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ORIGINAL PAPER

Respiratory Deposition Dose of $PM_{2.5}$ and PM_{10} Before, During and After COVID-19 Lockdown Phases in Megacity-Delhi, India

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Abstract: Considerable changes in particulate matter (PM) during COVID-19 lockdown in major cities around the World demand changes in exposure assessment studies of PM. The present study shows variations in respiratory deposition dose (RDD) of both fine ($PM_{2.5}$) and coarse (PM_{10}) particles before, during and after Covid-19 lockdown phases at three sites (with different pollution signatures) in Delhi—Alipur, Okhla and Pusa Road. Exposure assessment study showed mean $PM_{2.5}$ RDD (± S.D.) (µg/min) for walk and sit mode during before lockdown (BL) as 2.41(± 1.20) and 0.84(± 0.42) for Alipur, 2.71(± 1.60) and 0.94(± 0.56) for Okhla, and 2.54(± 1.28) and 0.88(± 0.44) for Pusa road, which decreased drastically during Lockdown 1(L1) as 0.85(± 0.35) and 0.30(± 0.12) for Alipur, 0.83(± 0.33) and 0.29(± 0.11) for Okhla, and 0.68(± 0.28) and 0.23(± 0.10) for Pusa road, respectively. Mean PM_{10} RDD (± S.D.) (µg/min) for walk and sit mode during before lockdown (BL) as 3.90 (± 1.73) and 1.36 (± 0.60) for Alipur, 4.74 (± 2.04) and 1.65 (± 0.71) for Okhla, and 4.25 (± 1.69) and 1.48 (± 0.59) for Pusa Road, respectively which decreased drastically during Lockdown 1(L1) as 2.19 (± 0.95) and 0.76 (± 0.33) for Alipur, 1.73 (± 0.67) and 0.60 (± 0.23) for Okhla and, 1.45 (± 0.50) and 0.50 (± 0.17) for Pusa Road, respectively. Significant decrease in RDD concentrations (Both $PM_{2.5}$ and PM_{10}) than that of BL phase have been found during Lockdown 1(L1) phase and other successive lockdown and unlock phases—Lockdown 2(L2), Lockdown 3(L3), Lockdown 4(L4) and Unlock1 (UL1) phases. Changes in RDD values during lockdown phases were affected by lesser traffic emission, minimized industrial activities, biomass burning activities, precipitation activities, etc. Seasonal variations of RDD showed Delhites are found exposed to more fine and coarse particles' RDD (walk and sit modes) before and after lockdown, i.e. during normal days than during lockdown phases showing potential health effects. People in sit condition found less exposed to fine and coarse RDD comparison to those in walk condition both during normal and lockdown days.

Keywords: $PM_{2.5}$; PM_{10}; RDD; COVID-19

1. Introduction

The presence of atmospheric particulate matter (PM) causes seven million of premature deaths worldwide per year [1]. Ambient PM is classified under group 1 carcinogen to humans [2] and considered one among most significant environmental risks to human health [3, 4]. As per previous empirical and experimental studies, PM is known to cause negative impacts on human health [5–7], climatic effects [8], adverse effects on ambient air quality and reduction in visibility [9, 10]. $PM_{2.5}$ is found to be linked with more health risks than PM_{10} [11] mainly due to its smaller size and longer residence time in the atmosphere [12]. According to a study, $PM_{2.5}$ exposures for long-term is estimated to increase mortality caused by cardiopulmonary diseases by 6–13% per 10 $\mu g/m^3$ of $PM_{2.5}$ [13, 14],

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whereas all-cause daily mortality associated with PM_{10} increases by 0.2–0.6% per 10 $\mu g/m^3$ of PM_{10} (WHO, [15].

The novel Coronavirus (2019-nCoV) first reported in December 2019 at Wuhan, China [16] and found to be linked with causing over 12.80 million cases and over 570 thousands deaths worldwide till 12 July 2020 [17]. On 11 March 2020, COVID-19 has been declared a pandemic by the World Health Organization (WHO) as it spread rapidly to several countries including India [18]. COVID-19 caused more than 855 thousands cases and more than 22 thousands deaths in India till 11 July 2020 [19, 20]. COVID-19 virus which belongs to Coronaviridae family has known to cause a variety of respiratory diseases in human beings [16, 21]. A strong correlation has been studied between PM's exposure and ecotoxicity, genotoxicity, and oxidative potential of PM, and morbidity from respiratory infections [22]. Also, PM exposures for a longer period have a potential impact on exacerbation of the severity of emerging diseases due to the presence of viruses like COVID-19 and SARS variants in the ambient atmosphere [23, 24]. According to previous studies, a small increase of 1 g/m^3 of $PM_{2.5}$ exposure (fine particulates) may increase the risk of mortality due to COVID-19 virus by 20 times if human body exposed over a time period of 15–20 years [25]. The impact of PM on the increase in COVID-19 cases was studied during a research carried out in Italy where "air pollution-to-human transmission" was found as a major cause for COVID-19 transmissions than "human-to-human transmission" [25]. Studies have reported that apart from direct human-to-human contacts, high outdoor and indoor PM levels contributing to urban air pollution may have a significant impact on the increased rates of confirmed COVID-19-total number, daily new and total deaths cases [26].

The exposure assessment studies are useful for impact assessment of particulate matter and takes an account of ambient PM concentrations as well as the frequency and duration for which the PM comes in contact with human body. The air pollutants exposure varies with gender, age, socio-economic status, and pre-existing health conditions of the subject, time spent by human beings in the different micro-environment as well as different meteorological conditions [27, 28]. Both epidemiological and toxicological studies confirmed the association between air pollutants emitted from traffic-related sources and human health effects due to air pollution exposure [29, 30]. Significant associations have been confirmed by various epidemiological studies between ambient PM exposure and various cardiovascular and respiratory diseases along with the increase in their respective mortality rates [31–33]. Respiratory lung deposition dose (RDD) of PM is used for health risk assessment studies during different physical activities and modes of commuting. In an urban environment, different modes of commuting causes different exposures to various air pollutants [34]. Commuting exposure studies for pollutants also consider the transport mode types for commuting, route opted, time of the day and fuel type used [35, 36]. Studies revealed that significant variations in PM concentrations inside the commuting vehicle are found that are closely linked with the changes taking place in the PM concentrations found outside the vehicle [37, 38]. Previous studies show deposition under moderate physical activities like walking to be three or more times greater than when at rest [39]. Therefore, there is an importance of studying RDD of ambient particulate matter to study deposition potential of PM into our lungs in different micro-environments and outdoor-environment during different physical activities (walk/sit) and modes of communication.

Studies have reported that fine PM fraction is greatly deposited in the airways during physical activities like exercise/walking as compared to rest [40]. With more intense level of physical activities, total respiratory deposition of PM will be higher which may enhance the adverse effects of PM. For example, people who exercise in a polluted urban environment are more vulnerable to air pollution effects than those who are at rest. The adverse health effects become more prominent for sensitive people like asthmatics, children, and elderly people [1]. More exposure to PM during physical activities can cause inflammation in the airways and worsen asthmatic responses [41] and may also trigger other respiratory health problems [42], cardiovascular disease [43–46], and cancer [47], leading to premature death [48]. The health risk from exposure depends on pollutants concentration entering into body as well as frequency and duration of contact of air pollutants with the body [49]. Since breathing rates define the amount of PM concentration inhaled into respiratory system, breathing rates during physical activities like walking or cycling are found to be greater than those sitting inside homes, car or bus leading to more exposure of human body to PM's RDD during physical activities than while sitting [50]. Therefore, RDDs are better indices for health risk assessment studies of PM during different modes of physical activities.

Higher levels of PM including fine ($PM_{2.5}$) and coarse (PM_{10}) have been found in the ambient atmosphere of Delhi, India [51, 52]. COVID-19 pandemic in India led to a nationwide lockdown starting from 24 March till 31 May 2020 which has caused lesser transportation activities and decreased industrial activities during lockdown event causing sudden decrease in air pollutants concentration in various parts of India [52–58]. Delhi is one of the hotspots of air pollution around the globe, and due to sudden changes in PM concentration during lockdown the change in exposure assessment due to PM during lockdown was studied. Since RDD concentration is directly linked to PM concentration, the present work explores the changes in RDD concentrations of both fine and coarse particulate matter (PM) at different sites of Delhi having different pollution signatures before, during and after lockdown phases in Delhi, India.

2. Material and Methods

2.1. Site Description

In the present study, Megacity-Delhi has been chosen as study area where three sites have been selected including Alipur as rural, Okhla as Industrial and Pusa Road as Traffic with residential area whose details are provided in Table 1. The study site Alipur is the administrative headquarters and a sub-division of North Delhi district and lies in Northern part of Delhi. Alipur area is rural, has residential colonies and lies nearby national highway. Pusa Road site is a representative of traffic pollution in Central Delhi region with compact residential colonies in nearby region. Okhla site lies in the south-east district of Delhi nearby Okhla industrial area and connected to the border of Uttar Pradesh, State of India. Okhla industrial estate has three phases including readymade and leather garment exporters, plastic and packaging industries, pharmaceutical manufacturing units, printing presses, machinery manufacturers, call centres, MNCs Office, Bank, etc. Apart from industrial estate, Okhla also has an extension of a residential area including various residential colonies.

2.2. Data Collection and Analysis

Real-time data for $PM_{2.5}$ and PM_{10} have been collected from air quality monitoring stations (for three sampling sites—Alipur, Okhla, and Pusa road) which are installed and being monitored in collaboration with Central Pollution Control Board (CPCB) [continuous ambient air quality monitoring, CAAQM & manual ambient air quality monitoring, MAAQM]; DPCC (Delhi Pollution Control Committee); IITM (Indian Institute of Tropical Meteorology), Pune; and, SAFAR (System of Air Quality and Weather Forecasting and Research). The collected data are converted into daily averaged data for concentrations ($\mu g/m^3$) of $PM_{2.5}$ and PM_{10} which have been used for RDD calculations. The raw data used here is available at CPCB online portal for air quality data dissemination [59] which has been analysed for air quality assessment studies for before and during the different lockdown periods of COVID-19 and unlock phases. The data analysis is in compliance with quality assurance or quality control (QA/QC) protocols which are carried out by CPCB such as timely calibration of the instruments. Data from January to June 2020 have been studied for analysing air quality, for before and during different COVID-19 lockdown and unlock phases as mentioned below:

Table 1 Site description

Site name	Site details	Latitude	Longitude	Altitude
Pusa road	Traffic area	28°38′36.10“N	77°11′9.94”E	230 m
Okhla	Industrial area	28°33′44.96“N	77°17′28.17”E	204 m
Alipur	Rural-residential	28°47′49.97“N	77° 8′0.12”E	214 m

2.2.1. *Different Phases of Before Lockdown, Lockdown and Unlock during COVID-19*

Before lockdown (BL): 1 January–24 March 2020 (~ 4 months);

Lockdown phase-1 (L1): 25 March–14 April 2020 (21 days);

Lockdown phase-2 (L2): 15 April–3 May 2020 (19 days).

Lockdown phase-3 (L3): 4 May–17 May 2020 (14 days);

Lockdown phase-4 (L4): 18 May–31 May 2020 (14 days).

Unlock phase-1.0 (UL1): 1 June–30 June 2020 (30 days);

For studying seasonal variations of RDD, $PM_{2.5}$ and PM_{10} concentration data have been analysed for the year 2019 and 2020. Seasonal variations have been studied for following four seasons—Winter (January–February), Pre-monsoon (March–May), Monsoon (June–September), Post-monsoon (October–December) classified as per India Meteorological Department [60].

2.3. Data Analysis

2.3.1. *Equations for Respiratory Deposition Dose (RDD) Estimation for Fine ($PM_{2.5}$) and Coarse Particles (PM_{10})*

The RDD estimation method used in this study is based on the International Commission on Radiological Protection [61] method of calculation. As per previous studies, RDD has been calculated using Eqs. 1, 2 and 3, respectively [49, 62–65] as mentioned below:

$$\text{RDD of PM (size, } i\text{; in } \mu\text{g/min)} = (V_T * f) * \text{DF}_i * \text{PM}_i \tag{1}$$

where V_T stands for the tidal volume (m^3 per breath), f represents typical breathing frequency (breath per minute), and DF_i shows deposition fraction of a size fraction i.

(Here, for $PM_{2.5}$, size fraction (i) or particle diameter (d_p) = 2.5 µm; and, for PM_{10}, d_p = 10 µm.

PM_i = Mass concentration in different size ranges (Here, mass concentrations (in µg/m^3) of $PM_{2.5}$ and PM_{10} is used for calculations of RDD for fine and coarse mode particles, respectively.)

$$DF = IF\left(0.058 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln dp} + \frac{0.943}{1 + \exp(0.508 - 2.58 \ln dp)}\right) \tag{2}$$

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076 d_p^{2.8}}\right) \tag{3}$$

The V_T and f values used in this study mainly depend on the physical activity and gender of a person. As similar trends of RDD have been reported for both male and female [49, 65], the RDD calculation used in this study has been done using values available for males only for brevity reasons and to understand a general trend of RDD for residents of Delhi. V_T and f values used here for walk mode are 12.5×10^{-4} m^3 per breath and 20 breaths per minute, respectively, whereas for sit mode, 7.5×10^{-4} m^3 per breath and 12 breaths per minute, respectively, for male [50]. DF_i for both fine and coarse size particles used here has been calculated using particle diameter (represented as d_p) of $PM_{2.5}$ and PM_{10}, respectively [50].

3. Results and Discussion

In the present study, RDD is calculated for both fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter as discussed below:

3.1. Variations in $PM_{2.5}$ RDD for Walk and Sit Cases Before, During and After COVID-19 Lockdown

$PM_{2.5}$ RDD values have been calculated for fine mode particle diameter (d_p) = 2.5 µm (Fig. 1a–c & Table 2). The daily variation reveals higher respiratory deposition dose (RDD) for $PM_{2.5}$ before lockdown for both walk and sit cases than during lockdown and unlock conditions at all the three sites (Fig. 1a–c). Lower $PM_{2.5}$ RDD was reported during L1 phase for both walk and sit conditions with gradual increase during L2, L3, L4 and UL1 phases with slight variations among RDD for the selected sites (Fig. 1a–c). Daily, $PM_{2.5}$ RDD values were lowest during L1 comparison with BL but among different sites, reported higher for Pusa Road site during L1 due to lower but ongoing vehicular activities as a result from lenient lockdown rules at this particular site. For Alipur site, higher daily $PM_{2.5}$ RDD values were reported during L4 due to increase in crop burning activities in nearby agricultural fields during L4 phase [70]. Mean $PM_{2.5}$ RDD (± Standard Deviation (S.D.)) for both walk and sit mode during BL is calculated (in µg/min) as 2.41 (± 1.20) and 0.84 (± 0.42) for Alipur, 2.71 (± 1.60) and 0.94 (± 0.56) for Okhla, and 2.54 (± 1.28) and 0.88 (± 0.44) for Pusa Road, respectively (Table 2). The values for mean $PM_{2.5}$ RDD (± S.D.) for both walk and sit mode decreased drastically during L1 as 0.85 (± 0.35) and 0.30 (± 0.12) for Alipur, 0.83 (± 0.33) and 0.29 (± 0.11) for Okhla, and 0.68 (± 0.28) and 0.23 (± 0.10) for Pusa Road, respectively, with increasing values in successive lockdown phases (Table 2). This signifies that RDD values for $PM_{2.5}$ were more for moving/walking persons than those sitting indoors and less for L1 phase than BL phase. Gupta and Elumalai, 2019, have reported that RDD of fine particles mostly affects alveolar region during physical activities like exercising [65]. Variations in mean $PM_{2.5}$ RDD concentrations (± S.D.) (in µg/min) during different phases (BL, L1, L2, L3, L4 and UL1) for both walk and sit modes are shown in Table 2.

Exposure assessment study using RDD is a major tool for health impact assessment studies, which considers the factors like physical activity of individuals, particle size and concentrations of fine and coarse particles as well as the time spent in a specific micro-environment [66, 67]. People's mobility reports also provide better indices for calculation of the time spent in various micro-environments. Google and Apple mobility reports [68, 69] confirmed that residents of Delhi have mostly resided inside their homes (outdoor activities showed 70–80% decrease in L1 from BL phase), while some people moved for groceries, retails and transit [70]. Although the RDD calculated here considers ambient $PM_{2.5}$ concentrations, the people living inside their homes may also be exposed to outdoor concentrations with windows open condition. According to a study conducted in warm season, indoor exposures to particles were found similar to that of outdoor particle exposures as a result of opening of windows for a longer periods [71]. The study shows that during lockdown (L1 phase), Delhites were exposed to lower RDD values ($PM_{2.5}$ and PM_{10}) of sit conditions, while majorly being at home (as per google/apple mobility reports) [68–70], whereas those walking outside were exposed with more RDD values than when in sit mode.

Kumar et al. [49] reported the RDD for fine particles for walk mode as 5–6 µg h^{-1} and for car mode as 1.8–2 µg h^{-1}. According to a study conducted at Barcelona, higher RDD values with almost similar values were

Table 2 Mean values of $PM_{2.5}$ and PM_{10} RDD (μg/min) for walk and sit mode before lockdown, during different lockdown and unlock phases (BL, L1, L2, L3, L4 and UL1) at three sites in Delhi

Sampling Locations	Phases/Events	$PM_{2.5}$ RDD for walk mode (μg/min)	$PM_{2.5}$ RDD for sit mode (μg/min)	PM_{10} RDD for walk mode (μg/min)	PM_{10} RDD for sit mode (μg/min)
Alipur	Before Lockdown (BL)	2.41 (± 1.20)	0.84 (± 0.42)	3.90 (± 1.73)	1.36 (± 0.60)
Okhla		2.71 (± 1.60)	0.94 (± 0.56)	4.74 (± 2.04)	1.65 (± 0.71)
Pusa Road		2.54 (± 1.28)	0.88 (± 0.44)	4.25 (± 1.69)	1.48 (± 0.59)
Alipur	Lockdown 1 (L1)	0.85 (± 0.35)	0.30 (± 0.12)	2.19 (± 0.95)	0.76 (± 0.33)
Okhla		0.83 (± 0.33)	0.29 (± 0.11)	1.73 (± 0.67)	0.60 (± 0.23)
Pusa Road		0.68 (± 0.28)	0.23 (± 0.10)	1.45 (± 0.50)	0.50 (± 0.17)
Alipur	Lockdown 2 (L2)	1.10 (± 0.40)	0.38 (± 0.14)	3.20 (± 1.04)	1.11 (± 0.36)
Okhla		0.94 (± 0.32)	0.33 (± 0.11)	2.35 (± 0.79)	0.82 (± 0.27)
Pusa road		0.97 (± 0.80)	0.34 (± 0.28)	1.08 (± 1.19)	0.72 (± 0.41)
Alipur	Lockdown 3 (L3)	1.41 (± 0.44)	0.49 (± 0.15)	2.96 (± 0.93)	1.03 (± 0.32)
Okhla		1.01 (± 0.31)	0.35 (± 0.11)	2.49 (± 0.67)	0.86 (± 0.23)
Pusa Road		1.24 (± 0.30)	0.43 (± 0.11)	2.52 (± 0.47)	0.87 (± 0.16)
Alipur	Lockdown 4 (L4)	1.49 (± 0.76)	0.52 (± 0.27)	3.93 (± 1.67)	1.37 (± 0.58)
Okhla		1.03 (± 0.53)	0.36 (± 0.18)	3.33 (± 1.37)	1.16 (± 0.48)
Pusa Road		1.00 (± 0.32)	0.35 (± 0.18)	2.87 (± 1.12)	1.00 (± 0.39)
Alipur	Unlock 1 (UL1)	1.07 (± 0.22)	0.36 (± 0.10)	2.78 (± 1.33)	0.97 (± 0.46)
Okhla		0.93 (± 0.22)	0.32 (± 0.08)	2.96 (± 1.38)	1.03 (± 0.48)
Pusa Road		0.81 (± 0.22)	0.28 (± 0.08)	2.12 (± 1.02)	0.74 (± 0.35)

observed for walk and cycle modes as 6.8 μg h^{-1} and 6.7 μg h^{-1}, respectively, whereas lower RDD values were found for commuting modes like bus and car modes as 5.4 μg h^{-1} and 5.6 μg h^{-1}, respectively [35]. Other studies reported highest RDD (mean ± S.D., Range μg h^{-1}) for $PM_{2.5}$ for walk mode as 4.9 ± 1.0,3.7–6.1 μg h^{-1}, lower RDD for bus mode as 2.7 ± 1.1; 1.9–4. μg h^{-1} and the lowest for car mode as 1.0 ± 0.2; 0.7–12 μg h^{-1}, among various mode of commuting [72]. Kumar et al. [49] suggested that commuters have been exposed to the lowest RDD for fine particles in cars (sit mode) in comparison with other commuting modes like bus, cycling and walk despite the presence of higher concentrations of fine particles inside the cars. The reason behind the fact observed as the physical activity (sitting) of commuters inside cars is modest in comparison with those who are walking and cycling. Our study revealed the highest daily $PM_{2.5}$ RDD before lockdown comparative to during lockdown phases (L1, L2, L3, L4, UL1), and L1 showed the lowest daily RDD both for walk and sit mode (Fig. 1a–c). Values for daily and mean RDD values (in μg/min) reported here are quite high in before lockdown conditions than the previous reported studies (in μg/hr) which shows that Delhi residents are exposed to quite higher RDD for fine particles present in the ambient concentrations during normal days. Apart from outdoor concentrations of PM, indoor conditions further increases fine particle concentrations which can enter into human lungs, bronchiole and finally may penetrate into alveolar regions of the respiratory system. Also, use of vehicles like buses or public modes of transport are characterized by the entrance of outdoor particles and high PM concentrations as a result of natural ventilation while opening of doors during inflow and outflow of travellers at bus stations/stop points which causes re-suspension of dust particles at higher rates [72–74]. Gulliver and Briggs [75] reported that inside vehicles PM RDD increases with the related health effects.

3.2. Variations in PM_{10} RDD for Walk and Sit Cases Before, During and After COVID-19 Lockdown

Respiratory deposition dose (RDD) values for PM_{10} concentrations were calculated for coarse mode particle diameter (d_{p}) = 10 μm (Fig. 1d–f and Table 2). The study shows higher daily RDDs for PM_{10} before lockdown for both walk and sit cases than during lockdown and unlock conditions (Fig. 1d–f). Mean PM_{10} RDD values (in μg/min) for walk and sit mode during BL are found as 3.90 (± 1.73) and 1.36 (± 0.60) for Alipur, 4.74 (± 2.04) and 1.65 (± 0.71) for Okhla, and 4.25 (± 1.69) and 1.48 (± 0.59) for Pusa Road, respectively (Table 2). PM_{10} mean RDD ((S.D.) in μg/min) for both walk and sit mode decreased during L1 as 2.19 (± 0.95) and 0.76 (± 0.33) for Alipur, 1.73 (± 0.67) and 0.60 (± 0.23) for Okhla, and 1.45 (± 0.50) and 0.50 (± 0.17) for Pusa Road,

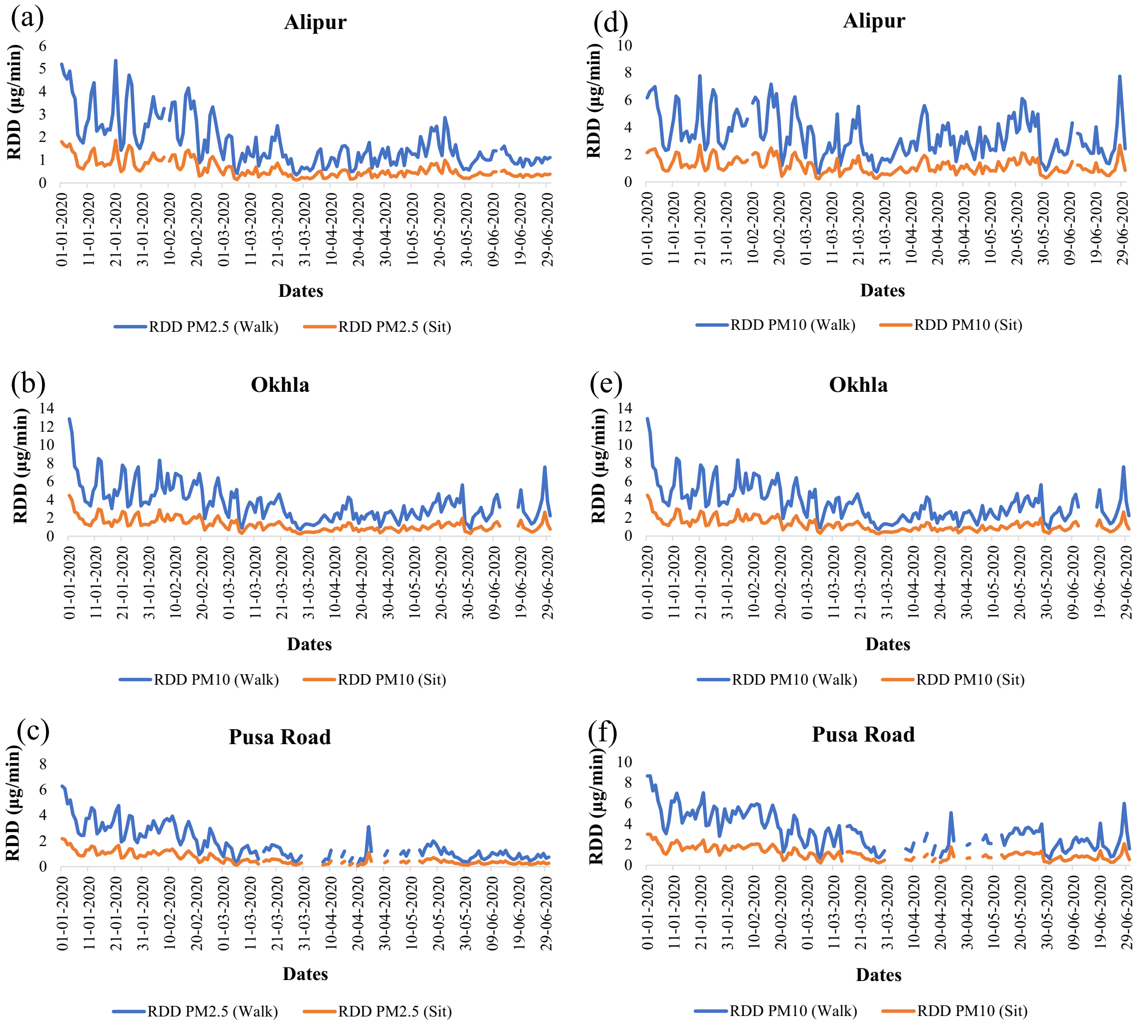

Fig. 1 Day-wise variations in RDD (µg/min) for $PM_{2.5}$ and PM_{10} (walk/sit mode) for three different sites identified by their region-specific signatures **a** Alipur **b** Okhla **c** Pusa Road before, during and after lockdown phases

respectively (Table 2). During L4 phase, Delhi (specifically Alipur site) was majorly contributed by biomass burning activities [70]. Both fine and coarse mode RDD values found to decrease during UL1 phase against L4 due to lesser biomass burning activities and more precipitation events (Table 2). Among site-wise variations, higher RDD values for both walk and sit mode were found for Okhla before lockdown, whereas for Alipur, higher RDD values found during whole lockdown period than the other sites (Table 2). The reason may be attributed to higher industrial operations at Okhla during BL phase which was minimized during lockdown phase (L1). Alipur being a rural area with sources like biomass burning from agricultural fields, vehicular emissions from highways, local waste burning, emissions from landfill dumping site present nearby shows comparatively lesser effect of lockdown conditions than the other sites in terms of PM_{10} RDD. Site-wise variations in mean PM_{10} RDD concentrations (± S.D.) (in µg/min) during different phases (BL, L1, L2, L3, L4 and UL1) for both walk and sit modes have been shown in Table 2. Among site-wise variations during BL phase, Okhla being an industrial area and thus having higher PM_{10} concentrations has higher RDD values followed by Pusa Road (Traffic contribution) and the lowest RDD for Alipur (Rural area). The study shows higher RDD values of coarse PM than the fine PM for both walk and sit mode during all phases (BL, L1, L2, L3, L4 and UL1) (Table 2).

Kumar et al. [49] reported the highest mean RDD for coarse particles (PM_{10}) during the walk and car mode as 40–66 µg h^{-1} and 0.8–1.3 µg h^{-1}, respectively. Emissions from traffic and re-suspension of dust particles during walking can increase coarse particle exposure during walk mode to the pedestrians [49]. The highest value of daily RDD (in µg/min) during before lockdown conditions for both walk and sit mode (Fig. 1d–f) is quite high in

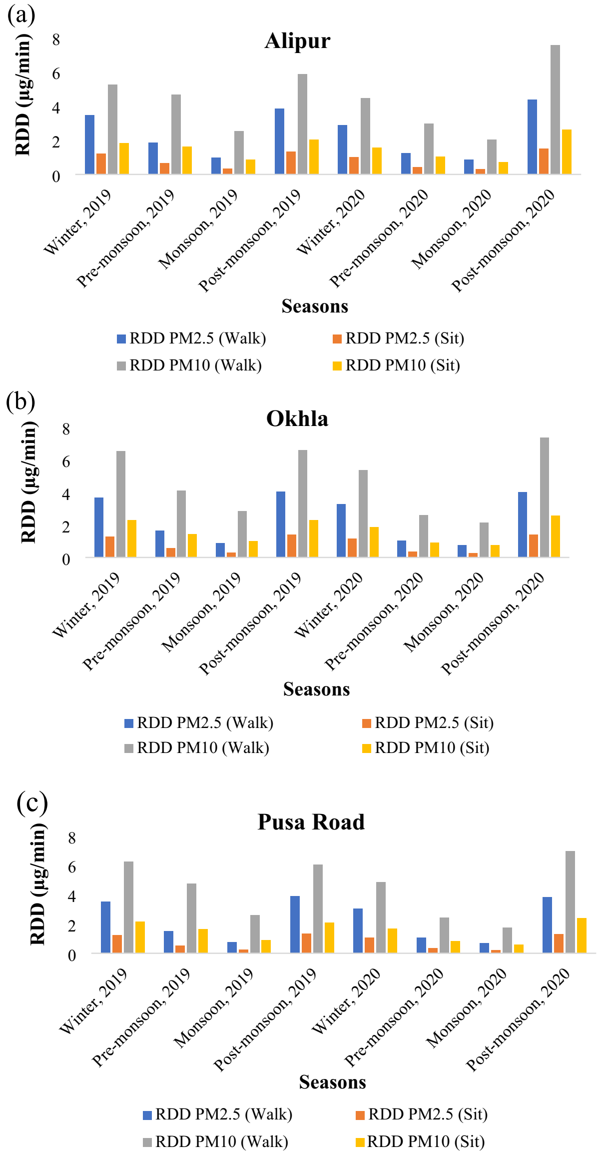

Fig. 2 Seasonal variations in RDD (µg/min) for $PM_{2.5}$ and PM_{10} (walk/sit mode) for three different sites **a** Alipur **b** Okhla **c** Pusa Road

comparison with the other reported studies (in µg/hr) showing higher exposure of Delhi residents towards coarse particle pollution during normal days.

3.3. Seasonal Variation of $PM_{2.5}$ RDD and PM_{10} RDD at Delhi

Figure 2 shows seasonal variations in RDD (µg/min) for $PM_{2.5}$ and PM_{10} (walk/sit mode) for three different sites—Alipur, Okhla and Pusa Road. The highest $PM_{2.5}$ RDD and PM_{10} RDD concentrations (µg/min) were reported for Post-monsoon and Winter season during year 2019 and 2020 at all the three sites for both walk/sit modes (Fig. 2a–c). In Delhi, Post-monsoon season is mainly characterized by high biomass burning and lower temperature with high relative humidity contents in atmosphere leading to higher PM concentrations thus affecting PM's RDD. Lower concentrations of both $PM_{2.5}$ and PM_{10} RDD (µg/min) during Pre-monsoon season, 2020 in comparison with that during 2019, are attributed to the effect of COVID-19 lockdown for both walk/sit modes at all the three sites (Fig. 2a–c). This shows significant reduction in PM's RDD values (despite similar meteorological conditions due to same seasons) as a result on stringent rules during lockdown conditions.

4. Conclusion

The study shows higher daily and mean respiratory deposition dose values (RDD) for $PM_{2.5}$ and PM_{10} before COVID-19 lockdown for both walk and sit cases than during lockdown and unlock conditions. This signifies that Delhites are exposed to higher particulate matter associated RDD values during normal days as in before lockdown conditions, whereas the RDD exposure decreased during COVID-19 lockdown conditions. Also, RDD values for walk mode found higher than the sit mode showing extent of RDD inhaled during physical activities like walking and commuting outside were higher than sitting inside homes. Google and Apple mobility reports also confirmed that Delhites were mostly remained inside their homes thus affected by PM's RDD in sit mode because of less outdoor activities during lockdown conditions. Values for RDD (µg/min) reported here are quite high in before lockdown condition than the previous reported studies (µg/hr) which shows that Delhi residents are exposed to higher RDD values for both fine and coarse particles present in the ambient concentrations during normal days. During COVID-19 lockdown, RDD decreased drastically at all the three sites, whereas site-wise comparison during lockdown phases showed higher RDD values for Pusa Road site during L1 due to lesser but ongoing vehicular activities at the site and for Alipur site during L4 due to crop burning activities in nearby fields. Okhla site was found to have lowest RDD values during L1 due to minimized industrial activities. Both fine and coarse mode RDD values found to decrease during UL1 phase against L4 due to less biomass burning activities and precipitation events leading to suppression of ambient particulate matter concentrations ($PM_{2.5}$ and PM_{10}) and hence lowering-related RDD. Seasonal variation in $PM_{2.5}$ RDD and PM_{10} RDD values showed higher concentration during Post-monsoon and Winter seasons (2019, 2020) for all the three sites as a result from source contribution and meteorological conditions. Pre-monsoon season, 2020, was characterized with lower RDD in comparison with that during 2019 due to stringent rules on source emissions during lockdown conditions. Since, changes in RDD are directly linked to PM concentrations and physical activities, this study shows significant role of RDD to determine potential health effects related to PM exposure during different physical activities (walk/sit).

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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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