to 300 m away from the road transportation line to obtain the relative impact of vehicular movement and other near-road emission sources that exist along the road corridors. Simultaneous vehicular emission inventory was also conducted for the traffic lines near to the 9 sampling sites. The geo-referenced study area, the locations of sampling sites, and traffic inventory road lines in Lucknow city are illustrated in Fig. 1.

Site-Specific Sampling for PM_{10} and Meteorological Data

Concurrent sampling of PM_{10} was carried out between 9 locations in the city during the COVID-19

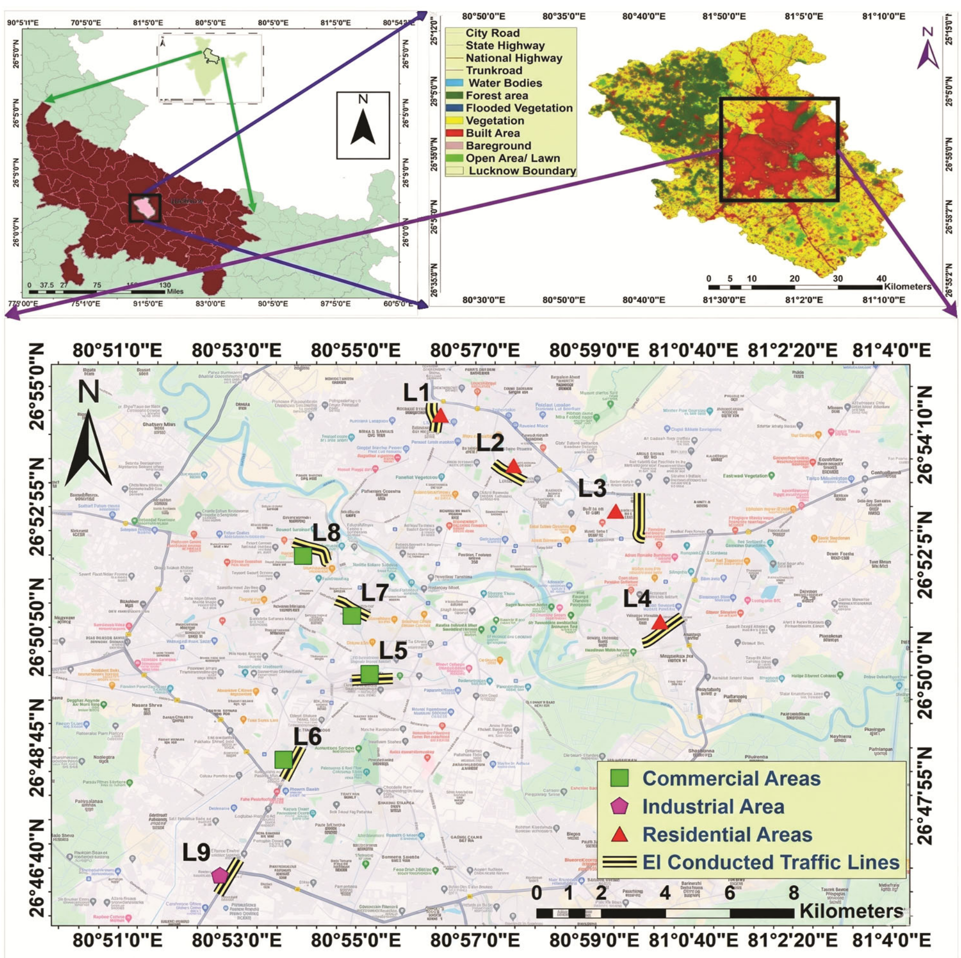

Fig. 1 — Land use patterns of the study region, and sampling locations of PM_{10} and meteorological monitoring, and traffic lines where vehicular emission inventory (EI) was conducted in Lucknow city

pandemic lockdown, partial lockdown, and unlock phases that occurred in subsequent pre-monsoon seasons in the sequential years, i.e., between March and April months of 2020, 2021, and 2022. The PM_{10} samples were collected twice weekly over a month with a 12-hour sampling duration, i.e., 8 AM to 8 PM, to include the influence of all urban activities as well as peak hour vehicle movements in the city. The key reasons to exclude the collection of PM_{10} samples during night time are (1) to avoid the irregularity of source-mix impact under sequential lockdown, (2) understand the variability in impact of vehicular and non-vehicular sources when all activities in the city functions at maximum capacity, and (3) exclude the influence of atmospheric stability and inversion effect on sample load, which are dominant during nocturnal hours. ARA-N-FRM instruments (Model: N-FRM, Make: ARA, and Sr. No.: 16284) of CSIR-IITR with an inlet-air flow of 1 m^3/min were passed through the 47 mm quartz membrane filter substrates to collect samples of ambient PM_{10}. Further, the same instrument aggregated met-station was used for simultaneous monitoring of local meteorological parameters (i.e., wind speed, wind direction, dry bulb temperature, relative humidity, solar radiation, and rainfall, etc.) for the entire sampling period at all respective 9 sampling sites. The instrument was placed 3 m above the ground with tripod support for representative meteorology, and filters were baked, desiccated, and pre-weighed before sampling. The concentration of PM_{10} in µg/m^3 was calculated with the standard gravimetric method concerning the dust mass collected on a filter substrate and suctioned air volume for the entire sampling period.[30,31]

Traffic Emission Inventory and Air Dispersion Modelling

A concurrent traffic survey along with PM_{10} sampling was carried out for the nearby roads (i.e., arterial/semi-arterial and city roads) to the 9 sampling sites in Lucknow through proper video recordings. Traffic counting for different types of vehicles plying on the road was carried out during the sequential year's COVID-19 lockdown, partial lockdown, and unlock phases. The total number of vehicles driving on the road was calculated based on the observed vehicle fleet survey count method.[32] The traffic survey vehicle data were classified into two-wheelers, three-wheelers, passenger cars, buses, and trucks. Further, fuel-type segregation was performed based on visual identification from the video recordings, i.e., CNG-buses and three-wheelers, and diesel-buses and trucks. Passenger cars were categorized as petrol, diesel, and CNG using regional fuel-mix statistics reported in transport databases and previous studies.[33,34] Due to limitations inherent to video-based observations, vehicle vintage and Bharat Stage–specific information could not be directly identified. Therefore, a mixed urban fleet assumption was adopted, consistent with standard emission inventory practices for Indian cities.[35] Vehicle Kilometres Travelled (VKT) was estimated by combining the category-wise traffic volume (vehicles per day) with the effective road length and average travel distance of the surveyed road segments. Emission load and VKT were applied as representative indicators to identify vehicle categories with the potential influence on near-road air quality. The emission load of ambient PM_{10} attributable to different vehicle categories was evaluated by multiplying the category-wise VKT with the corresponding emission factors (g/km) detailed in Table 1, which are adopted from recent and widely used studies and guidelines.[33,34,36–40]

The AERMOD View (Version 9.5, License Serial No: AER0009891) Lakes Environmental Software of CSIR-IITR was used to predict the dispersion extent of vehicular emissions from the traffic lines to near localities during regulated traffic movements under COVID-19 pandemic lockdowns in the city. Further, the model predictions were applied to understand the relative impact of vehicular emissions alone on ambient PM_{10} at 9 sampling sites in the city when concerning the operation and shutdown of other local sources. The site-specific meteorological data recorded at the 9 respective near road PM_{10} sampling sites in Lucknow was processed in the AERMET View to obtain surface-file and profile-file of the study region for input the planetary boundary layer and micro-meteorology influence to AERMOD dispersion model. Further, SRTM (Shuttle Radar Topography Mission)-GL1 30 m level elevation data

Table 1 — Emission Factors used for different vehicle types

Sl No.	Vehicle type	Emission factor of PM_{10} (g/km)
1	Two-wheelers (2W)[33,34]	0.04
2	Three-wheelers (3W)[41]	0.12
3	Car-Petrol[33,34]	0.04
4	Car-Diesel[33]	0.12
5	Car-CNG[42]	0.01
6	Bus-CNG[31]	0.04
7	Bus-Diesel[43]	0.6
8	Truck (Diesel, HDV)[44]	0.8

for the study region was applied through the AERMAP View to incorporate terrain conditions to the AERMOD model domain. The meteorology and terrain processor outputs and the aggregated vehicular emission loads from the near road lines of 9 sampling sites in the city were used as key inputs for AERMOD modelling for the respective COVID-19 lockdown, partial lockdown, and unlock phases. The model prediction outputs and the site-specific observed values of PM_{10} are compared to analyse the probable influence of vehicular sources on ambient PM_{10} during the change of restrictions on traffic movement in the city as base episode of COVID-19 lockdowns and unlock phases.

Results and Discussion

Traffic jams, vehicle mobility patterns, and traffic density trends for the different types of vehicles were surveyed during the sequential lockdowns and unlock phases of COVID-19 for the near-road network of air pollution sampling locations in the city. The vehicular survey data were assessed for the vehicle Emission Inventory (EI) in terms of the VKT (Vehicle Kilometre Travelled). The total number of VKT during the lockdown, partial lockdown, and unlock phases of COVID-19 is illustrated in Fig. 2. An incremental trend of VKT is observed for all vehicle categories in the three consecutive years. Among the vehicle types, petrol cars recorded the highest VKT with a distance travelled of ~2200 kilometres in 2022. A significant increase was also identified for diesel cars and diesel buses, which indicates the extensive use of buses and cars for transportation and commuting purposes in the city. On the other hand, the three-wheeler vehicles consistently recorded the lowest VKT, however, an incremental trend was noticed in three-wheeler vehicles over the three years. An overall significant increment of VKT from 2020 to 2022 was found to be maximum for trucks (5.2 times), followed by buses (4.4 times), three-wheelers (4.0 times), two-wheelers (3.5 times), and cars (2.7 times). Overall, the graph highlights a clear rising trend in vehicular usage in the city to cope the gradually increased urban demand and economic activity during the post-pandemic period.

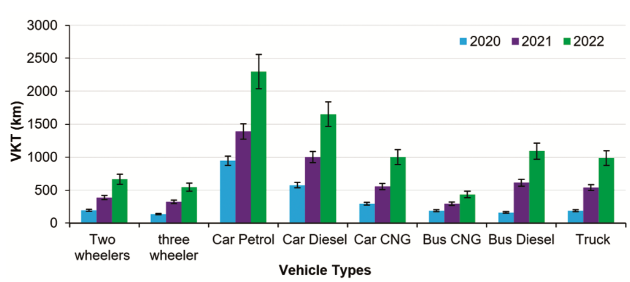

Fig. 2 — Vehicle kilometre travelled (VKT) for different types of vehicles

The emission load impact of different types of vehicles to the ambient PM_{10} at 9 sampling sites were assessed. The maximum PM_{10} emission load is identified from car-petrol, then followed by car-diesel, truck, bus-diesel, car-CNG, two-wheelers, three-wheelers, and bus-CNG. The comparison between analysis results of ambient PM_{10} sampling at 9 different functional areas and the corresponding near-road site-specific vehicular emissions of PM_{10} for the consecutive years of COVID-19 pandemic lockdowns (i.e., lockdown, partial lockdown, and unlock phase) in the city delineated in Fig. 3.

The mass concentration of PM_{10} was increased gradually from the complete lockdown to the unlock phase of COVID-19 at all the sampling sites in the city. Overall, the city traffic emission load of PM_{10} was also observed to increase ~ 1.9 times during the complete lockdown to partial lockdown, whereas from the partial lockdown to the unlock phase of COVID-19, its increment was identified with a factor of ~1.7. Further noticed that the levels of ambient PM_{10} breached the national standard (i.e., 100 μg/m^3) in all the lockdown phases due to the contributions from permitted emergency activities and existing urban background pollution in the city. Previous air quality studies also reported that the concentration of particle pollution had a decreased trend when the COVID-19 pandemic lockdown was started and subsequently the levels of pollution were found to increase progressively when the unlock phase was initiated for the respective cities in India.[45–49]

A maximum PM_{10} was recorded for the commercial sites than the residential and industrial sites, and L_5 was found highest among the 9 sites due to L_5 site being encircled by the dense urban sources-mix with congested traffic passages and curb-side high-rise buildings induced urban canopy effect. The data analysis revealed a significant correlation between the trend of PM_{10} and the corresponding site-specific vehicle emission rate of the three subsequent COVID-19 lockdown phases. Overall, the observed variations in ambient PM_{10} between residential, commercial, and industrial sites for all three COVID-19 pandemic phases indicated a relative influence of the urban land use settings as well as the distribution of

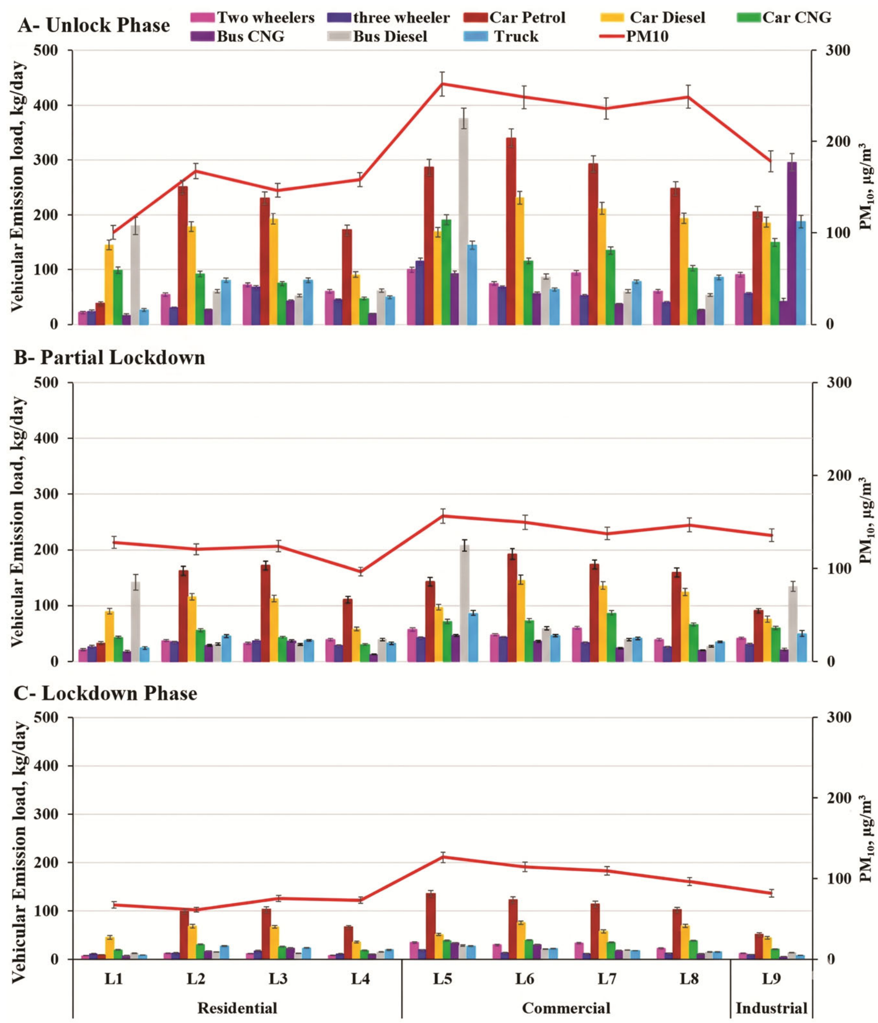

Fig. 3 — Concentration of ambient PM_{10} and road transportation emission load during Lockdown, Partial lockdown, and Unlock phases at 9 sampling locations in Lucknow

the multiple source mix. The gradual increase of VKT from strict lockdown to the complete relaxation phase of the pandemic, particularly by cars, buses, and trucks, indicated the strong impact of traffic emissions on urban air quality deterioration. Besides, the comparison between the values of traffic emission load and ambient PM_{10} concentrations for the pandemic lockdowns and unlock phases has also established a strong influence on the air quality trend by the urban land-use settings of the city.

The meteorological conditions during the summer season (March-April) of 2020–2022 in Lucknow associated to characteristics of pre-monsoon seasonal features. Ambient temperatures showed a consistent rise from early March to late April, which is typically ranged from 22–25°C to 35–40°C. Relative humidity remained moderate to low (~25% to 55%), reflecting dry atmospheric conditions that can lead to surface dust resuspension to ambient air. Rainfall was scanty and episodic (i.e., < 20 mm to 30 mm) across all three years, providing limited wet scavenging of particulate matter. Wind speeds were predominantly low (0.5 m/s to 2.1 m/s) with a notable share of calm conditions (8% to 18%) observed in all three years, indicating weak atmospheric ventilation. Wind-direction analysis revealed a persistent predominant flow from south-west with resultant vectors between 170° and 200°, implying consistent regional airflow toward the urban core. The wind-rose diagrams for the lockdown, partial lockdown and complete unlock phases are presented in Fig. 4. The concurrence of high temperature, low humidity, negligible rainfall, dynamic wind profiles in the summer can favourable to ambient air dispersion in Lucknow.

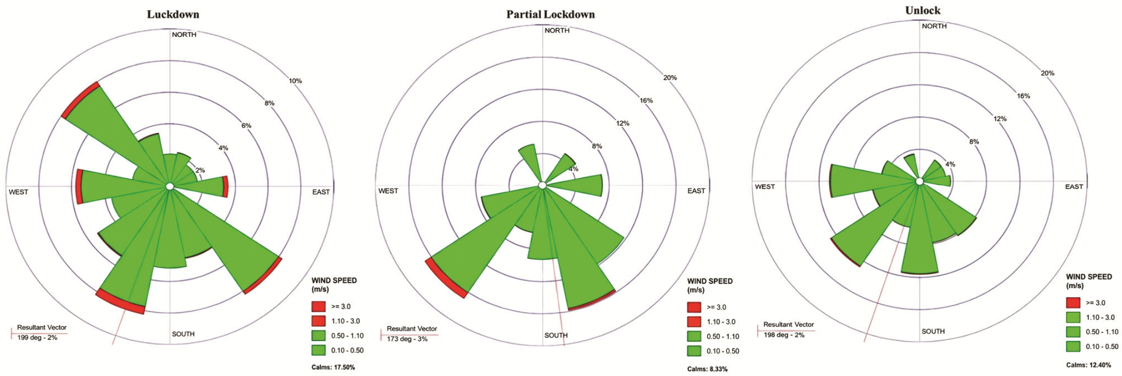

Fig. 4 — Windrose diagrams for Lockdown, Partial Lockdown and Complete Lockdown phases

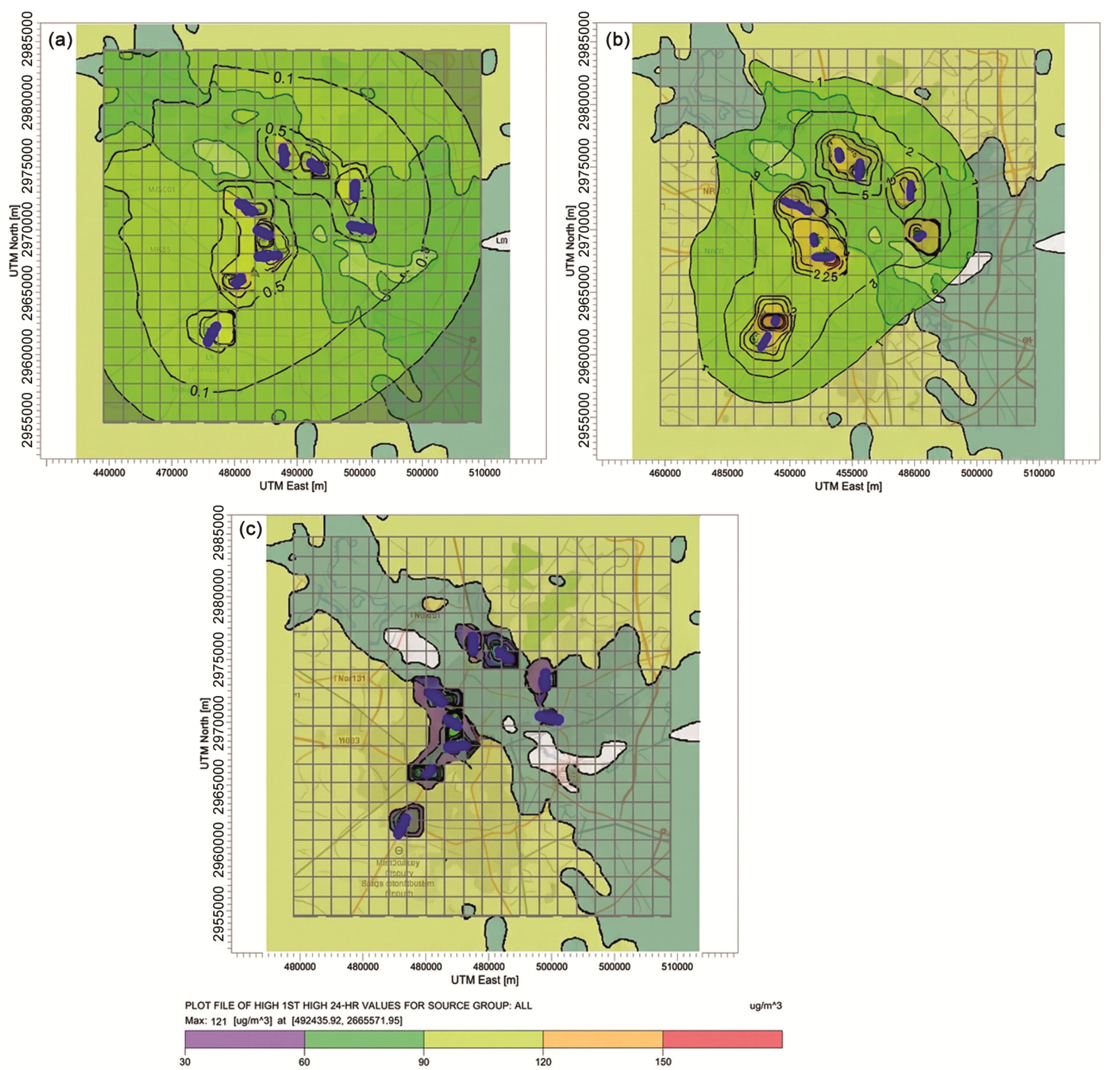

Fig. 5 — AERMOD model dispersion of PM_{10} due to road-traffic emissions during (a) unlock phase, (b) partial lockdown, and (c) lockdown of COVID-19 pandemic in Lucknow

AERMOD dispersion model run results for the three phases of COVID-19 lockdowns by the input of site-specific meteorological and terrain data, a load of near-road vehicular emissions, and air sampling sites as receptor points are illustrated in Fig. 5. The maximum ground-level concentration of PM_{10} was predicted at L_5 by 92 μg/m^3, 97 μg/m^3, and 111 μg/m^3 for complete lockdown, partial lockdown, and unlock phases, respectively. The computational model outputs indicated that the road traffic emissions contribution in the ambient PM_{10} at 9 sampling sites was sequentially increased from stringent restriction to complete relaxation for the city traffic. Further, the mean dispersion of vehicular emission of PM_{10} between the 9 receptor locations was observed propagating at a maximum distance of 0.2km to 1.5km starting from the middle of the road traffic line. However, the gradual increment of the dispersion of traffic emissions during sequential COVID-19 restrictions and subsequent resume of business-as-usual vehicular movement in the city indicated the significance of the impact of density of road traffic on urban air quality. AERMOD model predictions concerning traffic emission alone represent an important contributor of air pollution by vehicular movement at 9 sites in the city. The study excluded PM_{10} sampling during night time, which enabled the appropriate correlation between model results and ground observations along with the appropriate dispersion impact of vehicular emissions before the surface inversion built in the city during nights.

The comparison analysis between onsite observations of ambient PM_{10} and AERMOD model predictions based on vehicular emissions of PM_{10} during three consecutive COVID-19 restriction phases is shown in Fig. 6. The concentration of PM_{10} derived from the AERMOD model was identified as much lower than the site observations for all three phases. The vehicular emission load-induced impact on the atmosphere PM_{10} resulted in terms of the contribution by a range of 25% to 35%, 40% to 55%, and 60% to 70% for the unlock phase, partial lockdown, and lockdown phases of COVID-19, respectively, which is quite significant. A gradual reduction of the

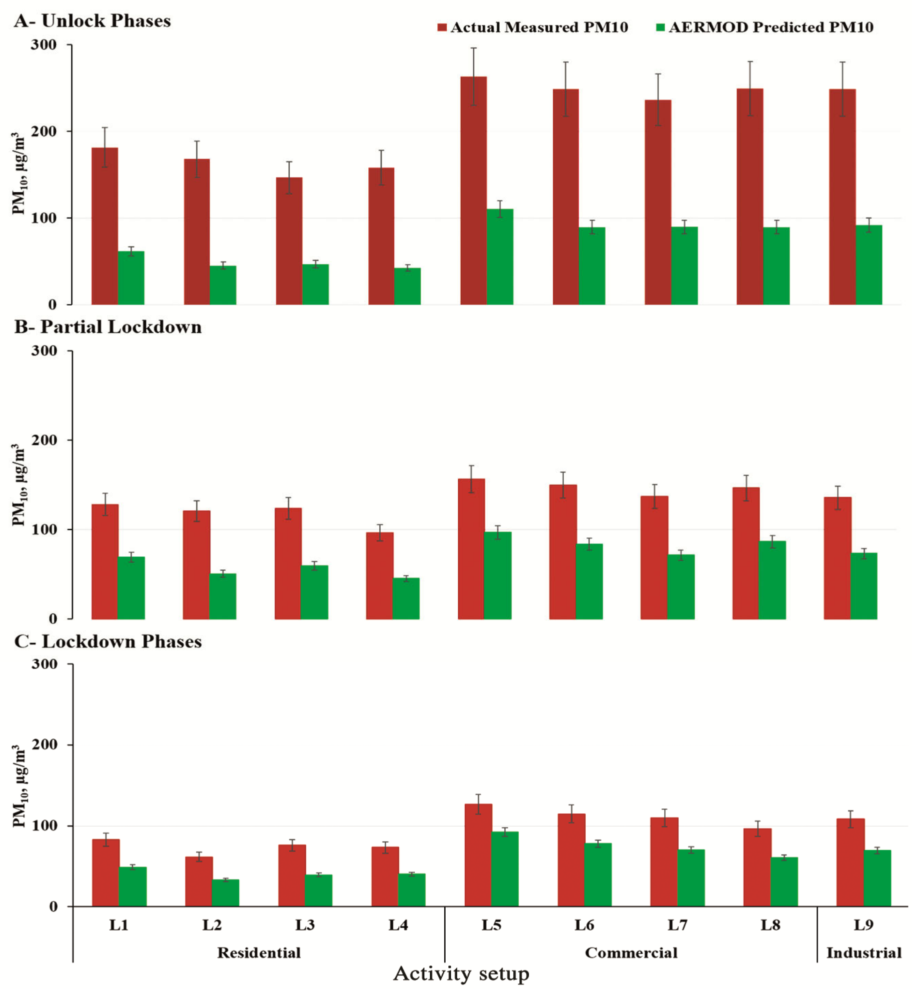

Fig. 6 — Comparison between ground-level observations and AERMOD model predictions of PM_{10} for 9 air sampling locations in Lucknow during (A) unlock (B) lockdown and (C) partial lockdown phases of COVID-19

contribution of vehicular emissions to the total measured PM_{10} from lockdown to the unlock phase of COVID-19 is notified, which indicates influence of local fugitive source-mix of the city other than road transport emissions.

Typically, the non-vehicular local source in Lucknow mainly is road re-suspended dust, cooking activities by hotels, restaurants, bakeries, food stalls, waste burning, industrial stacks, and diesel generator sets, crematoriums, activities of construction and demolition, etc.[50] Further, the difference between the PM_{10} of measured and model predictions for the residential sites is observed relatively less than the same observed at the commercial and industrial sites. This reveals the significant impact of the urban landscape setting on city's air quality. The recent source apportionment studies concerning land use and land cover patterns in Lucknow and other cities in India highlighted that most urban localities are encircled by local fugitives, therefore, the surrounding air quality is majorly influenced by local sources in which road traffic emissions is an important contributor.[4,49,51] Overall, The comparison between model predictions and site-specific measurements of PM_{10} for the three phases of COVID-19 restrictions showed a gradual incremental variation, which further indicated that the traffic emission contribution in ambient PM_{10} appears to be similarly influential in the atmosphere along with the additional sources such as road-dust, biomass burning, cooking fuels, construction activities, and other local fugitive source, which are not explicitly represented in the model.

The consistently high R^2 values (≈0.91–0.98) observed across all three years indicate that AERMOD effectively captures the relative temporal trends and dispersion behaviour of traffic-related PM_{10} (Fig. 7). The slight reduction in R^2 during the later phases (2022) reflects increasing source complexity. During the unlock phase, changes in ambient PM_{10} concentrations cannot be attributed exclusively to vehicular emissions. While increased traffic activity likely contributed to elevated PM_{10} levels, resuspended road dust, construction activities, biomass burning, and other local fugitive sources, along with variations in meteorological conditions, also played a substantial role. Although the present analysis focuses on PM_{10} as a representative indicator of near-road air pollutant, future studies integrating $PM_{2.5}$ and NO_x measurements, along with their correlation with PM_{10}, would enable a more comprehensive understanding of traffic-related exhaust and non-exhaust emission impacts in urban environments.

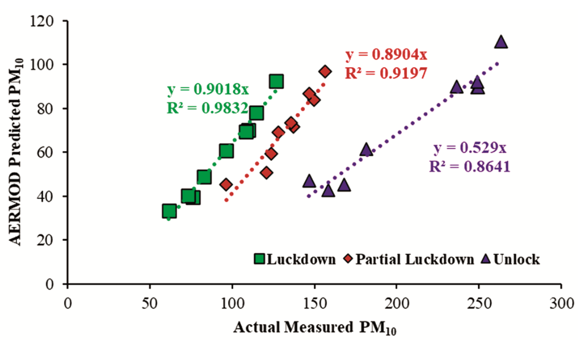

Fig. 7 — R^2 values between Actual measured PM_{10} and AERMOD Predicted PM_{10}

Conclusions

The study indicates that the mean PM_{10} in urban atmosphere increased from lockdown to unlock phases, and frequently breached its national standard. Emission inventory analysis for different types of vehicles represents the impact of cars is high, followed by buses and trucks movement in the city. The similar trends between vehicular emissions and PM_{10} measurements indicated that the traffic influences near-road PM_{10} over appreciable distances, and observations reflects the contributions from fugitive sources. The air dispersion of traffic emissions gradually increased during the sequential COVID-19 restrictions, therefore, suggesting the influence of the change in the city traffic on ambient PM_{10}. The study also suggested the importance of local fugitive sources, other than road transport emissions, in the adverse air quality of any city significantly. Further, the differences between the PM_{10} levels of model predictions and their ground measurements highlights the impact of the urban landscape on the ambient air quality.

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Ethics Approval Statement: Scientific and Ethical Vigilance Committee (SECo), CSIR-IITR has pursued the work, reviewed, and evaluated this manuscript for scientific communication and the allocated publication number is IITR/SEC/MS/2023/91.

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