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Seasonal variation assessment of ambient air quality during COVID-19 lockdown in Uttarakhand state, India

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सार – वर्तमान में, वायु प्रदूषण दुनिया भर में एक महत्वपूर्ण पर्यावरणीय खतरा बना हुआ है। हालाँकि, वायु प्रदूषकों की भिन्नता काफी हद तक मौसम में बदलाव (मॉनसून पूर्व, मॉनसून, मॉनसून उपरांत और शीत ऋतु), जलवायु परिस्थितियों और कुछ मानवजनित गतिविधियों से जुड़ी होती है। हाल ही में, दुनिया के विभिन्न हिस्सों में COVID-19 लॉकडाउन के कारण वायु प्रदूषकों के स्तर में उल्लेखनीय गिरावट देखी गई है। इसलिए, यह अध्ययन भारत के उत्तराखंड राज्य की वायु गुणवत्ता पर COVID-19 प्रतिबंधों (लॉकडाउन से पहले और लॉकडाउन के बाद) के प्रभाव का आकलन करने के लिए किया गया।प्रयोजनात्मक रूप से, उत्तराखंड प्रदूषण नियंत्रण बोर्ड द्वारा एकत्र किए गए 8 स्टेशनों से वायु गुणवत्ता डेटा का विश्लेषण किया गया। निष्कर्षों से पता चला कि PM_{10}, $PM_{2.5}$, SO_2, and NO_2 सहित वायु प्रदूषकों की औसत सांद्रता में सार्थक भिन्नता थी। हालाँकि, परिवेशी वायु प्रदूषण में कणिकापदार्थ शीर्ष योगदानकर्ताओं में से एक है, जबकि SO_2 और NO_2 जैसे गैसीय प्रदूषक केंद्रीय प्रदूषण नियंत्रण बोर्ड (CPCB) द्वारा दिए गए मानकों से नीचे हैं।वर्तमान अध्ययन ने पुष्टि की है कि पिछले वर्ष (2019) की तुलना में, 2020 में प्रारंभिक लॉकडाउन के दौरान, SO_2, NO_2, $PM_{2.5}$ और PM_{10} की सांद्रता में क्रमशः 9.46-86.4%, 20-74.6%, 35.6-62.6% और 14.7-65% की उल्लेखनीय कमी आई।जबकि अगले वर्ष (2021) की तुलना में क्रमशः -11.6 -96.5%, -9.5 -70.6%, 5.1-57.6% और -17.06-71.7% की उल्लेखनीय वृद्धि देखी गई। इसके अलावा, विभिन्न ऋतुओं में वायु प्रदूषकों में काफी भिन्नता और लॉकडाउन अवधि के दौरान वायु गुणवत्ता सूचकांक (एक्यूआई) में आश्चर्यजनक सुधार देखा गया। इस कार्य के निष्कर्षों से पता चलता है कि बाहरी मानवीय गतिविधियों में कमी से भारत के उत्तराखंड राज्य की परिवेशी वायु गुणवत्ता में महत्वपूर्ण सुधार हो सकता है।

ABSTRACT. Presently, air pollution remains a significant environmental threat across the world. However, variation of air pollutants is largely associated with changes in season (pre-monsoon, monsoon, post-monsoon, and winter), climatic conditions, and certain anthropogenic activities. Recently, a significant drop in the levels of air pollutants has been observed due to the COVID-19 lockdown in various parts of the world. Therefore, this study was performed to assess the impact of COVID-19 restrictions (pre-lockdown and post-lockdown) on the air quality of Uttarakhand state, India. Purposively, the air quality data from 8 stations collected by the Uttarakhand pollution control board was analyzed. The findings showed that there was a significant variation in the average concentration of air pollutants including, PM_{10}, $PM_{2.5}$, SO_2 and NO_2. However, particulate matter is amongst the top contributors to ambient air pollution while gaseous pollutants such as SO_2 and NO_2 are below the standards given by the Central Pollution

Control Board (CPCB). The present study confirmed that during the initial lockdown in 2020, the concentration of SO_2, NO_2, $PM_{2.5}$ and PM_{10} decreased significantly by 9.46-86.4%, 20-74.6%, 35.6-62.6%, and 14.7-65% respectively as compared to the previous year (2019) while a significant corresponding increase by -11.6-96.5%, -9.5-70.6%, 5.1-57.6% and -17.06-71.7% was observed, respectively in comparison to the succeeding year (2021). Moreover, a considerable variation of air pollutants in different seasons and a dramatic improvement in the air quality index (AQI) were observed during the lockdown period. The findings of this work suggest that the decrease in outdoor human activities could contribute a significant improvement in the ambient air quality of the state of Uttarakhand, India.

Key words– Air pollution, Anthropogenic activities, AQI, CPCB standards, $PM_{2.5}$.

1. Introduction

The development of technologies, expansion in urbanization, industrialization, and transportation have contributed to the rapid growth of human civilization (Giri and Pant 2018a). However, the drastically increased human population has been continuously creating a burden on all spheres of the earth (Goswami *et al*., 2021; Pant *et al*., 2017). This leads to poor management of natural resources and thus, progression towards a global threat as environmental pollution (Dandotiya 2020; Goswami *et al*. 2022; Singh *et al*. 2020), which ultimately leads to declination in life expectancy, disturbing ecosystem health, and economies (Giri and Pant 2018b; Liang and Gong 2020). Air pollution results when excess amounts of gases, particles, and aerosols are released due to anthropogenic activities and natural phenomena such as forest fires, earthquakes, tsunami, volcanic events, *etc*. which later alters the natural composition of the atmosphere (Kumar and Dash 2018; Giri and Pant 2018b). However, the atmosphere recovers its original composition slowly through several parameters like meteorological conditions, pollutant emission, dispersion, and physicochemical transformation, which influence the ambient air quality of a specific area (Liang and Gong 2020). Sources of NO_2 emission include vehicular emissions, industries, coal-fired power plants (Sulaymon *et al*. 2021), which lead to alveoli irritation and hindrance in pulmonary functions (Dandotiya 2020). Sulphur-containing fuels and coal-based thermal power plants are associated with SO_2 emissions (Singh *et al*., 2020), which lead to respiratory disorders, bronchitis, and lower birth rate (Dandotiya 2020). Globally, particulate matter (PM) has been known as one of the most critical environmental threats and is associated with morbidity and mortality due to respiratory and cardiovascular diseases (Pant *et al*. 2019; Sharma and Mandal 2017; Sulaymon *et al*. 2021). Globally, air pollution was recorded as the fifth-highest mortality risk factor with 147 million healthy lives lost in 2017 (Health Effects Institute 2019). In today's world, more than 90% of the population is living in an area where air quality exceeds the limits given by WHO (WHO, World Health Organization 2020). Continuous exposure to air pollution will be the cause of a rise in annual premature mortality rate by 0.2 million to 1.4 million in 2040, from which 60% of deaths are estimated to be caused by ambient air pollution (IEA 2021).

Recently, the unexpected outbreak of the coronavirus pandemic (SARC-CoV-2) has resulted in significant positive changes in the environment with the improvement in air quality across the globe (Adelodun *et al*. 2021a; Gope *et al*. 2021). COVID-19 was first identified in Wuhan, Central China in December 2019, affecting many countries by an infection that spreads mainly from humans to humans (Sulaymon *et al*. 2021; WHO 2020). In order to prevent the spread of COVID-19, a nationwide lockdown in India, restricting anthropogenic activities like transportation, construction, industries, schools, colleges, malls, flights, restaurants, and other non-essential activities, was initiated in various phases (Adelodun *et al*. 2021b; Mahato *et al*. 2020; MHA 2020; Roy *et al*. 2021). The first phase was implemented for 21 days (25^{th} March - 14^{th} April), then extended from 15^{th} April to 3^{rd} May, then 4^{th} May to 17 May, and a further 18 May to 31 May. All the lockdown processes lead to modifying overall air quality (Chakrabortty *et al*. 2021; Dhaka *et al*. 2020; Mahato *et al*. 2020; Roy *et al*. 2021; Sarkar *et al*. 2020). The fuel consumption rate during the lockdown period was reduced by 40%, 50-60%, 70% and 90% due to shut down in activities like industries, transportation, construction, and aviation, while household fuel consumption rate was increased by 12% (Singh *et al*. 2020). Overall, processes eventually lead to a decline in $PM_{2.5}$ level by 25-60% (Gope *et al*. 2021). This evidence has inspired researchers and policymakers to study the impression of reduced emissions on air quality across India. Tremendous declination in air pollution based on satellite data of the lockdown period due to the COVID-19 pandemic has also been observed in various studies (Liu *et al*. 2021; Singh and Chauhan, 2020; Adelodun *et al*. 2021c). In Wuhan city, an immediate increase in the concentration of NO_2, O_3 and PM_{10} was observed after the lockdown was over. It is an alarm that further control approaches must be implemented for constant improvement in air quality. Otherwise, we will return to a similar polluted world again (Sulaymon *et al*. 2021). Many studies from the megacities across the globe are available on the lockdown impacts and variability in the pollution parameters (Gao *et al*., 2020; Liu *et al*. 2021; Morales-Solís *et al*., 2021; Singh and Chauhan, 2020; Sulaymon *et al*., 2021; Vadrevu *et al*., 2020) including India. However, no such study has been done till date emphasizing air pollutants and lockdown due to COVID-19 in Uttarakhand state. Therefore, this study assessed the

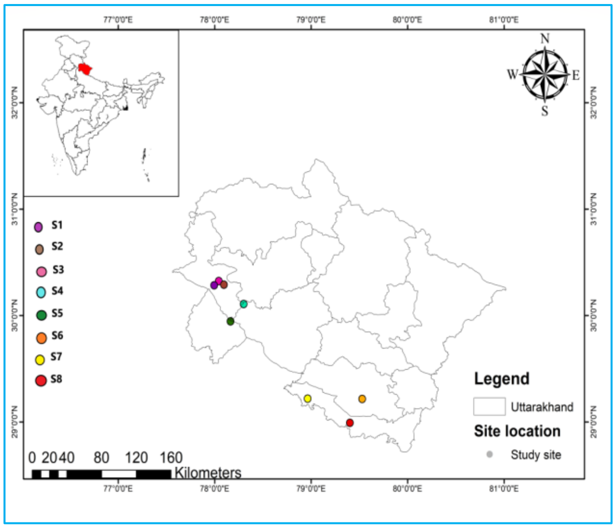

Fig. 1. Location map of air quality monitoring stations in Uttarakhand

TABLE 1

Air quality index (AQI) categories, ranges and their health impacts

AQI	Air Pollution Level	Levels of health concern
0-50	Good	Good
51-100	Satisfactory	Moderate
101-200	Moderately	Unhealthy for sensitive groups
201-300	Poor	Unhealthy
301-400	Very Poor	Very unhealthy
401-500	Severe	Hazardous

air quality changes at eight ground monitoring stations across Uttarakhand during the COVID-19 lockdown and trends in seasonal and monthly variation of ambient air pollutants along with air quality index (AQI).

2. Data and methodology

2.1. *Study area*

Uttarakhand lies between 28º 44' to 31º 28' N latitude and 77º 35' to 81º 01' E longitude and occupies an area of 53,483 km^2 and has a population of nearly 1.01 crores and is referred to as “Devbhoomi (Land of Gods)”. The Himalayan state of Uttarakhand has high altitude mountains as well as foothill plain landscapes and densely populated districts. The measurements of particulate ($PM_{2.5}$ and PM_{10}) and gaseous (SO_2 and NO_2) air pollutants for all the eight air quality monitoring stations were made by the Uttarakhand Pollution Control Board (ueppcb.uk. gov.in) and utilized for this study. The National Air Monitoring Programme (NAMP) by the Central Pollution Control Board (CPCB) has been monitoring ambient air quality at eight monitoring stations in Uttarakhand state, *viz*., Clock Tower (S1), Raipur Road (S2) and Himalayan Drug, Inter State Bus Terminal (ISBT), Dehradun (S3), Nagar Palika Parishad, Rishikesh (S4), State Industrial Development Corporation of Uttarakhand Limited (SIDCUL), Haridwar (S5), Government Hospital, Haldwani (S6), Government Hospital, Kashipur (S7) and Government Hospital, Rudrapur (S8) (Fig. 1). The locations have been categorized on a land-use basis, *i.e*., residential, industrial, or ecologically sensitive. The monitoring locations of Kashipur and Rudrapur are sensitive ones, while others come in the residential or industrial zone. The location of all these eight air quality monitoring stations is marked in Fig. 1.

2.2. *Data sources*

The monthly average measurements on the concentration of air pollutants were obtained from the online data source of Uttarakhand Pollution Control Board, India (http://ueppcb.uk.gov.in). The method used for measurement of SO_2 is the Improved West & Gaeke method, Jacob & Hochheiser modified method for NO_2 monitoring and the Gravimetric method for PM’s monitoring (NAAQS 2011). The database of meteorological parameters such as rainfall (R), temperature (T), relative humidity (RH), wind speed (WS) and wind direction (WD) was collected from IMD (India Meteorological Department), Dehradun on a daily basis.

2.3. *Data analysis*

The analysis is divided into four sections, the trend in monthly variation and seasonal variation of annual data (March, 2019-Feb, 2020) for SO_2, NO_2, $PM_{2.5}$ and PM_{10} concentration with air quality index (AQI). Assessment of pollutants during lockdown (March, April and May, 2020), pre-lockdown (March, April and May, 2019) and post-lockdown (March, April and May, 2021) periods was carried out to compare the percentage changes or variations during this period. Correlation analysis is performed among the mean concentration of pollutants, among the concentration of pollutants from pre-lockdown, lockdown, and post-lockdown period, and mean concentration of pollutants with the available meteorological parameters of highly polluted study sites S1, S2, and S3. Air mass backward trajectories using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT, PC-version) model (Draxler and Rolph, 2011) were also used to delineate the possible source region of pollutants.

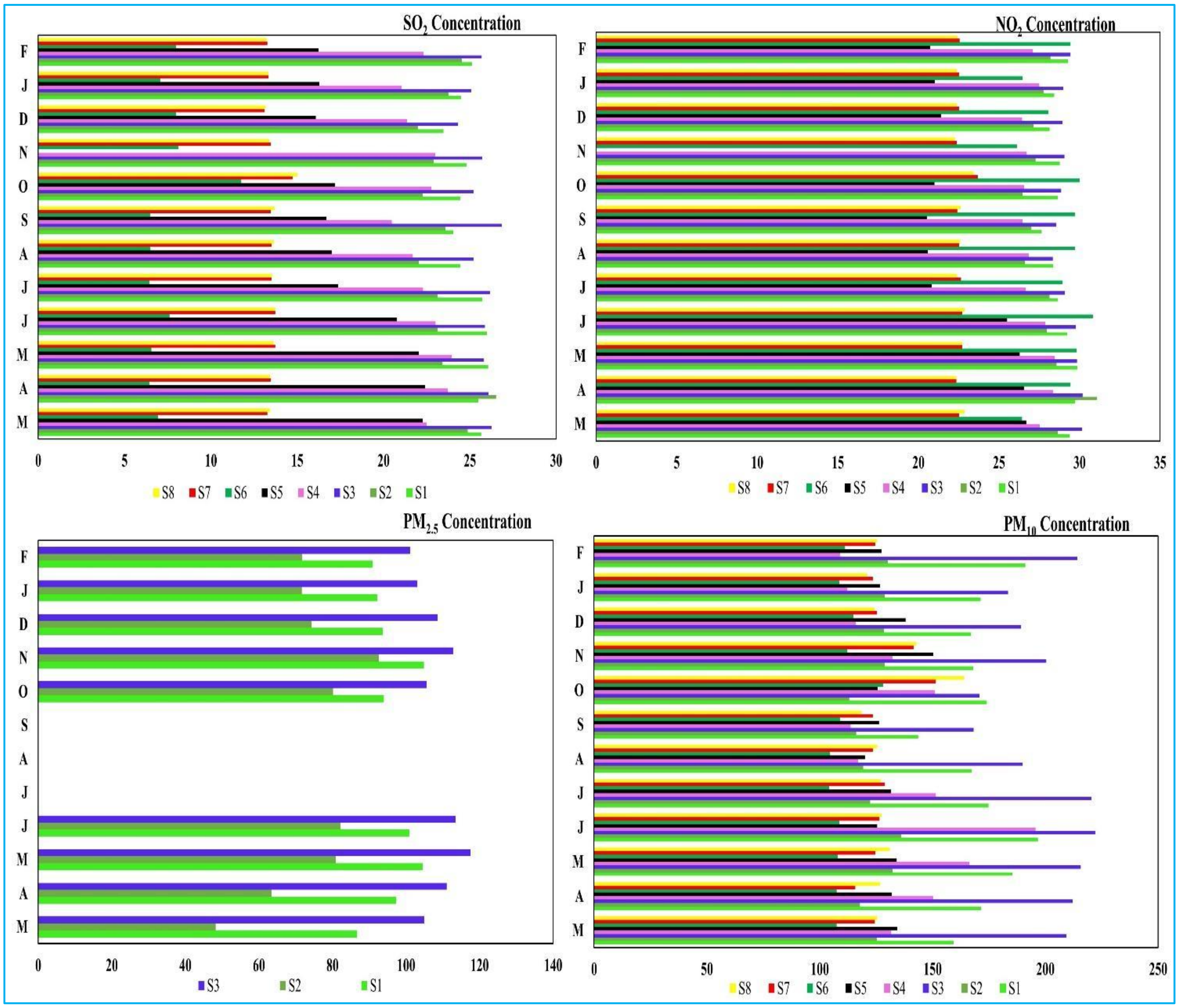

Fig. 2. Monthly average variation in concentration of pollutants during 2019-2020 (J to D: January to December)

2.3.1. *Air Quality Index (AQI)*

The index for reporting daily air quality is AQI. It states how clean or polluted the air is with its associated impacts on health. In this study, an attempt has been made to evaluate the AQI of the study sites and to categorize them based on their pollution potential as per the standards of the Government of India. The AQI ranges from 0 to 500. A higher AQI value shows a greater level of air pollution and health concerns (Table 1). AQI for the study sites is calculated by using the equation (1) (Rao and Rao 1998; Dadhich *et al*. 2018):

$$\text{AQI} = \frac{1}{4} \times \frac{\text{SO}_2\text{Actual}}{\text{SO}_2\,\text{Standard}} + \frac{\text{NO}_2\text{Actual}}{\text{NO}_2\,\text{Standard}} + \frac{\text{PMActual}}{\text{PMStandard}} \times 100 \qquad (1)$$

3. Results and discussion

3.1. *Monthly variation of pollutants*

The key sources of $PM_{2.5}$ and PM_{10} are emissions from industrial processes, construction works, road traffic, biomass burning, and dust re-suspension (Sharma and Mandal 2017). In the previous studies, Chauhan *et al*. (2010) and Joshi and Semwal (2011) observed that the PM's was the dominant air pollutants, which were above the permissible limit in the Haridwar region of Uttarakhand. Awasthi *et al*. (2016) observed that the industrial establishment has increased the concentration of different pollutants in the ambient air over six years of monitoring. However, it was observed that the concentration of SO_2 and NO_x have increased by 2-2.5 times, and RSPM and SPM have increased by 1.5-1.7 times during the study period. The monthly mean

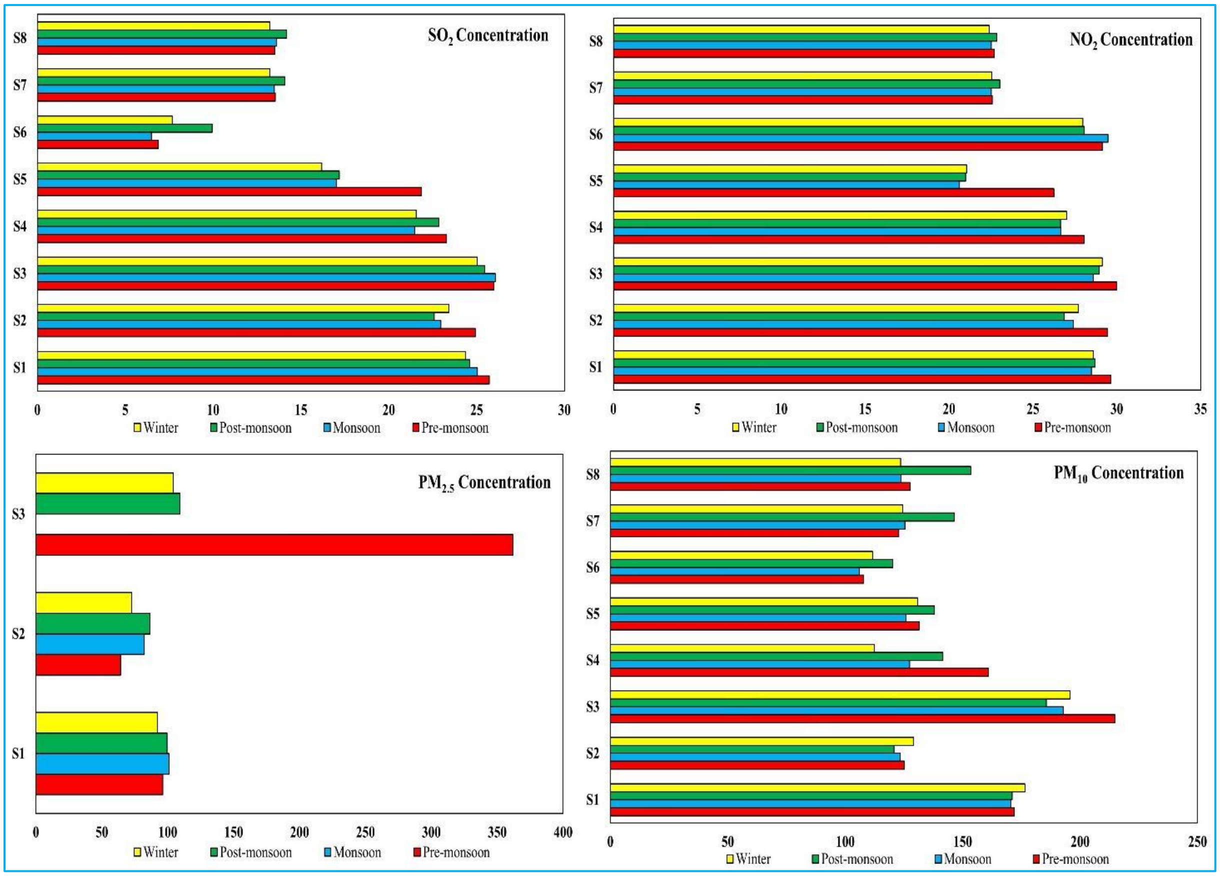

Fig. 3. Seasonal variation in concentration of pollutants during 2019-2020

concentration of air pollutants of eight monitoring sites is depicted in Fig. 2. The monthly mean concentration of SO_2 varies from 23.47-26.06 µg m^{-3}, 21.99-26.51 µg m^{-3}, 24.32-26.84 µg m^{-3}, 20.48-23.95 µg m^{-3}, 16.08-22.40 µg m^{-3}, 6.44-11.77 µg m^{-3}, 13.10-14.72 µgm^{-3}, 13.17-15.02 µg m^{-3} at monitoring sites S1 to S8, respectively. Similarly, the monthly average concentration of NO_2 was reported in the range of 27.66-29.87 µg m^{-3}, 26.48-31.1 µg m^{-3}, 28.35-30.19 µg m^{-3}, 26.44-28.46 µg m^{-3}, 20.60-26.69 µg m^{-3}, 26.12-30.82 µg m^{-3}, 22.35-22.72 µg m^{-3}, 22.26-23.43 µg m^{-3} at monitoring sites S1 to S8, respectively.

The average concentration of SO_2 and NO_2 was maximum during the April-May month while the minimum was during the December and October-November months of the year, respectively. The monthly mean concentration of PM_{10} was in the range of 143.58-196.74 µg m^{-3}, 113-136.15 µg m^{-3}, 168.16-222.01 µg m^{-3}, 109.02-195.71 µg m^{-3}, 120.17-150.3 µg m^{-3}, 104.27-128.07 µg m^{-3}, 115.78-151.47 µg m^{-3}, 118.46-164.08 µg m^{-3} at monitoring sites S1 to S8, respectively. The dataset of $PM_{2.5}$ is available only for 3 sites and the average concentration of $PM_{2.5}$ was maximum in November while minimum in the February-March month. Similarly, the average concentration of PM_{10} was maximum in January and minimum in the September month of the year. Stable weather conditions, lowering of the boundary layer and the formation of an inversion layer confines the pollutants by lowering the mixing heights which cause high pollution levels during winters (Dhaka *et al*., 2020). A strong rainfall pattern may be the reason for scavenging of pollutants from the atmosphere, which causes relatively less concentrations of SO_2, NO_2 and PM's during October- November.

3.2. *Seasonal variation of pollutants*

The Indian meteorological department (IMD) classifies the seasons as pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February), which is referred to here. The seasonal variation of air pollutants (SO_2, NO_2, $PM_{2.5}$ and PM_{10}) for monitoring sites is shown in Fig. 3. Strong monsoon patterns assist in scavenging pollutants during the monsoon season, as shown in industrial sites S3 and S5 where the concentration of pollutants was highest during the pre-monsoon or post-monsoon season and minimum during monsoon season.

TABLE 2

National Ambient Air Quality Standards (NAAQS)

Pollutant	Time-weighted average	Concentration in ambient air	
		Industrial areas, Residential, Rural & other areas	Ecological sensitive area
Sulphur dioxide (SO_2) (μgm^{-3})	Annual	50	20
	24 hours	80	80
Nitrogen dioxide (NO_2) (μgm^{-3})	Annual	40	30
	24 hours	80	80
PM_{10} (μgm^{-3})	Annual	60	60
	24 hours	100	100
$PM_{2.5}$ (μgm^{-3})	Annual	40	40
	24 hours	60	60
Ozone (O_3) (μgm^{-3})	8 hours	100	100
	1 hour	180	180
Lead (Pb) (μgm^{-3})	Annual	0.50	0.50
	24 hours	1.0	1.0
Carbon monoxide (CO) (mgm^{-3})	8 hours	02	02
	1 hour	04	04
Ammonia (NH_3) (μgm^{-3})	Annual	100	100
	24 hours	400	400
Benzene (C_6H_6) (μgm^{-3})	Annual	5	5
Benzo (a) Pyrene (BaP) (ngm^{-3})	Annual	1	1
Arsenic (As), ngm^{-3}	Annual	6	6
Nickel (Ni), ngm^{-3}	Annual	20	20

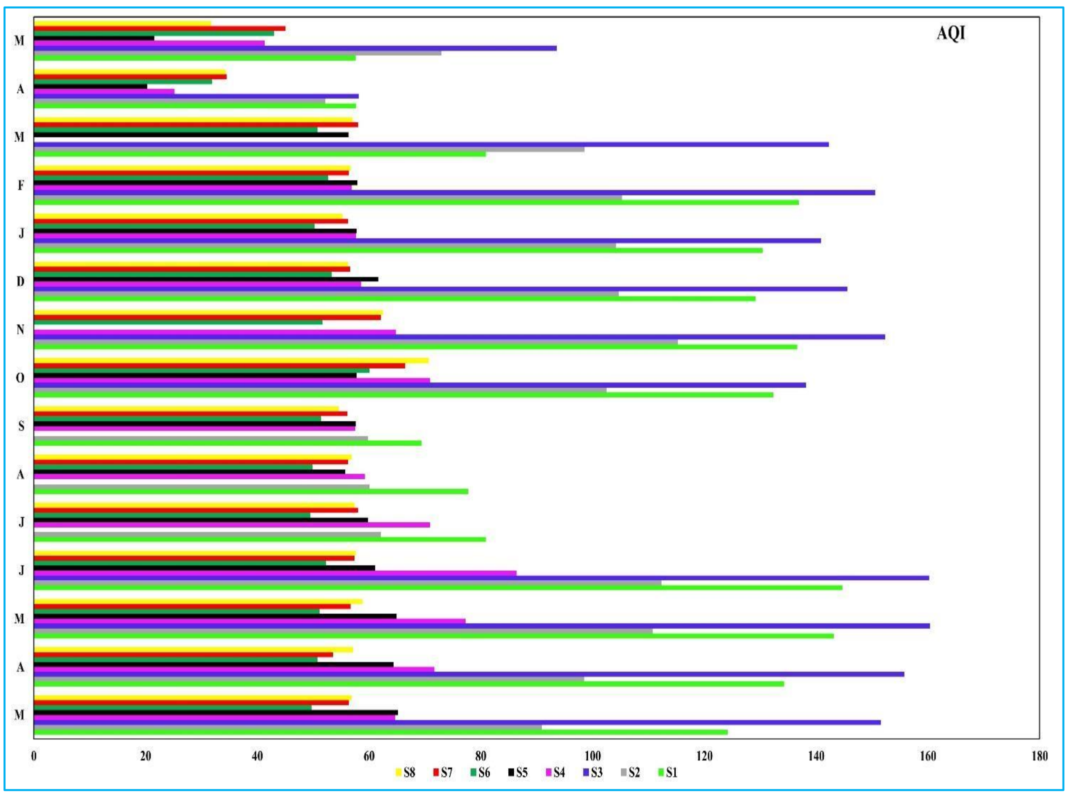

Fig. 4. Air Quality Index (AQI) during the year 2019-2020

TABLE 3

Percentage reduction in the concentration of pollutants

Site	SO_2		NO_2		$PM_{2.5}$		PM_{10}	
	April	May	April	May	April	May	April	May
S1	70.8	32	69.9	27.8	51	-	57	33
S2	74.6	40	74.6	35	41.5	42.7	35	24
S3	64.9	40.3	61.4	33.3	62.6	35.6	62.6	48.7
S4	74.8	52.2	73	48.8	-	-	61	45
S5	86.4	83.9	66.8	70	-	-	65	63
S6	21.5	9.4	43.5	20	-	-	36	14.7
S7	35.3	24.7	41	35.6	-	-	34	16.5
S8	35.7	62.8	40	27	-	-	35.4	20.5

Deep *et al*. (2018) also observed that the concentration of pollutants is higher during the pre-monsoon season as compared to the winter and the monsoon seasons. The mean concentration of SO_2 NO_2, $PM_{2.5}$ and PM_{10} was highest during the pre-monsoon season or winter season while the reduction in the concentration of pollutants during monsoon season was due to the scavenging of pollutants by rainfall. During winters, the air quality level was more polluted than other seasons (Chen *et al*. 2015; Kumar and Dash 2018). In another study, Deep *et al*. (2019) also analyzed the variability of SO_2, NO_2, SPM, and PM_{10} concentration in Dehradun city, from 2011 to 2014. The PM_{10} and SPM were found to vary above the permissible limits by CPCB (between 150-195 μgm^{-3} and 350-470 μgm^{-3} during winter and summer respectively).

From the above results, we found that the concentration of SO_2 and NO_2 were in the range of the prescribed limit by CPCB (Table 2) while the concentration of $PM_{2.5}$ and PM_{10} were above the permissible limit by CPCB in all the monitoring locations.

3.3. *Air Quality Index (AQI)*

The AQI level is in the range of 101-200 (Fig. 4), *i.e*., the atmosphere is moderately polluted for sampling sites S1 and S2 during most of the time in year, whereas it was found to be a satisfactory level (51-100) for other monitoring sites (S3, S4, S5, S6, S7 and S8). During winter, the AQI level was found higher than the pre-monsoon season, followed by the monsoon season. A significant improvement in AQI level to 'good' level during the lockdown period is observed in all the monitoring sites. During the lockdown, the AQI was significantly reduced in comparison to the previous year (2019) and the reduction percentage was comparably higher in the industrial sites due to the complete shutdown of industries during the lockdown period. The reduction in AQI level for April - May month are as follows: 57- 42%, 46-34%, 62-42%, 64.8-46%, 68-66%, 37-15%, 35-20% and 40-46% for site S1 to S8, respectively.

3.4. *Comparison of variation in pollutant concentration during the lockdown in 2020 with a dataset from 2019 and 2021*

The concentration of air pollutants like SO_2, NO_2, and PM_{10} shows a significant reduction during the lockdown. Ground-based observations by Liu *et al*. (2021) around California showed a drop of 31%, 38% and 49% in the concentration of $PM_{2.5}$, NO_2 and CO during the lockdown (March 19-May 7) as compared to pre-lockdown time (January 26-March 18) in 2020. Sulaymon *et al*. 2021 also analyzed a significant improvement in air quality with a decline in concentration of $PM_{2.5}$, PM_{10}, NO_2 and CO by 41.2%, 33.1%, 50.6%, and 16.6%, respectively in comparison to the pre-lockdown period in Wuhan city. The most prominent reduction (about 40-60%) was observed for NO_2, $PM_{2.5}$ and PM_{10} across India (Singh *et al*. 2020). Around 40-50% improvement in air quality with significant declination by 39%, 52.68% and 60% in the concentration of $PM_{2.5}$, NO_2 and PM_{10} was observed in the Delhi region as compared to last year (Mahato *et al*. 2020). The air quality has improved throughout the lockdown by a significant reduction in the concentration of $PM_{2.5}$, PM_{10}, SO_2, NO_2, NH_3 and CO by 45.38%, 40.84%, 33.81%, 37.8%, 17.06% and 19.76% from 223 monitoring stations, across the country (Chakrabortty *et al*. 2021). Approximately, 20-34%, 24-47% and 32-64% reduction of $PM_{2.5}$, PM_{10} and NO_2 were observed during the lockdown in 12 major cities across the globe (Kumari *et al*. 2020). The study by Singh and Chauhan (2020) also observed a promising decline in the concentration of $PM_{2.5}$, NO_2 and AQI over Delhi, Mumbai, Hyderabad, Kolkata and Chennai during the lockdown period (2020) compared with the same period

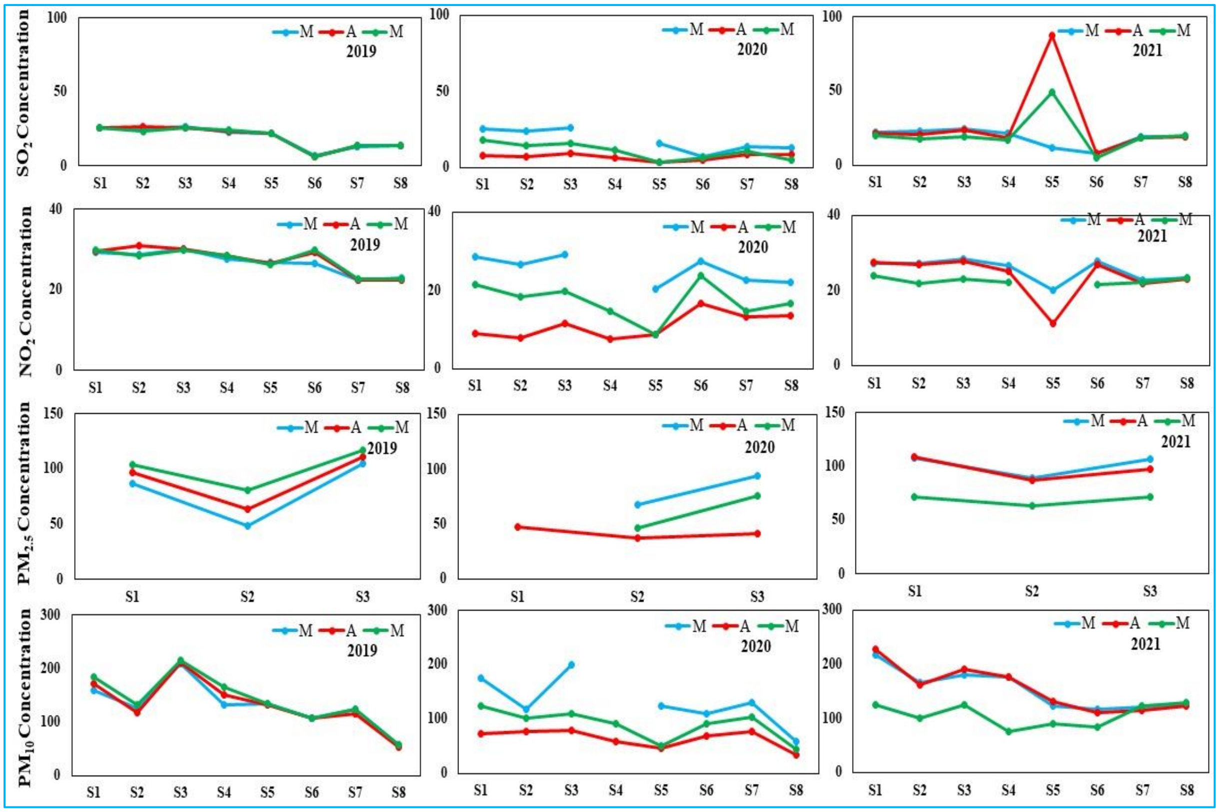

Fig. 5. Variation in concentration of air pollutants during the lockdown period

TABLE 4

Percentage increase in the concentration of pollutants

Site	SO_2		NO_2		$PM_{2.5}$		PM_{10}	
	April	May	April	May	April	May	April	May
S1	65.5	10.5	67.4	9.79	56.3	-	67.6	1.48
S2	67.8	19.8	70.65	15.75	57.46	26.8	52.81	-0.58
S3	61.5	18.8	58.19	13.47	57.6	5.1	58.63	11.4
S4	67.5	31.4	69.62	34.5	-	-	66.8	-17.06
S5	96.5	92.7	21.58	-	-	-	64.9	45.04
S6	36.3	-11.6	38.18	-9.5	-	-	37.8	-8.1
S7	53.8	43.6	39.56	33.98	-	-	34.05	15.07
S8	55	74.5	41.8	28.86	-	-	71.7	65.04

of the previous year (2019). Significant improvement in air quality from 'poor' category to 'good' category with adecline in concentrations of NO_2, PM_{10}, $PM_{2.5}$ by 55.23%, 57.92%, 58.71% in comparison to the pre-lockdown period was evaluated in West Bengal, India (Sarkar *et al*. 2020). In the top 10 major polluted cities of India, a reduction in $PM_{2.5}$ was about 39-65% during the lockdown (Roy *et al*. 2021) and a 40-70% reduction is noticed over the Delhi-National capital region (NCR) in the first week of lockdown as compared to pre-lockdown time (Dhaka *et al*. 2020). It is evident from Table 3 and Fig. 5 that a significant reduction in the concentration of air pollutants like SO_2, NO_2 and PM_{10} in Uttarakhand state during lockdown (March-May, 2020) in comparison to the average concentration before (March-May, 2019). Whereas, the concentration of SO_2, NO_2, $PM_{2.5}$ and PM_{10}

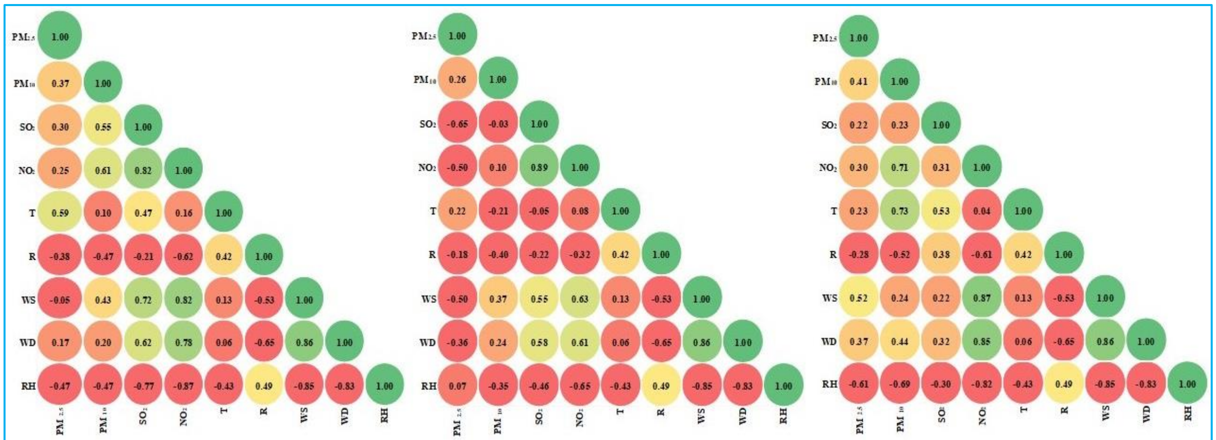

Fig. 6. Pearson correlation matrix showing relationship between concentration of air pollutants and meteorological parameters

TABLE 5

Correlation between concentration of air pollutants

Parameters	$PM_{2.5}$	PM_{10}	SO_2	NO_2
$PM_{2.5}$	1.00	1.00	1.00	1.00
PM_{10}		1.00	0.67	0.34
SO_2			1.00	0.33
NO_2				1.00

TABLE 6

Correlation between concentration of air pollutants during pre-lockdown, lockdown, and post-lockdown period

Parameters	2019				2020				2021			
	$PM_{2.5}$	PM_{10}	SO_2	NO_2	$PM_{2.5}$	PM_{10}	SO_2	NO_2	$PM_{2.5}$	PM_{10}	SO_2	NO_2
$PM_{2.5}$	1.00	0.98	0.99	0.92	1.00	0.54	0.46	0.57	1.00	0.94	0.65	0.48
PM_{10}		1.00	0.69	0.70		1.00	0.76	0.46		1.00	-0.03	0.57
SO_2			1.00	0.55			1.00	0.32			1.00	-0.73
NO_2				1.00				1.00				1.00

shows a significant increase after the lockdown (March-May, 2021) in comparison to lockdown (March-May 2020) as depicted in Table 4 and Fig. 5.

3.5. *Correlation among the ambient air pollutants*

The association between the concentration of various pollutants during the study period was determined by the Pearson correlation coefficient (shown in Table 5). The mean concentration of $PM_{2.5}$ is positively correlated (r = 1.00) with the concentration of PM_{10}, SO_2 and NO_2. The average concentration of PM_{10} is directly correlated with the concentration of $PM_{2.5}$ (r = 1.00), SO_2 (r = 0.67) and NO_2 (r = 0.34). Similarly, the mean concentration of SO_2 is directly correlated with the concentration of $PM_{2.5}$ (r = 1.00), PM_{10} (r = 0.67) and NO_2 (r = 0.33) and the mean concentration of NO_2 is also directly correlated with the concentration of $PM_{2.5}$ (r = 1.00), PM_{10} (r = 0.34) and SO_2 (r = 0.33). Correlation analysis of air pollutants during the pre-lockdown, lockdown, and post-lockdown periods is shown in Table 6. $PM_{2.5}$ shows a strong positive relationship with PM_{10}, SO_2 and NO_2 during the pre-lockdown and post-lockdown period in comparison to the lockdown period. During the lockdown period, pollutants are positively correlated with each other, whereas SO_2 shows a negative relationship with PM_{10} and NO_2 during the post-lockdown period. The correlation between the mean concentration of air pollutants and meteorological

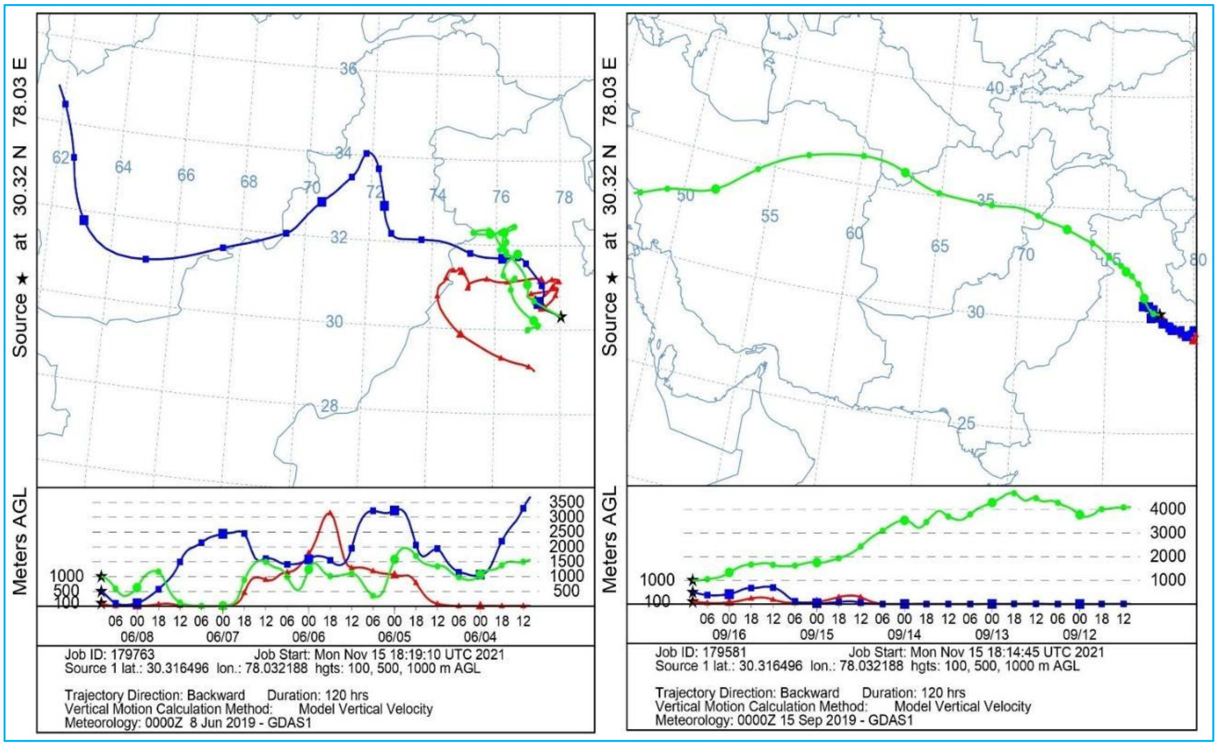

Fig. 7. HYSPLIT model calculated 5-day air mass backward trajectories

parameters for most polluted sites S1, S2, and S3 is shown in Fig. 6. The concentration of air pollutants ($PM_{2.5}$, PM_{10}, SO_2 and NO_2) shows a positive relationship with meteorological parameters like T, WS and WD whereas they show a negative relationship with R and RH. $PM_{2.5}$ shows a negative correlation (r = -0.50) with WS at sites S1 and S2, which means high winds help in the dispersion of pollutants confined over a place. Winds carry them away from one location to the other, thereby reducing the concentration over this monitoring site. Very Low winds are associated with stagnant or nearly stable conditions over a given location. Negative correlation coefficients of air pollutants with R may be due to the wet deposition by the rain (Bodor *et al*., 2020; Owoade *et al*., 2012). Likewise, RH also acts as a natural scrubber that regulates particle movement and then settles down the pollutants (Jayamurugan *et al*., 2013; Kayes *et al*., 2019). The positive correlation of pollutants with T may be due to the rise in concentration due to drying up after the washout process by rain (Kayes *et al*., 2019).

3.6. *Backward air mass trajectory analysis*

In order to delineate the possible source region of pollutants over the most polluted sites, *i.e*., S1, S2 and S3, we have analyzed 5-day air mass backward trajectories using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2011) for June and September months of 2019 (highest and lowest polluted months, respectively) at 100 m, 500 m and 1000 m above ground level. Fig. 7 shows the trajectories illustrating the higher mass concentration of pollutants that arrived during the pre-monsoon season and less during the monsoon season. It is found that the air mass travelled from the north-west region, including Northern Pakistan, Punjab and Haryana.

4. Conclusions

The emission of air pollutants is influenced by complex variables such as wind, temperature, burning materials, policies, and several other anthropogenic factors. This paper analyzed the annual-seasonal pattern and changes in air pollution before, during, and after the countrywide lockdown induced due to COVID-19. Pollutants like SO_2 and NO_2 are under the prescribed limits of NAAQS while $PM_{2.5}$ and PM_{10} are beyond the standards. The COVID-19 pandemic forced us to implement lockdown across the globe, which resulted in a noticeable improvement in air quality. We estimated that COVID-19 control measures resulted in a significant reduction in SO_2, NO_2, $PM_{2.5}$ and PM_{10} emissions by 9.46-86.4%, 20-74.6%, 35.6-62.6%, and 14.7-65%, respectively as compared to the previous year (2019) while a significant increase in the concentration of SO_2, NO_2, $PM_{2.5}$ and PM_{10} by -11.6-96.5%, -9.5-70.65%, to

5.1-57.6 and -17.06-71.7% in comparison to the following year (2021) were shown during the lockdown period. The AQI has improved from a 'satisfactory' and 'moderate' level to a 'good' level in all the selected study sites during the lockdown period in comparison to the pre-lockdown period. With the help of 5-day air mass backward trajectories analysis, it is found that the air mass travelled from the north-west region, from Northern Pakistan, Punjab and Haryana region.

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