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Assessing PM_{10} Transmission Changes under Different Lockdown Phases. A Case Study of the City of Colombo

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Abstract

Air pollution is a major man-made disaster, and most researchers have reported that lockdown events such as COVID-19 pandemic are likely to impact air quality. However, there are limited studies in Sri Lanka about spatial and temporal changes in PM_{10} before, during and after the COVID-19 pandemic. Therefore, this study focused on assessing the spatiotemporal impacts of COVID-19 on PM_{10} in the Colombo Municipal Council. Landsat 8 (OLI) data and observed PM_{10} data collected from the NBRO and US embassies in Sri Lanka and Arc GIS 10.5 were used to analyze the PM_{10} data. The study was conducted in 2019, 2020 and 2021. The year 2020 was identified according to three main phases: Before COVID-19 Lockdown Period, COVID-19 Lockdown Period and the Travel Restriction Period. In 2019 and 2021 were divided according to the 2020 phases, to identify the variations in PM_{10}. According to the results of this study, the accuracy assessment revealed a strong correlation (R2 = 0.89) between the calculated and observed PM_{10} concentrations. The city of Colombo is highly vulnerable to PM_{10}, and the TRP concentration in 2019 was reported to be high, at 182.33 µg/m3. The lowest PM_{10} concentration was 20.03 µg/m3, which was reported for LP in 2020. Most areas exceeded the World Health Organization standard value of 50 µg/m3 for PM_{10} during these three years. The highest PM_{10} concentrations can be found in port city area, city center, trade center (Fort), road junctions, industrial zones, construction areas, etc. Therefore, it is necessary to take necessary actions to reduce this man-made disaster to create a healthy environment for urban inhabitants.

Keywords: Air pollution, COVID-19, PM_{10}, Landsat, GIS

1. Introduction

Air pollution is a major man-made disaster worldwide and is currently one of the enormous ongoing threats faced by world public health (WHO, 2016). Approximately 90% of the world's population is estimated to reside in areas with air pollution levels beyond those judged safe for human health (WHO, 2018), which causes 7 million deaths annually (or 13% of all deaths worldwide) and a 2-year decline in average life expectancy (Greenstone and Fan, 2018). However, it is currently one of the main problems in developing countries (Othman et al., 2010). In the urbanization process in developing countries, population growth and human-induced anthropogenic activities are the core factors influencing air pollution. The most important air quality

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parameters are particulate matter, SO_2, NO_2, CO_2, O_3, and NH_3. PM with an aerodynamic diameter lower than 10 µm, called PM_{10} (Alvarez-Mendoza et al., 2019), is one of the main direct contaminants of air quality (WHO, 2018). PM_{10} has undesirable environmental impacts on air quality and is linked to public health issues such as respiratory diseases and cardiovascular disease (Joss et al., 2017; Kobza et al., 2018) and atmospheric visibility and climate change in developing countries.

The primary anthropogenic emission sources of particulate matter (PM_{10} and $PM_{2.5}$) are the household, transport, and industrial sectors (Gurjar et al., 2016). Industries, coal-based thermal power plants, and transportation are the main sources of NO_2 emissions in the atmosphere, while industries, home biomass burning, and transportation are the main sources of CO_2 emissions. The use of sulfur-containing fuel in coal-based thermal power plants and other sectors is related to SO_2 emissions (Sharma & Dikshit, 2015).

As a developing country, Sri Lanka faces several environmental issues, and air pollution is a key environmental, health and social problem in Sri Lanka. Poor urban air quality has been one of the major environmental problems (Premasiri, 2020) faced during the last few years in Sri Lanka, and according to the Central Environmental Authority (CEA), the annual average ambient PM_{10} concentration in Colombo has continued to increase within the 60 to 82 $\mu g/m^3$ range, with a slight increasing trend from 1998 to 2011, and it has consistently exceeded the latest WHO guideline value of 50 $\mu g/m^3$ for PM_{10}. Thus, the city of Colombo is very unhealthy in terms of particulate pollution (CEA, 2017). Motor vehicle emissions are the most significant cause of air pollution in the area. More than one million vehicles arrive in the city of Colombo through the eight entrances, and the number of vehicles leaving the city of Colombo is 173,611 per day. For these reasons, the city of Colombo can be recognized as a major air-vulnerable area in Sri Lanka.

Today, the spread of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic, called coronavirus disease 2019 (COVID-19), is aggressive. In Sri Lanka, the first case of COVID-19 was reported on 27th January 2020. From 27th January 2020 to 28th July 2021, there were more than 301,832 island-wide cases and more than 4,000 confirmed deaths (WHO, 2021). Most global researchers have attempted to identify how this pandemic has affected the environment sector, especially the air. Before COVID-19, high levels of urban air pollution, mainly through concentrations of particulate matter (PM)/dust, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), were observed around the world (Sargsyan et al., 2022). Notably, Kumari and Toshniwal (2020) noted that the recent COVID-19 pandemic has had a positive effect on environmental sectors such as air, water, and soil. Singh et al. (2020) proposed that the spread of the COVID-19 pandemic at the national level has caused major changes in air pollution worldwide. Consequently, as a result of the COVID-19 pandemic's global reduction in air pollutant emissions, air pollution-related causes of morbidity and mortality are expected to decline (Katoto et al., 2021).

Most researchers have reported that the COVID-19 pandemic has had a considerable impact on air quality in several cities/countries around the world. Different studies in various regions of the world have confirmed that national lockdowns have led to air pollutant reductions in the atmosphere (Skirience & Stasiskiene, 2021). Accordingly, the goal of this study was to determine the variations in the PM_{10} concentration in Sri Lankan air due to COVID-19. To this end, several papers were cited, and their summaries are provided below.

Venter et al. (2020) and Romano et al. (2021) showed that the COVID-19 pandemic resulted in unprecedented reductions in economic activity, and in 34 countries, lockdown events reduced the population-weighted concentrations of nitrogen dioxide and particulate matter by approximately 60% and 31%, respectively. Mendez-Espinosa et al. (2020) reported that the concentrations of PM_{10}, $PM_{2.5}$, and NO_2 decreased in Northern South America during the COVID-19 lockdown. Singh et al. (2020) reported that NO_2, PM_{10}, $PM_{2.5}$, CO_2, O_3, NH_3 and SO_2 decreased and O_3 increased during the lockdown period in the megacity of Delhi, India. Hashim et al. (2021) studied the impact of the COVID-19 lockdown on NO_2, O_3, $PM_{2.5}$ and PM_{10} concentrations and assessed air quality changes in Baghdad, Iraq.

In addition, Yuan et al. (2020) focused on spatiotemporal disparities and reductions in air pollutants during the COVID-19 pandemic in a megacity of the Yangtze River Delta in China. Hasnain et al. (2021) assessed air pollution before, during and after the COVID-19 pandemic in Nanjing, China, and their results showed that compared to that in the previous three years, 2017–2019, the reduction in PM_{10} in the lockdown period was -37.99%. In addition, Kumari and Toshniwal (2020) investigated the variations in air pollutants such as NO_2, $PM_{2.5}$, PM_{10}, O_3 and SO_2 during the pre and post-lockdown phases in major cities such as Beijing, Bengaluru and Delhi, Lima, Las Vegas, Peru, Spain, Moscow, Mumbai, Wuhan, Rome, and Sao Paulo. Menut et al. (2020) analysed the impact of the COVID-19 lockdown on air quality over Western Europe. Moreover, Khaniabadi et al. (2022) estimated the air temperature, $PM_{2.5}$, PM_{10} and relative humidity in Ahvaz, Iran, and their results revealed a significant reduction in PM_{10} (29.6%) during the lockdown period.

Furthermore, Doval-Minarro and Bueso (2023) analysed meteorological conditions and traffic intensity, and the concentrations of PM_{10}, NO, O_3, SO_2 and NO_2 were measured at three different locations-rural, urban, and industrial in Southeastern Spain (from 2016 to 2021). According to the literature review, most studies were conducted using GIS and remote sensing techniques to analyse the air quality concentrations during the COVID-19 period.

However, in Sri Lanka, very few studies have investigated the spatial pattern of PM_{10} before COVID-19 using GIS and remote sensing methods. Most studies have been conducted to describe the impact of PM_{10} on health in Sri Lanka both before and during the COVID-19 pandemic. However, few studies have explored spatial and temporal changes in PM_{10} before, during and after the COVID-19 pandemic in Sri Lanka and the Colombo MC Area. Hence, effective mapping and analysis of a city's PM_{10} concentration is essential for identifying the air quality situation and formulating effective policies (Mahato et al., 2020) in the future.

The results of this study provide a practical and theoretical approach for assessing air quality based on the RS and GIS and provide information for environmental protection, management, and sustainability in the country.

The main objective of this study was to determine the impacts of the COVID-19 outbreak on the PM_{10} concentration in the Colombo MC Area. Under this main objective, three specific objectives were identified as follows: [1] to estimate the PM_{10} data values using satellite images in the Colombo MC Area. [2] to examine the accuracy of those estimated data [3], to study the spatial-temporal distribution changes in the PM_{10} distribution in the Colombo MC Area.

2. Study Area

In this study, the Colombo Municipal Council, Sri Lanka, was considered the study area, and it is the main commercial capital in Sri Lanka (Figure 1). It is situated in the Western part of the Colombo District and consists of 47 wards. The total land extent is 37.3 $km^{2,}$ and it has since increased 41.35 sq. km due to the expansion of harbours (Dissanayake & Manawadu, 2016). According to the Department of Statistics, the urban population in Sri Lanka is 18.2%, and 77.6% of the urban population lives in the Colombo District. The total population of the city of Colombo in 2012 was 561,314, and the population density was 13,364 km^2 (DCS, 2012). Built-up areas are the major land use pattern in this area. Figure 1 shows a map of the study area.

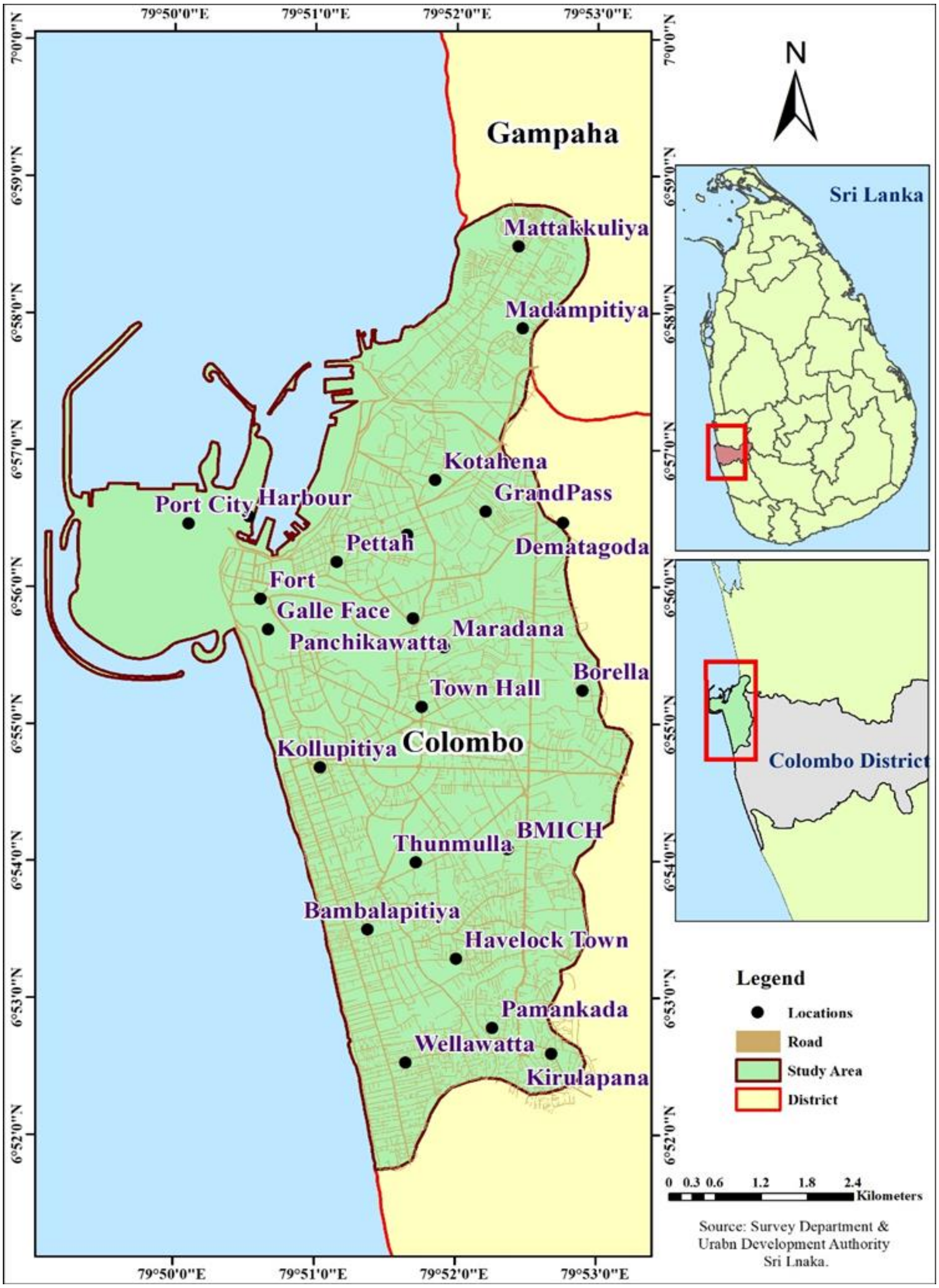


Figure 1: Map of the study area

3. Research Methodology

The methodology has been divided into several parts: data acquisition, pre-processing, data processing and accuracy validation. Data pre-processing and processing were performed using ArcGIS 10.5 software. The study was conducted over three years and one year was divided into three phases according to the 2020 COVID-19 period. The year 2020 can be divided into three main phases: before the lockdown period (BL-January to March 10), during the lockdown period (LP-March 11 to May 20), and during the travel restriction period (TRP-May 21 to December). These phases were divided into 2019 and 2021 to identify the changes in PM10.

3.1 Data Acquisition

Satellite images were collected and analysed for the periods after and during the new coronavirus outbreak in 2020. The data from 2019 (before COVID-19) and 2021 (after COVID-19) were analysed according to the 2020 COVID-19 phase in Sri Lanka. Landsat 8 data were used to estimate the PM_{10} concentration in the Colombo MC Area. All satellite data were downloaded from the USGS earth explorer website: https://glovis.usgs.gov/. The path/raw ratio was 141/55, and all satellite data were selected based on less than 10% cloud cover. The images were acquired in tiff format at 30×30 pixels.

3.2 Data Pre-processing

All Landsat images were georeferenced using the WGS 1984 coordinate reference, and radiometric and atmospheric corrections were performed for the visible bands (red, blue and green).

Typically, the received DN values can be converted into radiance using simple linear radiometric correction, and this method can be applied by transforming the values of DN to radiance or radiance to reflectance values. During image pre-processing, PM_{10} was estimated using the algorithms recommended by Saleh and Hasan (2014) and bellow equations were obtained from the Landsat 8 data handbook of the U.S. Geological Survey (USGS).

Table 1: Attribute data of the satellite images used in this study

Phases	Acquisition Date	Path/ Row	Cloud cover (%)	Rainfall (mm)*	Temperature (Max-Min (°C))*
Before covid-19 Lockdown Period (January to March 10)	2019.03.05	141/55	3.56	0.00	32.07 - 24.03
	2020.03.05		4.56	01.04	30.06 - 24.05
	2021.03.05		3.02	0.00	31.02 - 22.55
During covid-19 Lockdown Period (March 11 to May 20)	2019.04.16		2.35	0.00	32.07 - 23.08
	2020.04.17		3.25	0.00	33.75 - 23.71
	2021.04.16		4.01	0.00	30.61 - 26.22
Travel Restriction Period (May 21 to December)	2019.07.19		7.89	18.4	28.03 - 23.03
	2020.07.16		6.23	0.00	27.51 - 24.93
	2021.07.19		3.21	0.00	27.99 - 25.25

Source: Weather data were obtained from the global NASA power database

OLI spectral radiance data can be converted to TOA reflectance using reflectance rescaling coefficients provided in the Landsat 8 OLI metadata file. The following algorithms were used to convert the DN values to TOA reflectance:

$$\rho\lambda' = M\,\rho * Q\,cal + A\,\rho \quad ....(1)$$

where:

ρλ' = TOA planetary reflectance without correction for solar angle. (ρλ' does not contain a correction for the sun angle)

Mρ = Band-specific multiplicative rescaling factor from the metadata (Reflectance_Mult_Band_x, where x is the band number)

Aρ = Band-specific additive rescaling factor from the metadata (Reflectance_Add_Band_x, where x is the band number)

Q cal = Quantized and calibrated standard product pixel values (DN)

The TOA reflectance with a correction for the sun angle is then:

$$\rho\lambda = \frac{\rho\lambda}{\cos(\theta SZ)} = \frac{\rho\lambda}{\sin(\theta SE)} \quad \ldots\ldots\ldots\ldots (2)$$

where:

ρλ = TOA planetary reflectance

θSE = Local sun elevation angle. The scene center sun elevation angle in degrees is provided in the metadata (Sun Elevation).

θSZ = Local solar zenith angle; θSZ = 90° - θSE

3.3 Estimate Aerosol Optical Thickness (AOT) and PM_{10}

After image pre-processing, PM_{10} was estimated using the algorithms recommended by Saleh and Hasan (2014). The AOT algorithm for a single band or wavelength (λ) is simplified as:

$$\text{AOT}(\lambda) = \text{an R}(\lambda) \ldots\ldots\ldots (3)$$

Equation (5) is rewritten as a multiband equation as follows:

$$\text{AOT}(\lambda) = \text{a o R}\,\lambda 1 + \text{a 1 R}\,\lambda 2 + \text{a 2 R}\,\lambda 3 \ldots.. (4)$$

where

Rλ = atmospheric reflectance (i =1, 2, 3... corresponding to the wavelength for the satellite)

aj = algorithm coefficient (j =0,1,2,...), which is empirically determined

The relationship between the PM concentration and AOT is derived for a single homogeneous atmospheric layer containing spherical aerosol particles. Hence, it can be expected that the parameter PM directly correlates better with the AOT. Using the information obtained by spectral AOT retrieval, a method has been developed to retrieve particulate matter concentrations. By substituting AOT in terms of PM_{10} into equation (2) (Saleh and Hasan, 2014), the algorithm of PM_{10} with the spectral reflectance of multiband wavelengths (λi) is simplified as:

$$\text{PM10} = a_j \text{ o R}\,\lambda 1 + \text{a 1 R}\,\lambda 2 + \text{a 2 R}\,\lambda 3 \ldots.(5)$$

where

Rλi = atmospheric reflectance (i =1, 2, 3, 4 corresponding to satellite bands)

a_j = algorithm coefficient (j =0,1,2,3...) is empirically determined

Othman et al. (2010) and Saleh and Hasan (2014) reported that AOT and PM_{10} are linearly related. They found that the correlation was high and ranged from 0.78 to 0.95 (retrieved between the AOT values and PM_{10} measurements).

Finally, spatial analysis and statistical methods were used to identify the spatial and temporal patterns of the PM_{10} concentration in the Colombo MC area.

3.4 Data accuracy and validation

The accuracy was determined using observed PM_{10} data, and the variations in both the observed and estimated PM_{10} data were calculated via ANOVA and regression analysis.

The observed data were collected from NBRO (National Building Research Organization) and the US Embassy in Sri Lanka. These institutes observed four stations that covered the study area, such as Pelawatta, Gregory's Road, the US Embassy and the Meteorology Department Station. The accuracy assessment was performed for two days, which were selected using available satellite image dates and available data within the study period. The selected dates were 16.04.2021 and 19.07.2021. In Sri Lanka, there is a lack of PM_{10} data, and there are very few PM_{10} measurement stations for the whole country. The accuracy of the estimated data was determined, and using these methods, the procedure was applied to the study for different time periods.

3.5 Spatial and temporal variations in PM_{10}

In this study, spatial analysis was used to determine the spatial distribution patterns of air pollution in the study area. For this purpose, PM_{10} was analysed, and the spatial distribution of air pollutants in the study area was visualized using a color-range map and bar charts to determine the distribution of PM_{10} in the area. Figure 2 shows the overall methodology used in this study.

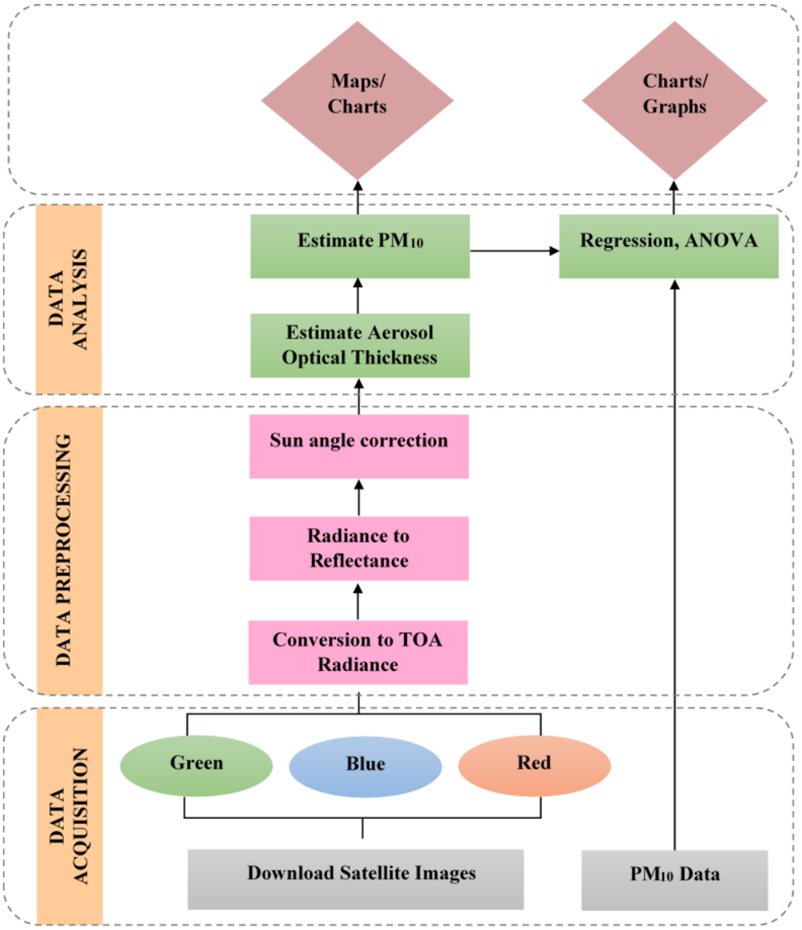


Figure 2: Methodology design used in this study

4. Results

The accuracy assessment was performed for two days during the study period. This study revealed that the accuracy of the estimated data was more than 80%, and ANOVA indicated that the F-crit value (5.9086) was greater than the F value (0.759) in 16.04.2021 and that the F-crit value (5.986) was greater than the F value (0.059) in 19.07.2021. These results clearly indicated that there was no significant difference between the calculated and observed PM_{10} concentrations in the study area.

Figure 3a and 3b show the results of the regression analysis between the observed data and the estimated data during the study period. The R^2 was 0.89 on 2021.04.16, and the R^2 was 0.86 on 2021.07.19 between the observed data and the estimated data. These results showed that there was no significant variance in the estimated data. Therefore, this methodology is very useful and can be used in future studies.

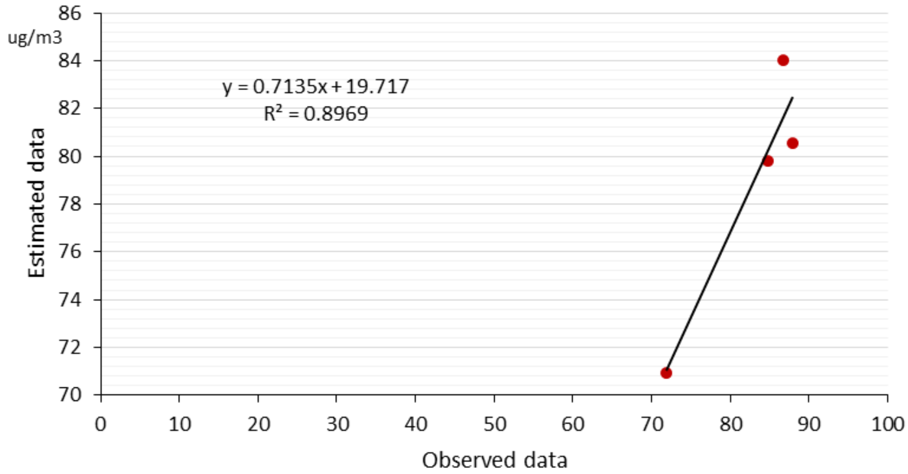


Figure 3a: Relationships between the observed and estimated data for 2021.04.16

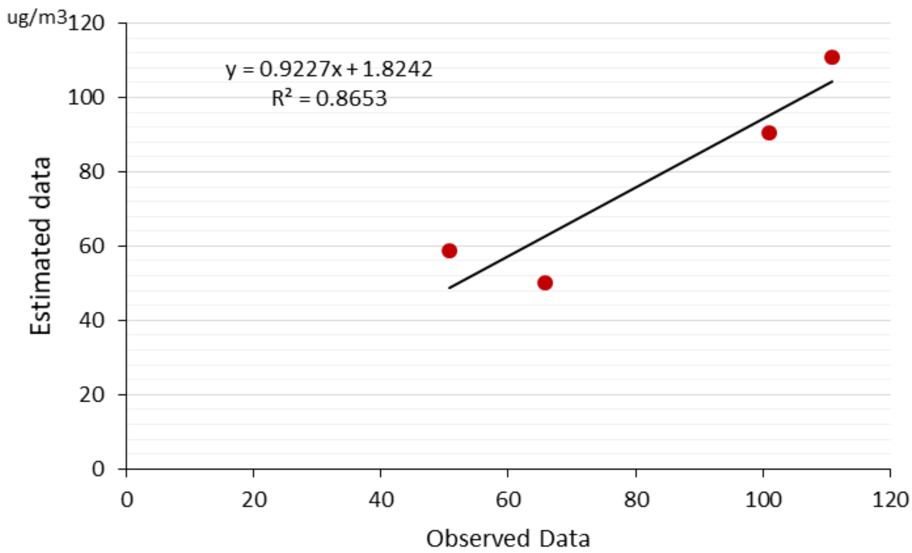
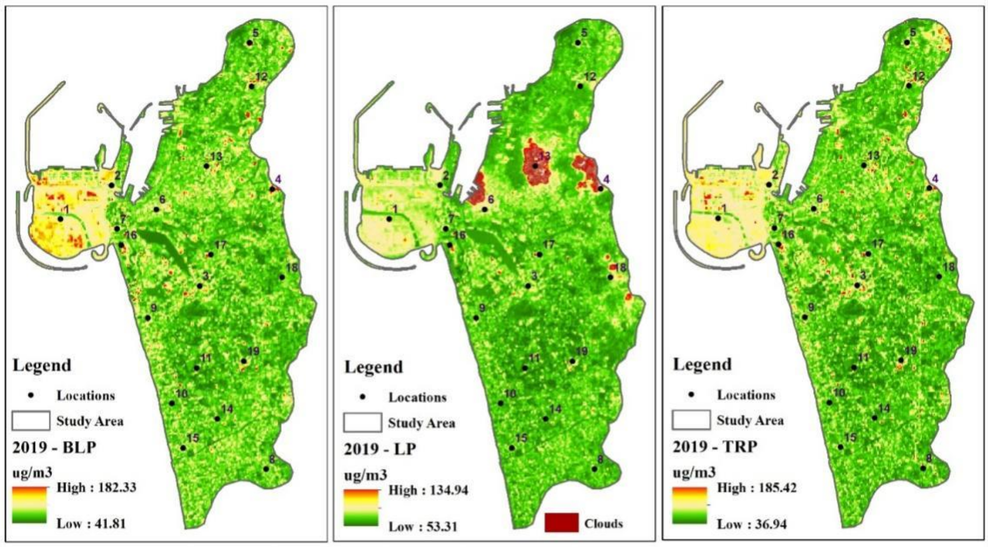


Figure 3b: Relationships between the observed and estimated data for 2021.07.19

After image analysis, this study identified the spatial distribution of PM_{10} in 2019, 2020 and 2021 across the study area. Figure 4 illustrates the spatial distribution pattern of PM_{10} in the Colombo MC Area in 2019 (based on before the lockdown period, during the lockdown period and during the travel restriction period with COVID-19 in 2020).

In 2019, the highest and lowest PM_{10} values were reported for TRP (185.42 µg/m^3 and 36.94 µg/m^{3,} respectively). The Port of Colombo city area, Galle face, Kotahena, Town Hall, Maradana, and Borella were identified as hotspots of PM_{10} during the TR phase in 2019.

Moreover, in 2019 (based on 2020 before the lockdown period, lockdown period and travel restriction period), PM_{10} contaminants fluctuated in the study area, and the PM_{10} concentration was greater than that in 2020 and 2021.



ID	Location- Name	ID	Location- Name	ID	Location- Name	ID	Location- Name
1	Port City	6	pettah	11	Thunmulla	16	Galle Face
2	Harbour	7	Fort	12	Mattakkuliya	17	Maradana
3	Town Hall	8	Kirulapana	13	Kotahena	18	Borella
4	Dematagoda	9	Kollupitiya	14	Havelock Town	19	BMICH
5	Mattakkuliya	10	Colomobo 04	15	Bambalapitiya		

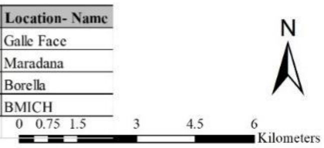
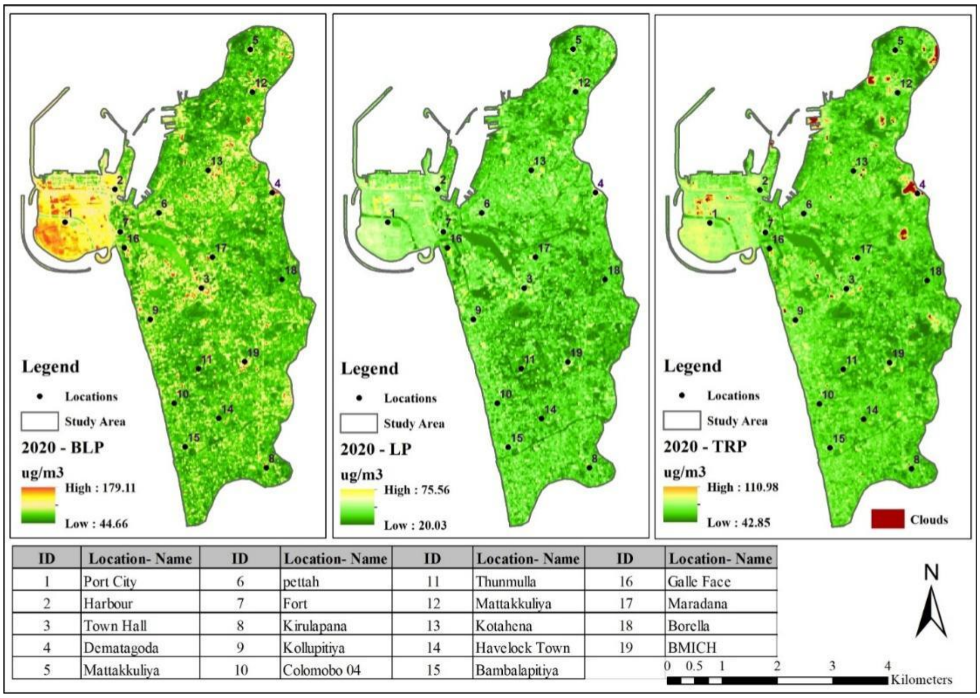


Figure 4: Spatial and temporal variability in air quality over the Colombo MC area in 2019

Figure 5 shows the spatial and temporal variability of PM_{10} in 2020. In 2020, the PM_{10} concentration decreased compared with that in 2019. In this year, the highest PM_{10} concentration was reported in the BLP, and it fluctuated over the area between 179.11 and 44.66 µg/m^3. The lowest values of PM_{10} were reported for LP, with values between 75.56 µg/m^3 and 20.03 µg/m^3. The PM_{10} concentration decreased more rapidly in this phase than in other phases of the year. This reduction occurred due to COVID-19 being spared in that year. Figure 4 shows that the most vulnerable areas, such as the Port of Colombo city area, Galle face, Kotahena, Town Hall, Maradana, and Borella, had lower PM10 concentrations on the LP than on the BLP in 2019.



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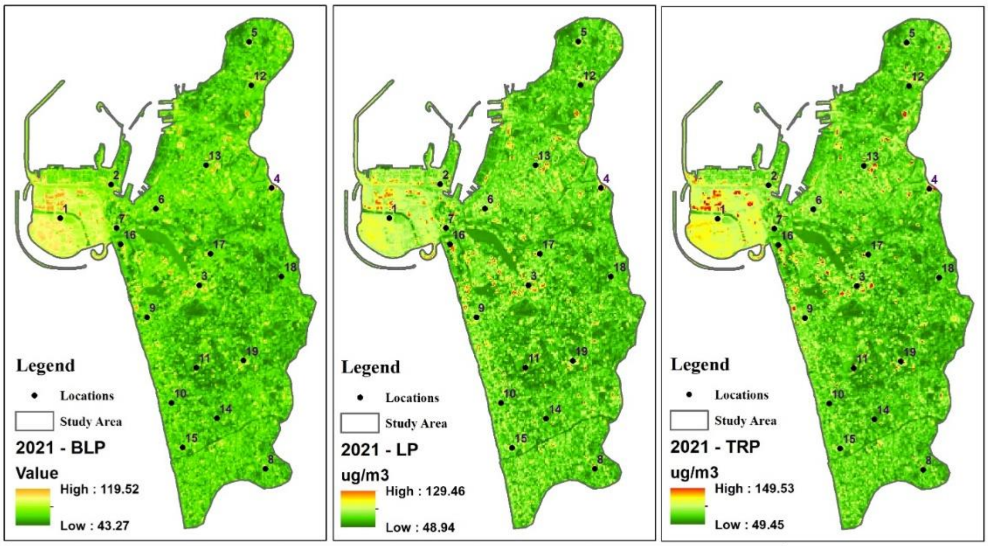
4	Dematagoda	9	Kollupitiya	14	Havelock Town	19	BMICH
5	Mattakkuliya	10	Colomobo 04	15	Bambalapitiya		

Figure 5: Spatial and temporal variability in air quality over the Colombo MC area in 2020

The PM_{10} concentration started to increase again with the TRP in 2020. However, it did not exceed the PM_{10} of BLP in 2019. In this phase, the government gave permission to travel and do other daily work on some days of the week. Therefore, the community has the chance to perform daily routing work on these days, and most of the PM_{10} release activities might have been performed on these days.

Figure 6 shows the spatial and temporal variability in PM_{10} concentrations in 2021. In this year, the lowest concentration of PM_{10} reported in BLP was between 119.52 and 43.27 $\mu g/m^3$. However, its values were greater than those of LP and TRP in 2020.



ID	Location- Name	ID	Location- Name	ID	Location- Name	ID	Location- Name
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4	Dematagoda	9	Kollupitiya	14	Havelock Town	19	BMICH
5	Mattakkuliya	10	Colomobo 04	15	Bambalapitiya		

Figure 6: Spatial and temporal variability in air quality over the Colombo MC area in 2021

The highest PM_{10} concentrations were reported in the TRP in this year, and the values were between 149.53 and 49.45 µg/m^3. Hence, in 2021, the PM_{10} concentration reported was greater than that in the previous year (2020), but it was lower than that in 2019. The concentration of PM_{10} fluctuated across the study area, and the highest concentrations were detected mostly in the upper part of the study area rather than in the lower part. The highest PM_{10} concentrations were found in the Galle face, Kotahena, Town Hall, Maradana, Borella, Kollupitiya, and BMICH in this year. On the other hand, this study focused on identifying PM_{10} variations at specific locations, and the results revealed trends in PM_{10} variation over the study period (2019, 2020 and 2021).

Figure 7 shows the concentrations of PM_{10} in the main areas of Colombo MC in 2019, 2020, and 2021 and the BLP based on the COVID-19 situation in 2020 in Sri Lanka.

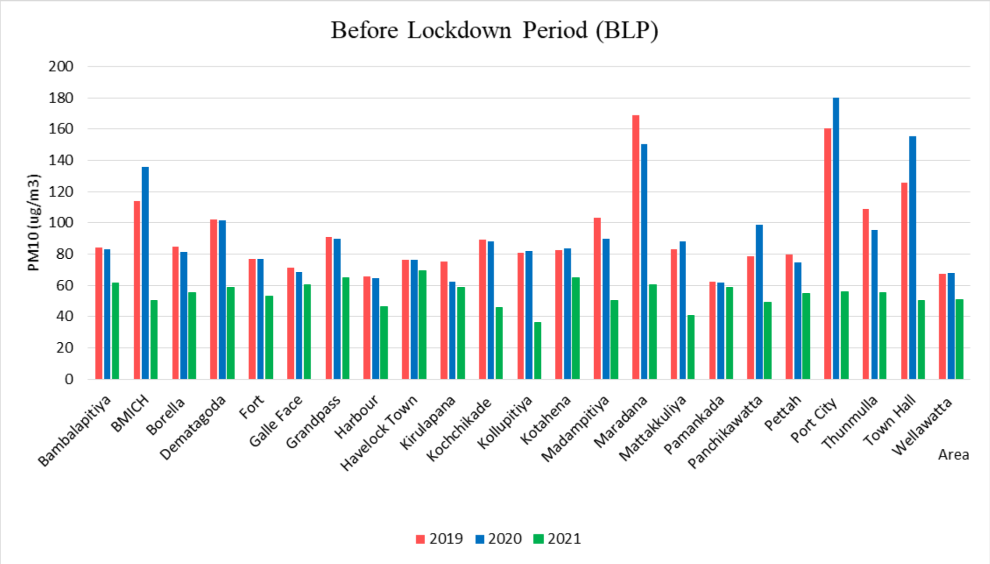

Figure 7: PM_{10} of BLP in the main areas of the Colombo MC in 2019, 2020, and 2021

This figure compares the PM_{10} concentration in BLP within three years. Therefore, before the lockdown period, the highest PM_{10} concentrations were reported in 2019 and 2020. Most areas exhibited the same range of PM_{10} in both phases, and Thunmulla, Pettah, Maradana, and Madampitiya exhibited the highest PM_{10} in BLP in 2019. The BMICH, Mattakkuliya, Port City, and Town Hall had the highest PM_{10} concentrations in 2020. The main reason for this is that COVID-19 has not affected Sri Lanka in this phase. Therefore, the country's daily routing had no difficulties, and all the participants worked normally during that period. The lowest PM10 concentration in this area was reported for BLP in 2021. The BLP in 2021 was the country recovery period, and there was a regulation for the daily work routines of the country. However, it was not completely locked down.

Figure 8 shows the concentrations of PM_{10} in the main areas of the LP in 2019, 2020, and 2021 based on the COVID-19 situation in 2020 in Sri Lanka. According to this figure, the highest PM_{10} concentration was reported in 2019, and the lowest PM_{10} concentration was reported in 2020. The Port City area had the highest reported PM_{10} concentration in 2019. In 2019, there was no COVID-19, and people did not experience any problems during this period. However, in 2020, the LP was in the lockdown period in Sri Lanka, and all of the countries working there were in this period (LP refers to Lockdown Period in Sri Lanka. Therefore, PM_{10} emissions were not active, and therefore, PM_{10} concentrations were reduced in the air.

However, the concentration of PM_{10} again started to increase in 2021 during this phase. Figure 6 shows that the PM_{10} concentration in 2021 increased compared with that in 2020 but decreased compared with that in 2019. In 2021, this phase was the country recovery period from COVID-19, and most regulations changed. Most of the country's day-to-day activities, such as office work, construction, transportation systems, and business, started during this period. Therefore, PM_{10} started to increase during this period.

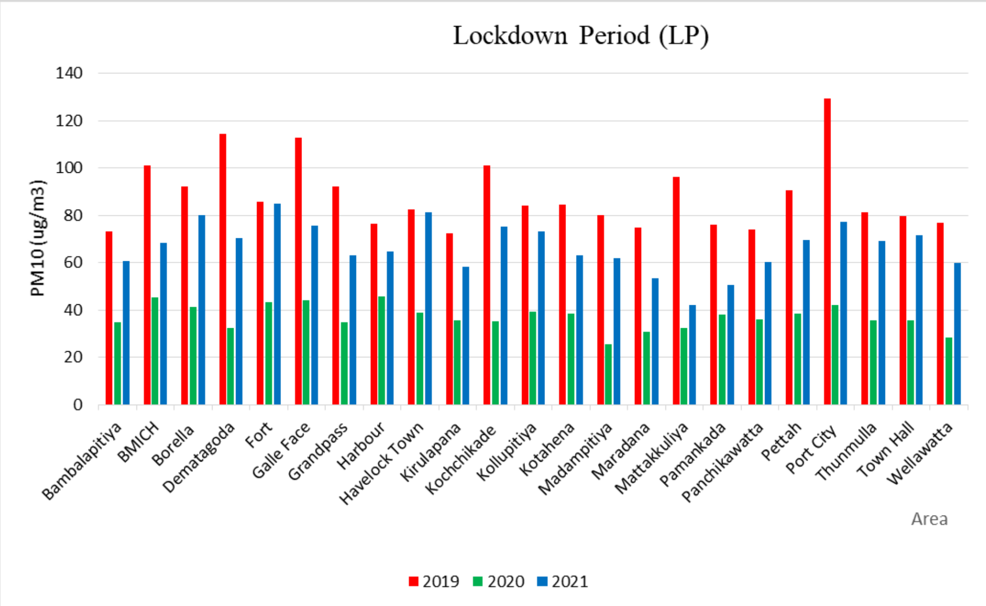

Figure 8: PM_{10} on the LP in the main areas of the Colombo MC in 2019, 2020 and 2021

Moreover, Figure 09 shows that the concentrations of PM_{10} in the main areas of the Colombo MC were the TRP in 2019, 2020, and 2021, which was based on the COVID-19 situation in 2020 in Sri Lanka. The highest value of PM_{10} was reported in 2019, and the lowest was reported in 2020. In 2021, the PM_{10} concentrations were greater than those in 2020 but lower than those in 2019. In addition, in 2021, the reported PM_{10} concentrations were higher than those in the 2021 lockdown phase. Port City, Galle Face and BMICH reported the highest values during the three years. After COVID-19 in 2020, the country slowly recovered to a normal state, and all sectors, such as the government, private, and agriculture, started to work. Therefore, the PM_{10} concentration in the air started to increase again.

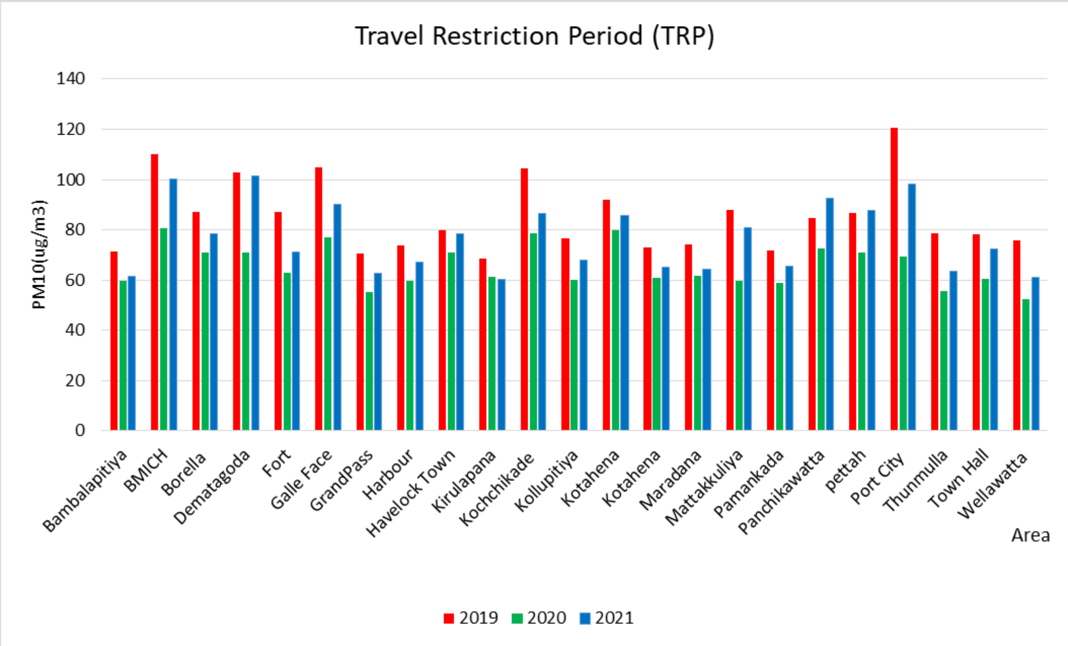

Figure 9: PM_{10} in TRP in the main areas of the Colombo MC in 2019, 2020 and 2021

5. Discussion

The Results section revealed that the PM_{10} concentration decreased during the COVID-19 lockdown period. On average, the variations were 78.48% for the lockdown phase and 63.68% for the travel restriction period in 2020. Singh et al. [15] reported that the levels of PM_{10} and $PM_{2.5}$ decreased by ~50% and 60%, respectively, during the lockdown in the North-western region of India. Barbara et al. (2022) [31] reported that the average $PM_{2.5}$ and PM_{10} concentrations decreased by -55.56% and -55.17% respectively, during the lockdown periods of 2019 and 2020 in Victoria, Mexico.

Seo et al. (2020) [32] showed that the $PM_{2.5}/PM_{10}$ ratio decreased to 24.5% after the implementation of social distancing, suggesting a decrease in anthropogenic emissions in Korea. According to the results of this study, the city of Colombo is highly vulnerable to PM_{10}, and before the COVID-19 pandemic, high PM10 concentrations were reported. The highest concentration of PM_{10} during these three years was 185.36 µg/m^3, which was reported in 2019. The lowest PM_{10} concentration was 20.03 µg/m^{3,} and it was reported in 2020. In addition, during the 2021 travel restriction period, the PM_{10} concentration slightly increased in this area.

Mahato et al. (2020) reported that, some amount of PM_{10} was released into the air from traffic and industrial sources after two weeks of lockdown, and this may be due to a slight relaxation of lockdown measures for necessary vehicles and localized industries in Delhi, India. Moreover, Gamelas et al. in 2021, noted a development in air quality regarding PM_{10}, which can be attributed to the restrictions of anthropogenic activities (such as traffic) promoted during the March-May 2020 national lockdown that occurred due to the pandemic in Portugal.

The city of Colombo is highly vulnerable to PM_{10}, and it had exceeded 50 $\mu g/m^3$ in some years. The highest concentration of PM_{10} is found in the central part of the city, and this area includes the Port City area, city center and main trade center area, road junctions, industrial zones, and construction areas. This may be due to urban center-oriented traffic flow and urban agglomeration.

This study revealed how human activities affect the PM_{10} concentration in the air, and several reasons can be attributed to this vulnerability in this study area. This study area is a highly urbanized area in the country and is the commercial capital of Sri Lanka. This area has more than 555,000 inhabitants and is home to nearly 500,000 people floating daily. Hence, millions of vehicles enter Colombo city through the eight entrances, and the number of vehicles leaving Colombo city is more than 173,000 per day. Therefore, traffic congestion is greater in this area than in other areas of Sri Lanka. Elangasinghe and Shanthini (2008) reported that PM_{10} concentrations indicate that PM pollution is significant along roads with high traffic intensity. Moreover, road density and building density are high, and more industries are located in these areas.

Moreover, there is a large amount of construction land in this area, and Port City construction projects have led to the reporting of highly particular matters in this area. These factors were identified as highly significant contributing factors to the PM_{10} concentration, and grasslands and water bodies were identified as having negative effects. Elangasinghe and Shanthini (2008) reported that the lowest PM_{10} concentration, approximately 4 $\mu g/m^3$, occurred within the Peradeniya Botanical Garden premises approximately 300 m away from Kandy-Peradeniya Road. Therefore, green areas and water areas help to reduce the PM_{10} concentration in the air. Moreover, the limited urban activities during the COVID-19 lockdown and travel restriction period caused a decrease in the concentration of PM_{10} in this area.

6. Conclusion

This study analysed the behaviour of PM_{10} air pollutants during the period of COVID-19 based on three phases i.e., before the lockdown period, during the lockdown period, and during the 2020 travel restriction period) in 2019, 2020, and 2021. According to the experiments and analysis results, the following conclusions can be presented:

The spatiotemporal patterns of PM_{10} in the Colombo MC Area were influenced by COVID-19 mitigation lockdown and reopening policies. The lockdown policy generally reduced the concentration of PM_{10} in the Colombo MC Area; the reopening increased the emissions of PM_{10} back to a normal trend compared to the previous and after-year levels.

High levels of PM_{10} can directly affect the health of urban residents. In particular, the incidents of respiratory diseases can increase, and sensitive groups may be marginalized. Therefore, essential measures should be taken to control harmful human activities and minimize the concentration of PM_{10} in the Colombo MC area, such as introducing methods to control mainly vehicle emissions and construction in the study area. Ecosystem-friendly public transport systems, awareness programs and urban agroforestry programs can be suggested to minimize the concentration of PM_{10} in the study area. Air quality management in urban environments is required to reduce industrial losses, safeguard human health, maximize worker productivity, and enhance indoor and outdoor air quality in any area (Singh et al., 2022).

This study has some limitations and future improvements. This study focused only on the PM_{10} concentration and its spatial–temporal variation with respect to COVID-19 and did not consider other conditions (weather parameters, health conditions etc.), which affect air quality. Moreover, this study only used Landsat images, and it was very difficult to obtain free images. Therefore, several improvements are needed in the near future, such as the use of other types of air quality parameters and their variations with respect to COVID-19 and studying of other conditions that affect air quality during the COVID-19 pandemic. Further, additional studies may focus on re-examining other types of satellites to retrieve air quality in Sri Lanka.

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References

Alvarez-Mendoza, C. I., Teodoro, A. C., Torres, N. & Vivanco, V. (2019). Assessment of remote sensing data to model PM_{10} estimation in cities with a low number of air quality stations: A case of study in Quito, Ecuador. *Environments-MDPI*, *6*(7). https://doi.org/10.3390/environments607008

Bárbara A., Macías-Hernández. & Tello-Leal, E. (2022). Analysis of Particulate Matter Concentration Changes before, during, and Post COVID-19 Lockdown: A Case Study from Victoria, Mexico. *Journal Atmosphere MDPI*, *13*, 827. https://doi.org/10.3390/atmos13050827

Central Environment Authority. (2017). *The CEA at the heart of great new challenges*. https://www.cea.fr/english/Documents/corporate-publications/cea-annual-report2017.pdf

Dissanayake P.R.T.K. & Manawadu L. (2016) Determination of Aerosol Particles and Risk Analysis of Asthma in the City of Colombo. *Conference proceedings International Conference of Remote sensing*.

Department of Census and Statistics. (2022). http://www.statistics.gov.lk/2012

Doval-Miñarro, M. & Bueso, M. C. A. (2023). Comparative Study of Air Pollutant Concentrations before the COVID-19 Pandemic and in the New Normal in the Región de Murcia (Spain) *Journal Atmosphere MDP*, *14*, 147. https://doi.org/10.3390/atmos14010147

Elangasinghe, M. & Shanthini, R. (2008). Determination of atmospheric PM10 concentration in Kandy in relation to traffic intensity. *Journal of the National Science Foundation of Sri Lanka*, *36*(3) 245–249. http://doi.org/10.4038/jnsfsr.v36i3.162

Gamelas, C., Abecasis, L., Nuno Canha, N. & Almeida, S. M. (2021). The Impact of COVID-19 Confinement Measures on the Air Quality in an Urban-Industrial Area of Portugal. *Journal Atmosphere MDPI*, *12*, 1097.

Greenstone, M. & Fan, C. Q. (2018). *Introducing the air quality life index*. AQLI Annual Report. https://aqli.epic.uchicago.edu/wp-content/uploads/2018/11/AQLI-Report.111918-2.pdf.

Gurjar, B., Khaiwal, R. & Nagpure, A. (2016). Air pollution trends over Indian megacities and their local-to-global implications. *Atmospheric Environment*., *142*. https://doi.org/10.1016/j.atmosenv.2016.06.030

Hashim, B.M., Al-Naseri, S.K., Al Maliki, A., Sa'adi, Z., Malik, A. & Yaseen, Z.M. (2021). On the investigation of COVID-19 lockdown influence on air pollution concentration: regional investigation over eighteen provinces in Iraq. *Environ Sci Pollut Res Int*, *28*(36), 50344-50362. doi: 10.1007/s11356-021-13812-x.

Hasnain, A., Hashmi, M. Z., Bhatti, U. A., Nadeem, B., Wei, G., Zha, Y. & Yehua Sheng, Y. (2021). Assessment of Air Pollution before, during and after the COVID-19 Pandemic Lockdown in Nanjing, China. *Journal Atmosphere MDPI*, *12*, 743.

Joss, M., Eeftens, M., Gintowt, E., Kappeler, R. & Künzli, N. (2017). Time to harmonize national ambient air quality standards. *International Journal of Public Health*, *62*. https://doi.org/10.1007/s00038-017-0952-y

Katoto, P. D. M. C., Brand, A. S., Bakan, B., Obadia, P. M., Kuhangana, C., Kayembe-Kitenge, T., Kitenge, J. P., Nkulu, C. B. L., Vanoirbeek, J., Nawrot, T. S., Hoet, P. & Nemery, B. (2021). Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19: a rapid systematic review. *Environmental health: a global access science source*, *20*(1), 41. https://doi.org/10.1186/s12940-021-00714-1.

Khaniabadi, Y.O., Sicard, P., Dehghan, B. (2022). COVID-19 Outbreak Related to PM10, PM2.5, Air Temperature and Relative Humidity in Ahvaz, Iran. *Dr. Sulaiman Al Habib Med J. 4*,182–195. https://doi.org/10.1007/s44229-022-00020-z.

Kobza, J., Geremek, M. & Dul, L. (2018). Characteristics of air quality and sources affecting high levels of PM_{10} and $PM_{2.5}$ in Poland, Upper Silesia urban area. *Environ. Monit.,190*, 515.

Kumari, P. & Toshniwal, D. (2020). Urban Climate Impact of lockdown on air quality over major cities across the globe during COVID-19 pandemic. *Urban Climate*, 34(August), 100719. https://doi.org/10.1016/j.uclim.2020.100719.

Mahato, S., Pal, S. & Ghosh, K. G. (2020). Science of the Total Environment Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi , India. *Science of the Total Environment*, *730*, 139086. https://doi.org/10.1016/j.scitotenv.2020.139086

Mendez-Espinosa, J. F., Rojas, N. Y., Vargas, J., Pachón, J. E., Belalcazar, L. C., & Ramírez, O. (2020). Air quality variations in Northern South America during the COVID-19 lockdown. *Science Total Environment*, *20*, 749:141621. https://doi.org/10.1016/j.scitotenv.2020.141621.

Menut, L., Bessagnet, B., Siour, G., Mailler, S. & Pennel, R., Cholakian, A. (2020). Impact of lockdown measures to combat Covid-19 on air quality over western Europe. *Sci. Total Environment*, *741*, 140426.

Othman, N., Mat-Jafri, M.Z. & San, L. H. (2010). Estimating particulate matter concentration over arid region using satellite remote sensing: a case study in Makkah, Saudi Arabia. *Mod. Appl. Science*, *4*, 11-21.

Premasiri, H.D.S. (2020). Absence of vehicles on road with island wide curfew has improved the air quality in urban areas of sri lanka. http://www.nbro.gov.lk/images/other_pdf/current_status_air_quality_in_sri_lanka_4.pdf

Romano, S., Catanzaro, V. & Paladini, F. (2021). Impacts of the COVID-19 Lockdown Measures on the 2020 Columnar and Surface Air Pollution Parameters over South-Eastern Italy. *Journal Atmosphere MDPI*, *12*, 1366. https://doi.org/10.3390/atmos12101366

Sargsyan, A., Galstyan, N., Nahatakyan, H. & Morales-Suárez-Varela, M. M. (2022). Assessment of Lockdown Effectiveness during COVID-19 Pandemic Using Air Pollution Data in Armenia in March–June 2019 and 2020: A Cross-Sectional Study. *Journal Atmosphere MDPI*, *13*, 1563.

Saleh, S.A.H. & Hasan, G. (2014). Estimation of PM10 Concentration using Ground Measurements and Landsat 8 OLI Satellite Image. *J Geophys Remote Sensing*, *3*, 120. doi:10.4172/2169-0049.1000120

Seo, J. H., Kim J.S., Yang, J., Yun, H., Roh, M., Kim J.W., Yu, S., Jeong, N.N., Jeon H. W., Choi J. S. & Sohn., J. R. (2020). Changes in Air Quality during the COVID-19 Pandemic and Associated Health Benefits in Korea. *Applied Sciences*, *10*, 8720. doi:10.3390/app10238720

Sharma, M. & Dikshit, O. (2015). Comprehensive study on air pollution and green house, A Report Submitted to Government of NCT Delhi and DPCC Delhi. 1, 334. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&authuser=1&q=Comprehensive+study+on+air+pollution+and+green+house+gases+%28GHGs%29+in+Delhi+sharma&btnG=#d=gs_cit&t=1649516058346&u=%2Fscholar%3Fq%3Dinfo%3AVZV8ysV-8GgJ%3Ascholar.google.com%2F%26output

Singh, H., Meraj, G., Singh, S., Shrivastava, V., Sharma, V., Farooq, M., Kanga, S., Singh, S. K. & Kumar, P. (2022). Status of Air Pollution during COVID-19-Induced Lockdown in Delhi, India. *Journal Atmosphere MDPI, 13*, 2090. https://doi.org/10.3390/atmos13122090.

Singh, V., Singh, S., Biswal, A., Kesarkar, A.P., Mor, S. & Ravindra, K. (2020). Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. *Environmental Pollution*, *266*, 3, 115368. https://doi.org/10.1016/j.envpol.2020.115368.

Skiriene, A. F. & Stasiskiene, Z. (2021). COVID-19 and Air Pollution: Measuring Pandemic Impact to Air Quality in Five European Countries. *Atmosphere MDPI*, *12*, 290. https://doi.org/10.3390/atmos12030209

USGS earth explorer. (2022). https://glovis.usgs.gov/

Venter, Z.S., Aunan, K., Chowdhury, S. & Lelieveld, J. (2020). COVID-19 lockdowns cause global air pollution declines. *PNAS*, *117*, 18984–18990.

World Health Organization (WHO). (2016)

https://www.who.int/news-room/detail/2016

World Health Organization (WHO). (2018) https://www.who.int/news-room/detail/2018

World Health Organization (WHO). (2022, July 08). https://www.who.int/news-room/detail/ 2021.

Yuen, K.S., Ye, Z.W. & Fung, S.Y. (2020). SARS-CoV-2 and COVID-19: The most important research questions. *Cell Biosci*, 10, 40. https://doi.org/10.1186/s13578-020-00404-4.