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# Air quality trends in coastal industrial clusters of Tamil Nadu, India: A comparison with major Indian cities

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ABSTRACT

India developed several industrial clusters nationwide, including in the state of Tamil Nadu to boost manufacturing. Three coastal cities, namely, Thoothukudi, Cuddalore, and Manali are developed as industrial clusters in Tamil Nadu. For the first time, we documented air quality trends in these industrial cluster cities of Tamil Nadu and compared them with those in Indian major cities, namely, Delhi, Mumbai, Kolkata, and Chennai. Between 2015-2020, data on key air quality parameters, such as particulate matter ($PM_{10}$ and $PM_{2.5}$), nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), and National Air Quality Index (NAQI) measured in these cities were analyzed. Our results suggest that the air quality parameters in coastal industrial cluster cities did not exhibit much seasonal variability owing to the influence of coastal meteorology compared to the hinterland cities, such as Delhi. Among the cities, Delhi showed the highest $PM_{10}$, $PM_{2.5}$, $NO_2$ concentration levels, and NAQI, while Mumbai had the highest $SO_2$ concentration levels. We observed that over the years, the concentration levels of $NO_2$ were showing a decreasing trend in all the cities. While the concentration levels of $PM_{10}$ (except, Mumbai, Chennai, and Kolkata), $PM_{2.5}$ (except, Mumbai), $SO_2$ (except, Kolkata), and NAQI (except, Mumbai, Manali, and Cuddalore) were showing a declining trend. The observed declining trend could be attributed to the air pollution reduction measures implemented in these cities. However, we also observed that many cities were in non-attainment of the National Ambient Air Quality Standards (NAAQS) for $PM_{10}$ and $PM_{2.5}$ but attained the NAAQS for $NO_2$, except for a couple of years in Delhi and Kolkata. Whereas, all the cities attained the prescribed NAAQS for $SO_2$. The findings of this study will serve as the baseline information for policymakers and air quality scientists interested in achieving clean air.

## 1. Introduction

Over the past few decades, India has achieved remarkable economic growth, leading to the upliftment of a large population from poverty (UNDP, 2022). This impressive economic progress can be attributed to rapid industrialization, urbanization, construction, power generation, and various other development activities (Wang et al., 2018). However, rapid industrialization and urbanization have adversely impacted human health and the environment (Voumik et al., 2022). Over the years, increased emissions of air pollutants have significantly deteriorated air quality in many urban regions of India (CAF, 2019; Guttikunda and Nishadh, 2022; Pandey et al., 2021).

Air quality is determined by comparing the observed concentration of criteria air pollutants, such as particulate matter (PM, e.g., $PM_{10}$ and $PM_{2.5}$) and gaseous pollutants like nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), carbon monoxide (CO), ozone ($O_3$), and others, with the National Ambient Air Quality Standards (NAAQS) set by the authorities. If the observed pollutant concentration complies with the NAAQS, the air quality is considered as good; otherwise, it is categorized as bad. The Central Pollution Control Board (CPCB) prescribes the NAAQS for India and updates them regularly (CPCB, 2009). In recent years, the air quality index (AQI), represented by a single numerical value, has emerged as an effective tool for communicating air quality information to the public and raising awareness about its harmful impacts on human health and

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the environment (Suman, 2021; Sisodiya et al., 2022).

PM is airborne particles of varying size and composition emitted from various anthropogenic activities, such as industrial operations, power generation, motor vehicles, incinerators, road dust, municipal waste and agricultural residue open burning, and forest fires (Chowdhury et al., 2007; Yadav et al., 2013; Pant et al., 2015). PM impacts human health, climate change, and the environment (Fuzzi et al. 2015; Manisalidis et al., 2020). Long exposure to PM can lead to premature mortality in patients suffering from lung or heart disease, non-fatal heart attacks, aggravated asthma, reduced lung functionality, throat irritation, coughing, and difficulty breathing (Sasmita et al., 2022). While $NO_2$ is a highly reactive gas. It is a precursor of ozone ($O_3$) and photochemical smog, namely, peroxyacetyl nitrate (PAN) in the atmosphere (Lee et al., 2013). Cars, trucks, and buses are primary sources of $NO_2$ emissions, followed by power plants, diesel-powered heavy construction equipment, and industrial boilers. Exposure to elevated $NO_2$ concentration could lead to health problems, such as respiratory diseases and even mortality (Pandey et al., 2005; Ghude et al., 2008; Pandey et al., 2021). Whereas, $SO_2$ is an indicator of air pollution by oxides of sulfur ($SO_x$). The largest source of $SO_2$ in the atmosphere is the combustion of fossil fuels, such as the use of coal in power plants and other industrial facilities. $SO_2$ is also emitted from industrial processes like metal extraction from ores, ships, vehicles, and heavy machinery that burn fossil fuels with high sulfur content (Mallik et al., 2013; Kuttippurath et al., 2022). Long-term exposure to $SO_2$ can damage the human respiratory system and make breathing difficult. People with asthma, especially children, are sensitive to the $SO_2$ effects (Ahmad and Sharma, 2014). Gaseous $SO_x$ harms trees and plants at higher concentrations by damaging foliage and reducing plant growth (Lee et al., 2017). In addition, $SO_2$ and other $SO_x$ can contribute to acid rain, which damages sensitive ecosystems and causes haze that reduces visibility (Tecer and Tağıl, 2013).

As of 2020, India has developed about 3,400 industrial clusters and business parks to boost the manufacturing sector and promote economic growth (Rathore, 2022). Unfortunately, the effects of these industrial clusters and business parks on local air quality have not been studied comprehensively. Some studies documented the effects of industrial emissions on air quality and health in Delhi, Mumbai, Kolkata, and Chennai (Rizwan et al., 2013; Meo et al., 2022; Puttaswamy et al., 2022). Also, some studies conducted in industrial cities of Tamil Nadu, such as in Manali (Manju et al., 2002), Coimbatore (Mohanraj and Azeez, 2005), and Cuddalore (Balashanmugam, 2012) were for short-term (less than a year) and primarily focused on air quality measurements. There is a need for a comprehensive and systematic study of air pollution in these industrial clusters including the trend in the levels of air pollutants with changes in meteorology and emissions from various sources including effects on human health and the environment.

In this study, for the first time, we documented the trends in air quality in industrial clusters of Tamil Nadu, namely, Thuthukudi, Manali, and Cuddalore in coinfluence of industrial activities and coastal meteorology and compared them with those in major cities of India (e.g., Delhi, Mumbai, Kolkata, and Chennai) using the air quality data measured from January 2015 to December 2020 in Thoothukudi, Delhi, Mumbai, Kolkata, and Chennai and from January 2017 to December 2020 measured in Manali and Cuddalore.

## 2. Materials and methods

### 2.1. Study area

The study area covers three industrial clusters, namely, Thoothukudi (formerly Tuticorin), Cuddalore, and Manali, located along the coastal

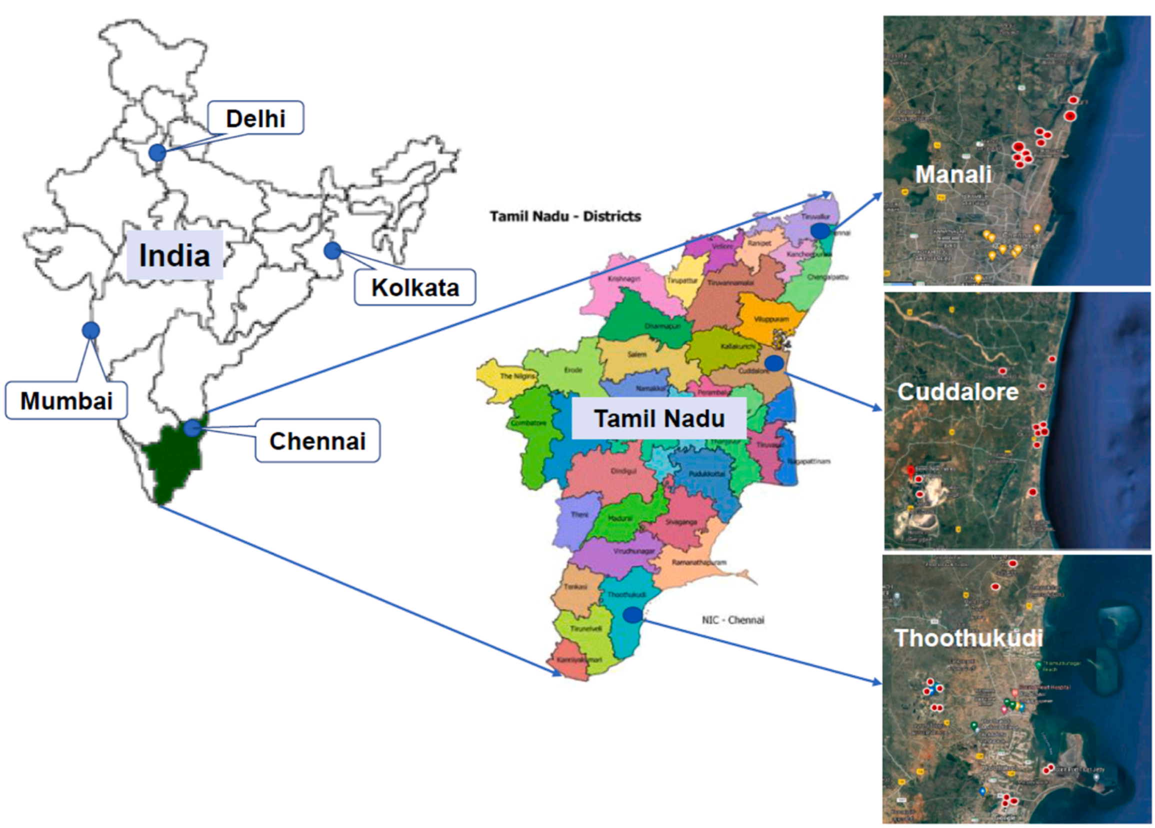


**Fig. 1.** Geographical location of Thoothukudi, Cuddalore, and Manali in Tamil Nadu. Additionally, the location of Delhi, Mumbai, Chennai, and Kolkata is also depicted in the figure. The red circles on the map indicate the presence of large industries in the industrial areas of Thoothukudi, Cuddalore, and Manali. Names of these industries and other major industries operated in Thoothukudi, Cuddalore, and Manali are given in Table 1.

region in Tamil Nadu - a southern state of India. Fig. 1 showed the geographic locations of Thoothukudi (8.53 °N, 78.36 °E), Manali (13.16 °N, 80.23 °E), and Cuddalore (11.75 °N, 79.75 °E). The area of Thoothukudi City municipal corporation is 353.07 $km^2$, with a population of 237,830 (as per the 2011 census).

Given its proximity to the Gulf of Mannar, Thoothukudi serves as a port city. It is a commercial seaport that serves the inland cities of southern India and is one of the sea gateways of Tamil Nadu. Thoothukudi is an emerging energy and industrial hub of India. Manali, on the other hand, is an industrial and residential part of Chennai, located in the northern part of Chennai district in Tamil Nadu. The population of Manali is about 35,248 (as per the 2011 census). Cuddalore is the headquarter of the Cuddalore district, situated south of Chennai. Cuddalore covers a 101.6 $km^2$ area with a population of 308,781 (as per the 2011 census) and houses many chemical, pharmacological, and energy industries.

### 2.2. Meteorological observations

Thoothukudi, Cuddalore, and Manali are the coastal cities in Tamil Nadu. These cities experienced a hot semi-arid climate characterized by sweltering summers, hot winters, and occasionally heavy rain during the northeast monsoon in November and December. Summer (March-June) is characterized by high humidity. Fig. 2 displays the temporal variations of key meteorological parameters, namely, temperature, relative humidity, rainfall, wind speed, and wind direction recorded from January 2016 to December 2017 at the Thoothukudi weather station operated by the State Industries Promotion Corporation of Tamil Nadu Limited (SIPCOT). Meteorological data for Cuddalore and Manali is unavailable. However, since Cuddalore and Manali are situated 377 km and 542 km, respectively, away from Thoothukudi along the coastal region (see Fig. 1), we assumed overall meteorological conditions at Cuddalore and Manali might not be much different than those at Thoothukudi.

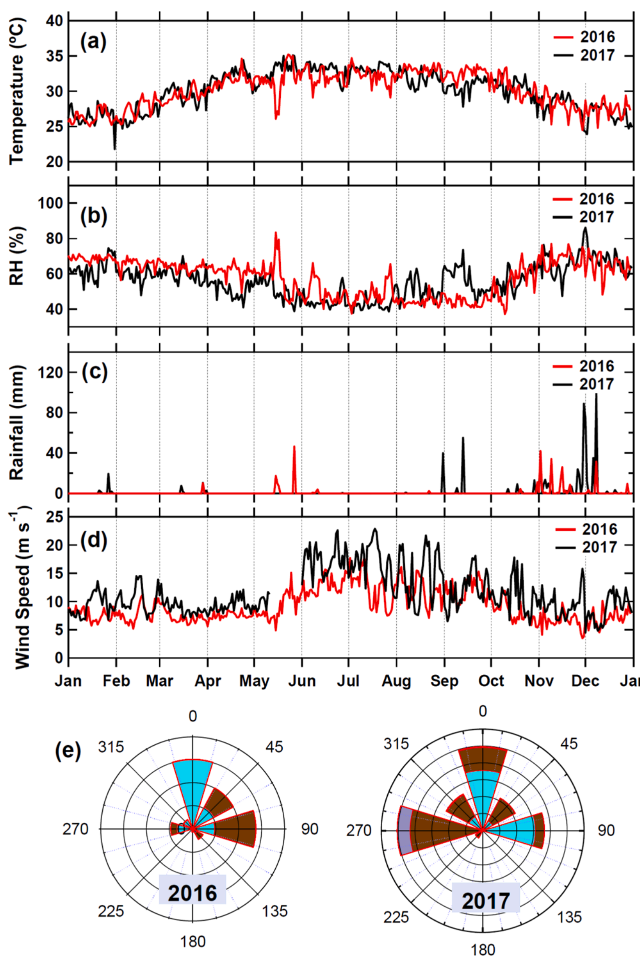


**Fig. 2.** Temporal variations of meteorological parameters in Thoothukudi during 2016 and 2017, including (a) temperature (degree centigrade (°c)), (b) relative humidity (percent (%)), (c) rainfall (millimeter (mm)), (d) wind speed (meter per second (m $s^{-1}$)), and (e) wind direction (degrees relative to north).

As shown in Fig. 2, Thoothukudi experienced hot weather in summer, with a maximum temperature of about 35 (°C) during May and June, while relatively cool weather in winter, with a minimum temperature of about 25 (°C) during December and January (Fig. 2a). Given that Thoothukudi is a coastal city where land-sea breeze circulation is predominant, relative humidity (RH) levels at Thoothukudi did not change significantly over the years, with RH levels varying from about 60-70% from November to January and about 40-50% during June to September (Fig. 2b). In 2017, the city received relatively higher rainfall during October and November, with an average rainfall of about 60-70 mm, while in 2016, it received lower rainfall during November and December, with an average rainfall of about 30-40 mm (Fig. 2c). Thootukudi experienced higher turbulent wind speeds during June to September months of summer in both years, with an average wind speed of about 15-20 m $s^{-1}$, while it was about 10 m $s^{-1}$ during the rest of the years (Fig. 2d). In 2016, and 2017, the dominant wind direction was northeast and northwest, respectively (Fig. 2e).

### 2.3. Air pollution emission sources

Thoothukudi, Cuddalore, and Manali are industrial clusters in Tamil Nadu and various types of industries have been operating in these industrial clusters. Table 1 provides a list of major industries located in Thoothukudi, Cuddalore, and Manali. Thoothukudi, being a port city, houses several power plants and other industrial facilities. In 2016, the CPCB categorized Thoothukudi as a non-attainment city due to its failure to comply with the $PM_{10}$ NAAQS for five consecutive years (CPCB, NAMP). Despite this, no systematic quantitative estimation of air pollutant emissions has been conducted in Thoothukudi so far. Recently, the Tamil Nadu Pollution Control Board (TNPCB) made a preliminary assessment of emissions of air pollutants in Thoothukudi and identified road dust, vehicular exhaust, industries, wood or coal used in cooking, municipal solid waste and agricultural residue open burning as the main sources of air pollution in Thoothukudi and neighboring regions (TNPCB, 2019a). It is worth mentioning that the significant increase in mobile sources, with a total of 766,793 registered vehicles as of March 31, 2018, has further exacerbated air pollution issues in the Thoothukudi region, including 59,350 cars, 675,113 two-wheelers, 26,661 commercial vehicles, 5,669 autorickshaws, and over 940 industries (large, medium, and small size) (TNPCB, 2019b).

In the Manali region, primary air pollutant emission sources include coal combustion in industrial boilers, goods manufacturing, desulfurizing of petroleum products, the use of rice husk as a biofuel, and mobile sources, as documented by Arulprakasajothi et al. (2018). On the other hand, emissions from the transport sector, industrial operations, and construction activities are the main sources of air pollution in Cuddalore, as indicated by Balashanmugam (2012). No information is available on emissions of air pollutants from the residential sector from all three industrial clusters of Tamil Nadu.

### 2.4. Data collection and analysis

Nationwide, India operates a network of more than 450 Continuous Ambient Air Quality Monitoring Stations (CAAQMS). These CAAQMS are located in various parts of India and operated by the CPCB, State Pollution Control Boards (SPCBs), Delhi Pollution Control Committee (DPCC), Indian Meteorological Department (IMD), and Indian Institute of Tropical Meteorology (IITM). CPCB hosts the central data portal for

**Table 1**
List of major industries in industrial clusters of Tamil Nadu.

| Thoothukudi | Cuddalore | Manali |
|---|---|---|
| - Vedanta-Sterlite Copper<br>- Vedanta-Thermal Power Plant<br>- V.V. Titanium Pigments<br>- Kog-Ktv Food Products (India) Ltd.<br>- Adsorbent Carbons (P) Ltd.<br>- Tuticorin Thermal Power Plant<br>- NTPL-NLC Thermal Power Plant<br>- Greenstar Fertilizer<br>- Tuticorin Alkali Chemicals<br>- Coastal Energen Thermal Power Plant<br>- Maha Cements<br>- Travancore Chemicals and Manufacturing Co. Ltd.<br>- Dharangadara Chemical Works Ltd,<br>- South India Carbonic Gas Industries Ltd.<br>- Tuticorin Manufacturing of carbonic oxide<br>- Southern Petrochemical Industries Corporation Ltd. (SPIC)<br>- Loyal Textile Mills Ltd.<br>- Heavy Water Plant<br>- Sterlite Industries (India) Ltd.<br>- Tuticorin – Copper Smelting<br>- Kilburn Chemicals Ltd.<br>- Arasan Textile Mills (P) Ltd.<br>- Transworld Garnet India (P) Ltd. | - NLC India Ltd, TPS Ii 2nd Expansion<br>- Solara Active Pharma Sciences Ltd.<br>- E.I.D. Parry (India) Limited,<br>- Crimson Organics Private Ltd.<br>- Chemplast Sanmar Vinyls Ltd<br>- NOVA Life Science<br>- Kawman Pharma (A Division Of K.P. Manish Global Ingredients Private Ltd)<br>- Sudhakar Chemicals (P) Limited<br>- Taqa Neyveli Power Company Pvt Ltd<br>- Asian Paints Limited (Captive Power Plant)<br>- IL&FS Tamil Nadu Power Company Limited<br>- Tanfac Industries Limited<br>- DFE Pharma India Private Limited<br>- J.K. Pharma-Chem Limited<br>- Sri Arunachala Enterprises<br>- Mercury Engineering Contractors<br>- Tecforce Engineering<br>- Jayam Constructions<br>- P D R Constructions<br>- S Sundaram And Sons<br>- Indira Industries<br>- Sri Rajarajeswari Engineering<br>- Ganapathy Diesel Engine Service Center<br>- Priya Engineering Corporation | - Chennai Petroleum Corporation Limited (CPCL)<br>- ETPS Expansion Thermal Power Project<br>- Mena Leather Manufacturers and Exporters<br>- Sri Venkateshwara Leather Company<br>- Splendid Leather Manufacturer<br>- Krithika Leathers (Formerly General Leather Export Co)<br>- SSB Industries<br>- NATCO Pharma Limited<br>- Piramal Pharma Limited<br>- IMAC Alloy Casting Private Limited<br>- Madras Fertilizers Limited (MFL)<br>- Manali Petro Chemical Ltd (MPL)<br>- Futura Polymers Ltd<br>- Cetex Petro Chemicals Ltd<br>- Tamil Nadu Petroproducts Limited (TPL)<br>- Sriram Fibres Ltd (SRF)<br>- Madras Rubber Factory (MRF)<br>- Kothari Chemicals and Pesticides<br>- Balmer Lawrie & Co<br>- Infra Tanks and Polymers<br>- The Huntsman Polyurethenes<br>- ICI Limited<br>- SRF Limited<br>- Toshiba JSW Power Systems Private Limited |

air pollutants monitored at these CAAQMS (CPCB, CCRAQM). Verma and Kamyotra (2021) has discussed in detail the spatial distribution of CAAQMS in the country. For this study, 24-hour averaged air quality data for key criteria pollutants (e.g., $PM_{10}$, $PM_{2.5}$, $SO_2$, and $NO_2$) were downloaded from the CPCB data portal (CPCB, CCRAQM). The $PM_{10}$, $PM_{2.5}$, $SO_2$, and $NO_2$ data presented in this study for Delhi, Mumbai, Kolkata, and Chennai are the average of all CAAQMS operated in respective cities. For Thoothukudi, air quality data was measured at AVM Jewellery, Raja Agency, and SIPCOT. Air quality data measured at AVM Jewellery mainly represents air pollutants from commercial and residential activities. In contrast, air quality data measured at Raja Agency was mainly influenced by emissions from the seaport and thermal power plants and nearby transport activities, while the SIPCOT air quality data mainly represents emissions from industrial activities (TNPCB 2019a; TNPCB 2019b). Air quality data were collected from Ambient Air Quality Monitoring Stations (AAQMS) located at SIPCOT-Cuddalore and Manali. For this study, 24-hour averaged National Air Quality Index (NAQI) data were downloaded from the CPCB website (CPCB, NAQI). If the number of CAAQMS in a city is more than one, CPCB publishes 24-hour averaged NAQI from all the CAAQMS operated in the city. For the air quality data collected at the CAAQMS, CPCB conducts quality assurance and quality control (QA/QC) and transforms the data into standard quality (CPCB QA/QC). The key air pollutants and NAQI data used in this study were collected at AAQMS located at AVM Jewellery, Raja Agency, and SIPCOT for Thoothukudi, at SIPCOT for Cuddalore, and in Manali. These AAQMS are operated by the TNPCB (TNPCB, AAMP).

Apart from basic statistical analysis (e.g., average, standard deviation, etc.) of air quality parameters, we used a linear regression model (formula $Y = mX + c$) for trend analysis of concentration levels of air quality parameters with time (where Y is the air pollutant, X is the time, m is the slope, and c is the intercept). The linear regression model is commonly used in scientific studies to understand the correlation between two variables including trend analysis. Trend analysis reveals the change in the concentration levels of air pollutants (i.e., increase, decrease, no change) over the period implying to study the effectiveness of implementation of air pollution mitigation policies and technologies. In addition to trend analysis, we also calculated a net change in the concentration levels of air pollutants from the level observed in 2015 to that in 2020. The detailed trend analysis and a net change in concentration levels of air pollutants have been discussed in subsequent sections.

## 3. Result and discussion

### 3.1. PM

The concentration levels of air pollutants, specifically PM (e.g., $PM_{10}$ and $PM_{2.5}$) in ambient air exhibit variations with time, influenced by changes in meteorological conditions and intensity of emissions of air pollutants. The relationship between the concentration levels of air pollutants in ambient air and meteorological conditions and emission intensity has been studied extensively in various locations worldwide, such as Beijing and Nanjing (Zhou et al., 2020), Guangzhou (Verma et al., 2010), Hedo (Verma et al., 2011; Kondo et al., 2011), Seoul (Seo et al., 2018), Bangkok (Sangkham et al., 2021), among others.

Fig. 3(a & b) illustrated the temporal variations in the monthly average concentration levels of $PM_{10}$ and $PM_{2.5}$ in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali from January 2015 to December 2020. $PM_{10}$ and $PM_{2.5}$ data are included in Table 2. It is to note that $PM_{10}$ and $PM_{2.5}$ data for some cities were not available for a certain period. For example, air quality data for Thoothukudi and Manali were available from January 2017 to December 2020 only. The $PM_{10}$ and $PM_{2.5}$ data shown in Fig. 3 and Table 2 are the average of all CAAQMS and AAQMS operated in the respective cities. The trend analysis, i.e., change in the concentration levels of $PM_{10}$ and $PM_{2.5}$ over the years in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali, and the government-prescribed NAAQS for $PM_{10}$ and $PM_{2.5}$ are also included in Fig. 3 (c & d).

The concentration levels of $PM_{10}$ and $PM_{2.5}$ showed prominent seasonal variations. Their levels were high during winter and lower in summer or rainy seasons and showed their dependency on meteorological conditions assuming that the emissions of $PM_{10}$ and $PM_{2.5}$ in these cities were not changed significantly during the year, except in north Indian cities, such as Delhi which found to be greatly influenced by biomass burning in the region during winter (Sawlani et al, 2019; Lan et al, 2022). Among all the cities included in Fig. 3, Delhi and Kolkata have shown consistently high seasonal variations in the concentration levels of $PM_{10}$ and $PM_{2.5}$ with higher levels in winter and slightly lower in summer or during monsoon. Kolkata and the surrounding eastern part of India is a gateway of air pollution outflow from the Indo-Gangetic Plan (IGP) to the Bay of Bengal, prominently seen in winter (Srinivas et al, 2015; Sasmita et al, 2022).

Chennai and Mumbai also demonstrated seasonal variations in the concentration levels of $PM_{10}$ and $PM_{2.5}$ but their seasonal variations are of low intensity compared to Delhi and Kolkata. Seasonal variations in the concentration levels of $PM_{10}$ and $PM_{2.5}$ observed in Manali are

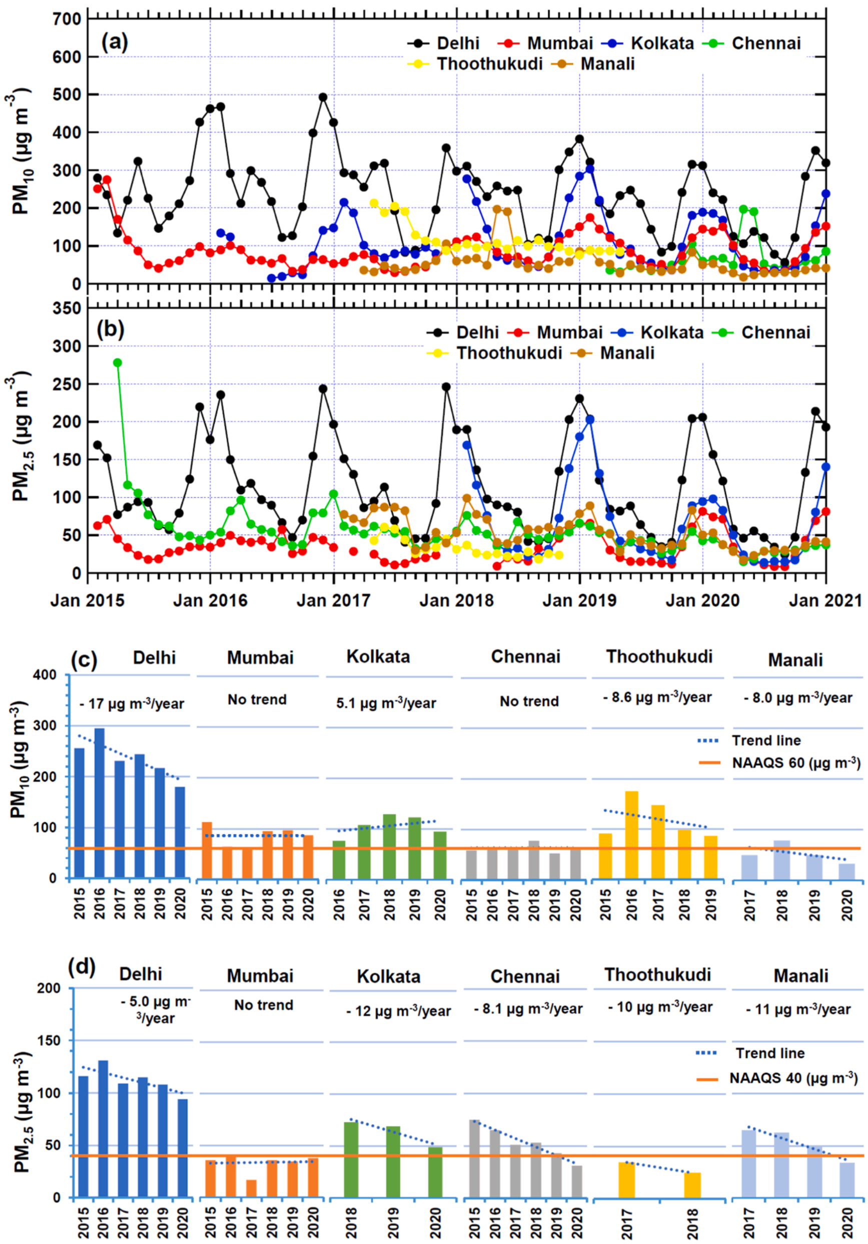


**Fig. 3.** Temporal variations in $PM_{10}$ and $PM_{2.5}$ concentration levels in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali from 2015 to 2020: (a) Monthly $PM_{10}$, (b) Monthly $PM_{2.5}$, (c) Yearly $PM_{10}$, and (d) Yearly $PM_{2.5}$. The figure also includes trend analysis for yearly $PM_{10}$ and $PM_{2.5}$, along with the Government-prescribed National Ambient Air Quality Standards (NAAQS) for $PM_{10}$ and $PM_{2.5}$.

similar to that observed in Chennai because Manali is closer to Chennai and experiences atmospheric transport of air pollutants from Chennai. Variations in the concentration levels of $PM_{10}$ and $PM_{2.5}$ observed in Thoothukudi were very low compared to those in Delhi and Kolkata but similar to those of Manali and Chennai because Thoothukudi, Manali, and Chennai are coastal cities and experience similar meteorological conditions, even though PM emission intensity in these cities varied significantly (Fig. 3). Seasonal variations in the concentration levels of $PM_{10}$ and $PM_{2.5}$ observed in this study were similar to those observed by Rahman et al. (2020) and Mandal et al. (2022) in Delhi, Sandeep et al. (2013) in Mumbai, Karar et al. (2006) in Kolkata, Laxmipriya et al. (2020) in Chennai, and Sivaramasundaram and Muthusubramanian (2010) in Thoothukudi.

Table 2 presents the annual average concentrations of $PM_{10}$ and $PM_{2.5}$ observed in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali from 2015 to 2020, along with a net change in the concentration levels and trend analysis of $PM_{10}$ and $PM_{2.5}$ over the years in these cities.

In Delhi, the annual average observed concentrations of $PM_{10}$ were 256, 295, 231, 244, 217, and 180 µg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 76 µg $m^{-3}$ $PM_{10}$ from the level observed in 2015 to that is 2020 (Table 2). The trend analysis revealed that $PM_{10}$ concentration has been decreased by 17 µg $m^{-3}$/year ($r^2 = 0.69$) in Delhi (Fig. 3c & Table 2). Similarly, in Mumbai, the annual average concentration levels of $PM_{10}$ were recorded as 113, 65, 61, 95, 97, and 87 µg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and demonstrated a net decrease of 26 µg $m^{-3}$ $PM_{10}$ observed from 2015 to 2020. However, the $PM_{10}$ concentration levels fluctuated over the years, therefore no trend ($r^2 = 0$) in $PM_{10}$ concentration was observed in Mumbai (Fig. 3c). Likewise, in Kolkata, the annual average $PM_{10}$ concentration levels were observed as 77, 108, 129, 123, and 95 µg $m^{-3}$ in 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net increase of 18 µg $m^{-3}$ $PM_{10}$ from the level

**Table 2**
Yearly average concentrations of $PM_{10}$, $PM_{2.5}$, $NO_2$, $SO_2$, and NAQI observed in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, Coimbatore, and Cuddalore. A net change in the concentration levels of air pollutants and the trend analysis are included in the Table.

| Air quality parameter | City | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Net change (2015-2020) | Trend Analysis Air pollutant change per year | Overall trend |
|---|---|---|---|---|---|---|---|---|---|---|
| **$PM_{10}$ (μg $m^{-3}$)** | Delhi | 256 | 295 | 231 | 244 | 217 | 180 | -76 | -17 ($r^2 = 0.69$) | Dec. |
| | Mumbai | 113 | 65 | 61 | 95 | 97 | 87 | -26 | ($r^2 = 0$) | NT |
| | Kolkata | NA | 77 | 108 | 129 | 123 | 95 | +18 | 5.1 ($r^2 = 0.15$) | Inc. |
| | Chennai[*] | 59[*] | 65[*] | 62 | 78 | 53 | 63 | +4 | ($r^2 = 0$) | NT |
| | Thoothukudi[#] | 91 | 175 | 148 | 99 | 87 | NA | -4 | -8.6 ($r^2 = 0.12$) | Dec. |
| | Manali[$] | NA | NA | 50 | 79 | 50 | 33 | -17 | -8.0 ($r^2 = 0.29$) | Dec. |
| **$PM_{2.5}$ (μg $m^{-3}$)** | Delhi | 116 | 131 | 109 | 115 | 108 | 94 | -22 | -5.0 ($r^2 = 0.58$) | Dec. |
| | Mumbai | 36 | 41 | 17 | 36 | 35 | 38 | +2 | ($r^2 = 0$) | NT |
| | Kolkata | NA | NA | NA | 73 | 69 | 49 | -24 | -12 ($r^2 = 0.87$) | Dec. |
| | Chennai[*] | 75[*] | 65[*] | 51 | 53 | 43 | 31 | -44 | -8.1 ($r^2 = 0.95$) | Dec. |
| | Thoothukudi[#] | NA | NA | 35 | 25 | NA | NA | -10 | -10 ($r^2 = 1$) | Dec. |
| | Manali[$] | NA | NA | 64 | 62 | 50 | 33 | -31 | -11 ($r^2 = 0.91$) | Dec. |
| **$NO_2$ (μg $m^{-3}$)** | Delhi | 50 | 60 | 51 | 46 | 45 | 37 | -13 | -3.3 ($r^2 = 0.65$) | Dec. |
| | Mumbai | 38 | 42 | 20 | 31 | 23 | 21 | -17 | -3.8 ($r^2 = 0.57$) | Dec. |
| | Kolkata | NA | 44 | 48 | 28 | 41 | 28 | -16 | -3.9 ($r^2 = 0.44$) | Dec. |
| | Chennai | 21 | 19 | 19 | 20 | 16 | 11 | -10 | -1.7 ($r^2 = 0.71$) | Dec. |
| | Thoothukudi[#] | 18 | 22 | 13 | 11 | 11 | 9 | - 9 | -2.3 ($r^2 = 0.72$) | Dec. |
| | Manali[$] | NA | NA | 24 | 20 | 17 | 13 | -1 | -0.9 ($r^2 = 0.72$) | Dec. |
| **$SO_2$ (μg $m^{-3}$)** | Delhi | 12 | 18 | 19 | 14 | 14 | 13 | +1 | ($r^2 = 0$) | NT |
| | Mumbai | 22 | 31 | 23 | 28 | 21 | 12 | -10 | -2.1 ($r^2 = 0.37$) | Dec. |
| | Kolkata | NA | 5 | 14 | 6 | 10 | 10 | +5 | ($r^2 = 0$) | NT |
| | Chennai | 10 | 6 | 10 | 9 | 8 | 8 | -2 | ($r^2 = 0$) | NT |
| | Thoothukudi[#] | 13 | 14 | 14 | 13 | 11 | 6 | -7 | -1.3 ($r^2 = 0.66$) | Dec. |
| | Manali[$] | NA | NA | 14 | 12 | 13 | 10 | -4 | -0.9 ($r^2 = 0.72$) | Dec. |
| **NAQI** | Delhi | 219 | 254 | 228 | 225 | 215 | 185 | -34 | -8.3 ($r^2 = 0.48$) | Dec. |
| | Mumbai | 98 | 91 | 108 | 108 | 103 | 95 | -3 | ($r^2 = 0$) | NT |
| | Kolkata | NA | 87 | 106 | 128 | 137 | 111 | +24 | 7.9 ($r^2 = 0.41$) | Inc. |
| | Chennai | 112 | 150 | 114 | 99 | 88 | 69 | -43 | -8.4 ($r^2 = 0.85$) | Dec. |
| | Thoothukudi[#] | NA | NA | NA | 95 | 86 | 82 | -13 | -6.5 ($r^2 = 0.95$) | Dec. |
| | Cuddalore[€] | NA | NA | NA | NA | 55 | 57 | +2 | 2.0 ($r^2 = 1.0$) | Inc. |
| | Manali[$] | NA | NA | NA | 57 | 63 | 55 | -2 | ($r^2 = 0$) | NT |

[*] In Chennai, the concentration levels of $PM_{10}$ were less than that of $PM_{2.5}$ due to the non-availability of data for several stations.
[#] Average of 3 monitoring stations, namely, AVM Jewellery, Raja Agency, and SIPCOT for Thoothukudi
[$] Average of Manali-Village and Manali-Chennai
[€] Average of SIPCOT-Cuddalore, Eachankadu Village, and Imperial Road;
Inc. (+): increasing trend;
Dec. (-): decreasing trend;
NT: No trend (if $r^2 = 0$)

observed in 2016 to that in 2020. The trend analysis also revealed a slightly increasing trend (5.1 μg $m^{-3}$/ year, $r^2 = 0.15$) in $PM_{10}$ levels in Kolkata (Fig. 3c & Table 2). Whereas, in Chennai, the annual average $PM_{10}$ concentration levels were 59, 65, 62, 78, 53, and 63 μg $m^{-3}$ observed in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, with a net increase of 4 μg $m^{-3}$ $PM_{10}$ from the level observed in 2015 to that in 2020. Since $PM_{10}$ fluctuated in Chennai over the years, no trend ($r^2 = 0$) was observed there. Likewise, in Thoothukudi, the annual average concentrations of $PM_{10}$ were observed as 91, 175, 148, 99, and 87 μg $m^{-3}$ in 2016, 2017, 2018, and 2019, respectively, and showed a net decrease of 4 μg $m^{-3}$ $PM_{10}$ from 2015 to 2020 and showed a slightly decreasing trend of 4 μg $m^{-3}$/year ($r^2 = 0.12$). Similarly, in Manali, the annual average $PM_{10}$ concentrations were 50, 79, 50, and 33 μg $m^{-3}$ observed in 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 17 μg $m^{-3}$ $PM_{10}$ from the level observed in 2017 to that in 2020 and revealed a decreasing trend of 8 μg $m^{-3}$/year ($r^2 = 0.29$) (Fig. 3c &Table 2).

The yearly average concentration levels of $PM_{2.5}$ observed in Delhi, Mumbai, Chennai, Kolkata, Thoothukud, and Manali from 2015 to 2020 are illustrated in Table 2 including the change in concentration levels and trend analysis over the years. In Delhi, the annual average concentrations of $PM_{2.5}$ were 116, 131, 109, 115, 108, and 94 μg $m^{-3}$ observed in 2015, 2016, 2017, 2018, 2019, and 2020, respectively. The observation showed that there was a net decrease of 22 μg $m^{-3}$ $PM_{2.5}$ in Delhi from the level observed in 2015 to that in 2020 (Table 2). The trend analysis revealed that $PM_{2.5}$ concentration showed a decreasing trend by 5 μg $m^{-3}$/year ($r^2 = 0.58$) in Delhi (Fig. 3d & Table 2). Similarly, in Mumbai, the annual average concentration levels of $PM_{2.5}$ were observed as 36, 41, 17, 36, 35, and 38 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and a net increase of 2 μg $m^{-3}$ $PM_{2.5}$ from the level observed in 2015 compared to that in 2020. The $PM_{2.5}$ concentration values were fluctuating over the years in Mumbai, therefore, no trend ($r^2 = 0$) was observed there in the $PM_{2.5}$ level. On the other hand, the annual average concentrations of $PM_{2.5}$ in Kolkata were recorded as 73, 69, and 49 μg $m^{-3}$ in 2018, 2019, and 2020, respectively, and showed a net decrease of 24 μg $m^{-3}$ $PM_{2.5}$ from the level measured in 2018 to that is 2020 and revealed a prominent decreasing trend by 5 μg $m^{-3}$/year ($r^2 = 0.87$) over the years in Kolkata. Likewise, in Chennai, the annual average concentration levels of $PM_{2.5}$ were 75, 65, 51, 53, 43, and 31 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 44 μg $m^{-3}$ $PM_{2.5}$ from the measured value in 2015 to that in 2020. It revealed a prominent decreasing trend of 8.1 μg $m^{-3}$/year ($r^2 = 0.95$) during the observation years. Whereas, in Thoothukudi, the annual average concentrations of $PM_{2.5}$ were measured as 35 and 25 μg $m^{-3}$ in 2017 and 2018, respectively, with a net decrease of 10 μg $m^{-3}$ in these years. Similarly, in Manali, the annual average concentrations of $PM_{2.5}$ were 64, 62, 50, and 33 μg $m^{-3}$ observed in 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 31 μg $m^{-3}$ from the level measured in 2017 to that in 2020. The observation demonstrated that $PM_{2.5}$ showed a prominent decreasing trend of 11 μg $m^{-3}$/year ($r^2 = 0.91$) in Manali from 2017 to 2020 (Fig. 3d & Table 2). The observation revealed a decreasing trend in the concentration levels of $PM_{10}$ (except Mumbai and Chennai) and $PM_{2.5}$ (except Mumbai) in the cities (Fig. 3c&d and

Table 2). These decreasing trends in the concentration levels of PM (both $PM_{10}$ and $PM_{2.5}$) could be attributed to the air pollution reduction measures taken by the authorities. However, details of air pollution reduction measures taken by the government need to be analyzed, which is out of the scope of this study.

Furthermore, the annual average concentrations of $PM_{10}$ and $PM_{2.5}$ observed in Delhi and Kolkata from 2015 to 2020 were consistently higher than the prescribed NAAQS threshold of 60 μg $m^{-3}$ for $PM_{10}$ and 40 μg $m^{-3}$ for $PM_{2.5}$ (Fig. 3c & d). In Mumbai, the annual average concentrations of $PM_{10}$ observed in 2016 and 2017 complied with the NAAQS but not in 2015, 2018, and 2019. Whereas the annual average concentrations of $PM_{2.5}$ in Mumbai from 2015 to 2020 complied with the prescribed 40 μg $m^{-3}$ NAAQS for $PM_{2.5}$. Similarly, in Kolkata, the observed $PM_{10}$ and $PM_{2.5}$ did not comply with the prescribed NAAQS for $PM_{10}$ and $PM_{2.5}$. In Chennai, the annual average concentrations of $PM_{10}$ barely met the prescribed NAAQS for $PM_{10}$, whereas annual average concentrations of $PM_{2.5}$ did not meet the prescribed NAAQS for $PM_{2.5}$ (except in 2020). In Thoothukudi, the observed annual average concentration of $PM_{10}$ did not meet the prescribed $PM_{10}$ NAAQS. Because of high $PM_{10}$ concentration levels, Thoothukudi has been included in the list of non-attainment cities as the city did not attain $PM_{10}$ NAAQS consecutively for five years (CPCB, NAMP). However, Thoothukudi complied with the $PM_{2.5}$ NAAQS in 2017 and 2018. The annual average $PM_{10}$ concentrations in Manali met the $PM_{10}$ NAAQS from 2017 to 2020 (except 2018) but did not meet the $PM_{2.5}$ NAAQS (except 2020) (Fig. 3c&d).

### 3.2. $NO_2$

Fig. 4(a) illustrated the temporal variations in the monthly average concentration levels of $NO_2$ in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali from January 2015 to December 2020. It may

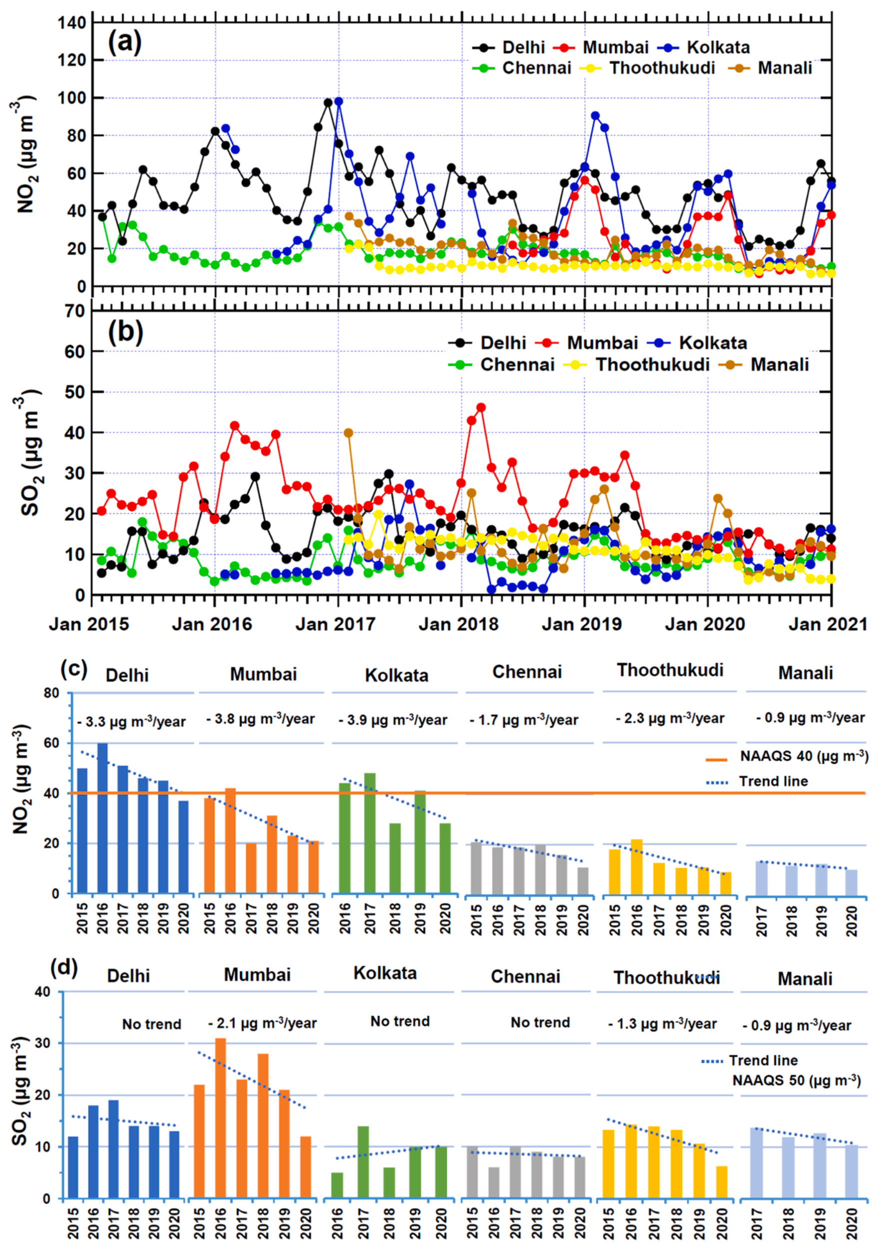


**Fig. 4.** Temporal variations in the concentration levels of $NO_2$ and $SO_2$ in Delhi Mumbai, Chennai, Kolkata, Thoothukudi, and Manali from 2015 to 2020: (a) monthly $NO_2$ (b) monthly $SO_2$, (c) yearly $NO_2$, and (d) yearly $SO_2$. Trend analysis for yearly $NO_2$ and $SO_2$ and the government-prescribed National Ambient Air Quality Standards (NAAQS) for $NO_2$ and $SO_2$ are also included in the figure.

be noted that $NO_2$ data for some cities were unavailable for certain study periods. Fig. 4(c) presents the variations in the annual average concentrations of $NO_2$ observed in Delhi, Mumbai, Chennai, Kolkata, Thoothukudi, and Manali along with trend analysis. The corresponding values of the annual average concentration levels of $NO_2$ can be found in Table 2. Both Fig. 4(c) and Table 2 also included a net change in the concentration levels of $NO_2$ from 2015 to 2020 and that trend analysis of $NO_2$ levels in these cities. These analyses provide insights into the changes in the $NO_2$ concentration levels over time. The concentrations of $NO_2$ depicted in Fig. 4(a & c) and Table 2 represent the average values obtained from all CAAQMS and AAQMS operated in the cities.

Similar to $PM_{10}$ and $PM_{2.5}$, Delhi, Mumbai, and Kolkata have exhibited higher seasonal variations in the concentration levels of $NO_2$ over the years, with higher levels observed during winter and lower levels during summer or monsoon seasons. On the other hand, Chennai, Thoothukudi, and Manali have shown lower seasonal variations in $NO_2$ concentrations compared to Delhi, Mumbai, and Kolkata (as shown in Fig. 4(a)). The seasonal variations in the concentration levels of $NO_2$ in this study were similar to those observed by Sharma et al., 2010 in Delhi, Ramachandran et al. (2013) and Prabakaran et al. (2017) in Mumbai and Chennai, and Chatterjee (2022) in Kolkata.

As shown in Table 2, the observed annual average concentration levels of $NO_2$ in Delhi were 50, 60, 51, 46, 45, and 37 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 13 μg $m^{-3}$ $NO_2$ from the level measured in 2015 to that in 2020. The trend analysis revealed that the $NO_2$ concentration level in Delhi consistently decreased by 3.3 μg $m^{-3}$/year ($r^2 = 0.91$) from 2015 to 2020. Similarly, in Mumbai, the annual average concentrations of $NO_2$ were observed as 38, 42, 20, 31, 23, and 21 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and demonstrated a net decrease of 17 μg $m^{-3}$ $NO_2$ from the level observed in 2015 to that in 2020, and with a decreasing trend by 3.8 μg $m^{-3}$/year ($r^2 = 0.57$) during 2015 to 2020. Whereas in Kolkata, the observed annual average concentrations of $NO_2$ were 44, 48, 28, 41, and 28 μg $m^{-3}$ in 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 16 μg $m^{-3}$ $NO_2$ from the level measured in 2015 to that in 2020, and revealed a decreasing trend by 3.9 μg $m^{-3}$/year ($r^2 = 0.44$) from 2016 to 2020. Likewise, in Chennai, the observed annual average concentrations of $NO_2$ were recorded as 21, 19, 19, 20, 16, and 11 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, with a net decrease of 10 μg $m^{-3}$ $NO_2$ from the level in 2015 to that in 2020, and showed a decreasing trend by 1.7 μg $m^{-3}$/year ($r^2 = 0.71$) during 2015 to 2020. On the other hand, $NO_2$ annual average concentrations observed in Thoothukudi were 18, 22, 13, 11, 11, and 9 μg $m^{-3}$ in 2015, 2016, 2017, 2018, and 2019, respectively, and showed a net decrease of 9 μg $m^{-3}$ $NO_2$ from the level measured in 2015 to that in 2020 and demonstrated a decreasing trend of 2.3 μg $m^{-3}$/year ($r^2 = 0.72$) during 2015 to 2020. Similarly, in Manali, the annual average concentrations of $NO_2$ were 24, 20, 17, and 13 μg $m^{-3}$ observed in 2017, 2018, 2019, and 2020, respectively, with a net decrease of 11 μg $m^{-3}$ $NO_2$ from 2017 to 2020, and showed a decreasing trend of 0.9 μg $m^{-3}$/year ($r^2 = 0.72$) during 2015 to 2020 (Table 2).

Similar to $PM_{10}$ and $PM_{2.5}$, the $NO_2$ concentration levels have been showing decreasing trends in all cities over the years (Fig. 4c), similar to that shown by Sicard et al. (2023) for Indian cities. These decreasing trends in the concentration levels of $NO_2$ in these cities could be attributed to the air pollution reduction measures implemented by the authorities. From the NAAQS compliance perspective, the annual average concentrations of $NO_2$ observed in Delhi from 2015 to 2019 were consistently higher than the NAAQS $NO_2$ threshold of 40 μg $m^{-3}$. Whereas, the observed annual average concentrations of $NO_2$ from 2015 to 2020 in Mumbai (except 2016), and Kolkata (except 2016 and 2017) complied prescribed NAAQS for $NO_2$. On the other hand, the $NO_2$ concentration levels in Chennai, Thoothukudi, and Manali were below the prescribed NAAQS threshold for $NO_2$ and thus these complied with $NO_2$ NAAQS.

### 3.3. $SO_2$

Fig. 4(b) showed temporal variations in the concentration levels of monthly averaged $SO_2$ observed in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, and Manali. Fig. 4(d) showed variations in the annual average concentrations of $SO_2$ observed in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, and Manali. Fig. 4(d) and Table 2 included annual average concentration values of $SO_2$ observed in these cities along with trend analysis and a net change in the $SO_2$ concentration values over the years. The concentrations of $SO_2$ shown in Fig. 4 and Table 2 are the average of all the AAQMS operated in the cities.

Similar to PM and $NO_2$ levels in Delhi, Mumbai, and Kolkata, the concentration levels of $SO_2$ in these cities have shown higher seasonal variations over the year, with higher levels in winter and lower in summer or during monsoon. For most of the period, the concentration levels of $SO_2$ were higher in Mumbai. Dahiya and Myllyvirta (2019) noted that $SO_2$ concentration levels were high in Mumbai compared to other parts of India due to the excess use of coal, oil and gas in the city. Whereas, Chennai, Thoothukudi, and Manali have shown lower seasonal variations in $SO_2$ concentration levels over the years compared to those recorded in Delhi, Mumbai, and Kolkata (Fig. 4b). Previous studies have demonstrated similar seasonal variations in the concentration levels of $SO_2$ in Delhi by Datta et al., (2010) and Chennai by Prabakaran et al. (2017).

As shown in Table 2, the observed annual average concentrations of $SO_2$ in Delhi were 12, 18, 19, 14, 14, and 13 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, with a slightly net increase of 1 μg $m^{-3}$ $SO_2$ from the level observed in 2015 to that in 2020. However, the concentration values of $SO_2$ fluctuated over the year, thus no trend ($r^2 = 0$) in $SO_2$ levels has been observed in Delhi. Whereas, in Mumbai, the annual average concentration levels of $SO_2$ were 22, 31, 23, 28, 21, and 12 μg $m^{-3}$ observed in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 10 μg $m^{-3}$ $SO_2$ from the level measured in 2015 to that in 2020 and revealed a prominent decreasing trend of 2.1 μg $m^{-3}$/year ($r^2 = 0.37$) during 2015 to 2020. On the other hand, the observed annual average concentration levels of $SO_2$ in Kolkata were 5, 14, 6, 10, and 10 μg $m^{-3}$ in 2016, 2017, 2018, 2019, and 2020, respectively. Although, in Kolkata, a net increase of 5 μg $m^{-3}$ $SO_2$ was observed from the level in 2015 to that in 2020, but no trend ($r^2 = 0$) has been observed since values of $SO_2$ varied over the years. Likewise, in Chennai, the observed annual average concentrations of $SO_2$ were observed as 10, 6, 10, 9, 8, and 8 μg $m^{-3}$ in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, with a net decrease of 2 μg $m^{-3}$ $SO_2$ from 2015 to 2020, but no trend ($r^2 = 0$) was observed since values of $SO_2$ in Chennai varied over the years. Similarly, the annual average concentrations of $SO_2$ in Thoothukudi were 13, 14, 14, 13, 11, and 6 μg $m^{-3}$ observed in 2015, 2016, 2017, 2018, and 2019, respectively, with a net decrease of 7 μg $m^{-3}$ from the level measured in 2015 to that in 2020, and showed a clear decreasing trend of 1.3 μg $m^{-3}$/year ($r^2 = 0.66$) during 2015 to 2020. Whereas, in Manali, the annual average concentrations of $SO_2$ were 14, 12, 13, and 10 μg $m^{-3}$ observed in 2017, 2018, 2019, and 2020, respectively, a net decrease of 4 μg $m^{-3}$ $SO_2$ from 2017 to 2020 and revealed a decreasing of 0.9 μg $m^{-3}$/year ($r^2 = 0.37$) during 2017 to 2020. (Fig. 4d & Table 2). It could be noted, the yearly averaged concentrations of $SO_2$ observed in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, and Manali were found below the NAAQS threshold of 50 μg $m^{-3}$ NAAQS for $SO_2$.

### 3.4. NAQI

In India, CPCB published a real-time NAQI of more than 450 CAAQMS. NAQI is calculated by taking a weighted average of 8 criteria pollutants, namely $PM_{10}$, $PM_{2.5}$, $SO_2$, $NO_2$, CO, $O_3$, $NH_3$, and Pb, in a single value matrix. Details of equations used for calculating NAQI have been discussed in the Report on National Air Quality Index (CPCB, 2014) and by Verma and Kamyotra, 2021).

Fig. 5 showed temporal variations in the NAQI values in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, Cuddalore, and Manali between 2015 to 2020. Fig. 5(a) illustrated temporal variations in the monthly averaged NAQI in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, Cuddalore, and Manali, while Fig. 5(b) shows annual average NAQI in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, Coimbatore, Cuddalore, and Manali. Trend analysis and net change in NAQI values over the years are also included in Fig. 5(b) and Table 2.

The NAQI values recorded between 2015-2020 in Delhi, Mumbai, Kolkata, and Chennai have shown distinct seasonal variations. The NAQI of Delhi was consistently higher than those observed in Kolkata, Mumbai, and Chennai. The monthly average NAQI of Delhi often varied between 300-400 during winter, while the NAQI of Kolkata, Mumbai, and Chennai was below 200, except for a few occasions in Kolkata in the winter of 2019 (Fig. 5b). The NAQI values at Thoothukudi, Manali, and Cuddalore always remained below 100 and were categorized as satisfactory, except in 2016 and 2017 in Thoothukudi (Fig. 5b), indicating a sign of healthy air quality in all three cities of Tamil Nadu.

As shown in Fig. 5(b) and Table 2, Delhi's annual average NAQI levels were 219, 254, 228, 225, 215, and 185 in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and demonstrated a net decrease of 34 NAQI and showed a prominent decreasing pattern by 8.3 NAQI/year ($r^2$ = 4.8) during 2015 to 2020. Similarly, in Mumbai, the annual average NAQI levels were 98, 91, 108, 108, 103, and 95 in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a slight net decrease of 3 NAQI from 2015 to 2020. However, NAQI values were fluctuating in Mumbai, thus no trend ($r^2 = 0$) was observed over the years. Whereas, in Kolkata, the annual average NAQI levels were 87, 106, 128, 137, and 111 in 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net increase of 24 NAQI from the level in 2015 to that in 2020 and revealed an increasing trend of 7.9 NAQI per year ($r^2 = 0.41$) during 2015 to 2020. On the other hand, the NAQI levels in Chennai were recorded as 112, 116, 95, 99, 88, and 69 in 2015, 2016, 2017, 2018, 2019, and 2020, respectively, and showed a net decrease of 43 NAQI from the level calculated in 2015 to that in 2020, and showed a decreasing trend of 8.4 NAQI per year ($r^2 = 0.85$) during 2015 to 2020 (Table 2). Similarly, the NAQI levels at Thoothukudi were 95, 86, and 82 in 2018, 2019, and 2020, respectively, with a net decrease of 13 NAQI from the level in 2015 to that in 2020 and revealed a decreasing trend of 6.5 NAQI per year ($r^2 = 95$) during 2018 to 2020. In Cuddalore, the NAQI levels were 55 and 57 in 2019 and 202, respectively, showing a slightly increasing trend of 2 NAQI per year ($r^2 = 1$) from 2019 to 2020. Whereas, In Manali, the NAQI levels were 57, 63, and 55 in 2018, 2019, and 2020, respectively, with a net decrease of 2 NAQI from the level in 2018 to that in 2020, but no trend ($r^2 = 0$) in NAQI was observed for Manali during 2018 to 2020.

It may be noted, although Delhi's annual average NAQI levels show a decreasing trend from 2016 onward, which is a good sign of improving air quality in Delhi, however, NAQI levels varied from 185 - 254 from 2015 to 2020, which was categorized as moderate to poor (Fig. 5b). Thus, extra efforts are needed in Delhi for further improvement in the NAQI levels by further reducing emissions of air pollutants from various sectors. Likewise, Mumbai's annual average NAQI levels varied from 91 to 108 from 2015 to 2020 and were categorized as satisfactory. In Kolkata, the NAQI levels ranged from 87-137 and were classified as moderate air quality. Similarly, in Chennai, the NAQI levels varied from 69 to 116 from 2015 to 2020 and were categorized as satisfactory. The NAQI levels in Chennai showed a decreasing trend from 2016 onward, indicating that air quality in Chennai is improving. It is to note, Mumbai, Kolkata, and Chennai are coastal cities and regularly experienced a land-see breeze circulation, and thus air of these cities is diluted by clean air from the sea (Verma et al., 2010). Such phenomena are not available in Delhi, and therefore high pollution level is normally observed in Delhi. In Delhi, apart from emissions of air pollutants, persistent stagnant meteorological conditions, particularly in winter, plays a crucial role in the elevation of air pollution levels in the city and neighboring regions (Sawlani et al., 2019). The annual average NAQI levels in Thoothukudi, Manali, and Cuddalore were always below 100 from 2015-2020, except 2016 and 2017 in Thoothukudi. The air quality of these four cities of Tamil Nadu was satisfactory and consistently improving over the years

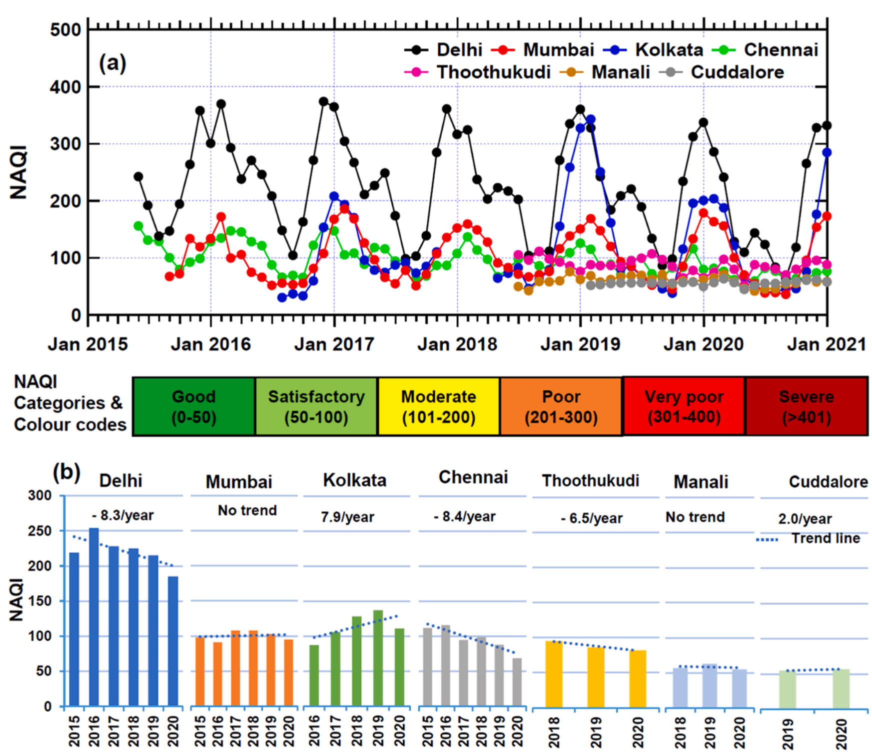


**Fig. 5.** Temporal variations in the concentration levels of NAQI in Delhi Mumbai, Chennai, Kolkata, Thoothukudi, Manali, and Cuddalore between 2015 and 2020: (a) monthly averaged NAQI (b) yearly averaged NAQI. Trend analysis for yearly NAQI is also included in the figure.

(Fig. 5b).

Furthermore, using the NAQI values, Fig. 6 showed a year-wise number of days with status of air quality (i.e., good, satisfactory, moderate, poor, very poor, and severe) in Delhi, Mumbai, Kolkata, Chennai, Thoothukudi, Manali, and Cuddalore. India started publishing real-time NAQI levels in May 2015 onward in Delhi and Chennai, in August onward 2015 in Mumbai, and in July onward 2016 in Kolkata. The number of days with a specific NAQI category level, shown in Fig. 6, revealed that the air quality in major Indian cities, namely, Delhi, Mumbai, Kolkata, and Chennai, have been improving over the years.

In Delhi, the number of days with moderate and satisfactory NAQI levels has been increasing, while the number of days with poor, very poor, and severe NAQI levels has been decreasing. In Delhi, in 2015, the number of days with moderate and satisfactory NAQI was 76 and 23, respectively; while in 2020, it increased to 127 and 95, respectively (Fig. 6). In Mumbai, the number of days with good NAQI level has been increasing while those with satisfactory, moderate, and poor are decreasing. In Mumbai, the number of days with good NAQI level was 56 in 2016, which increased to 118 in 2020 (Fig. 6). Similarly, in Kolkata, the number of days with a good NAQI was 36 in 2017, which increased to 144 in 2020. In Chennai, the number of days with satisfactory and good NAQI has been increasing, while the number of days with

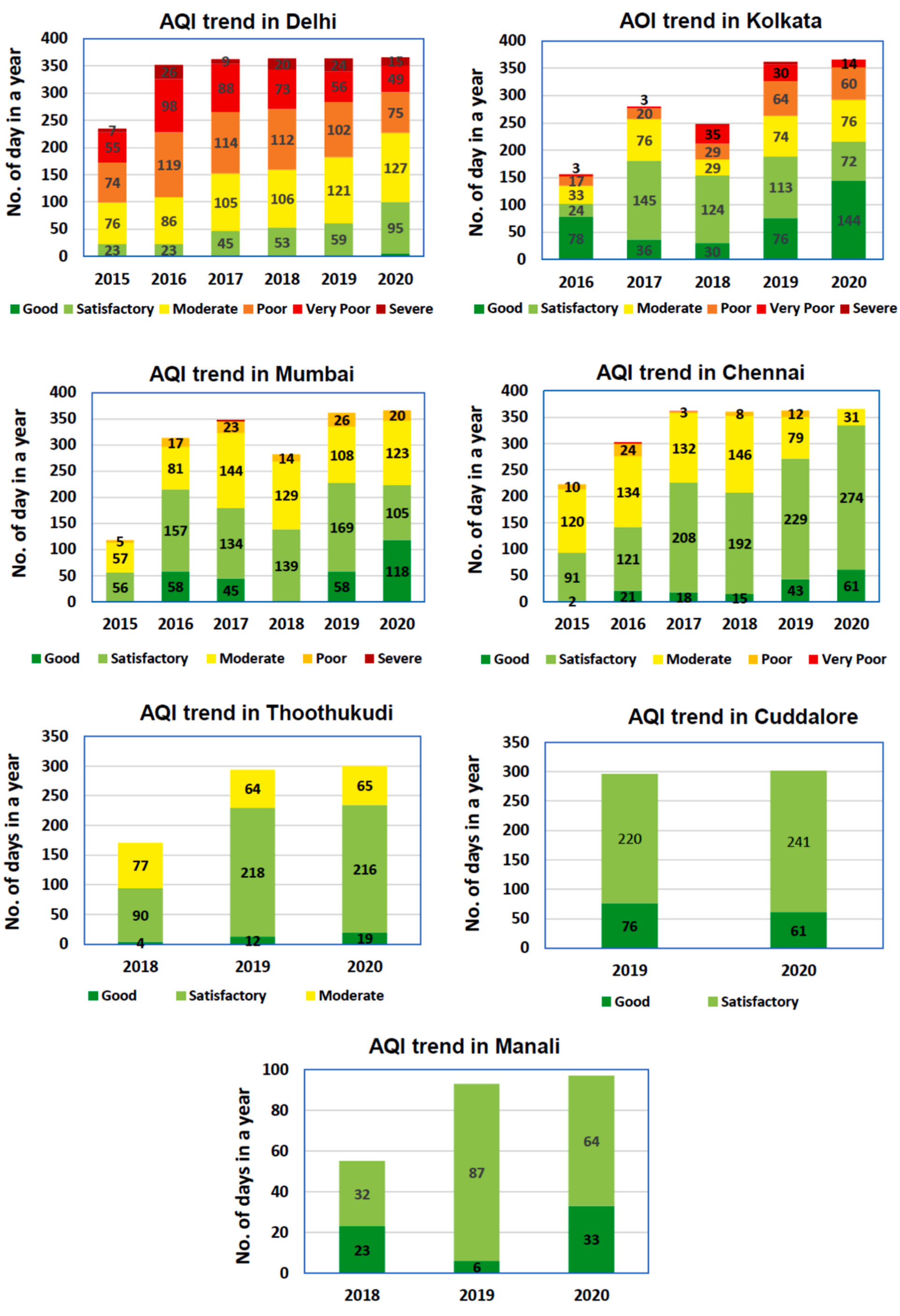


**Fig. 6.** Based on NAQI values, the year-wise number of days with the status of air quality (i.e., good, satisfactory, moderate, poor, very poor, and severe) observed in Delhi Mumbai, Chennai, and Kolkata Thoothukudi, Manali, and Cuddalore.

moderate and poor NAQI levels is decreasing. In Chennai, the number of days with satisfactory and good NAQI were 121 and 21, respectively, in 2016, which has increased to 274 and 61, respectively, in 2020 (Fig. 6).

The real-time display of NAQI in Thoothukudi and Manali was started in June 2018, while in Cuddalore in January 2019. In Thoothukudi, Manali, and Cuddalore, the NAQI values were less than 100, categorized as satisfactory and good, with a sign of steady improvement in air quality in these industrial clusters (Fig. 5b and Table 2). At Thoothukudi, in 2018, the number of days with moderate, satisfactory, and good NAQI was 77, 90, and 4 days, respectively, while in 2020, the number of days with moderate, satisfactory, and good NAQI increased to 65, 216, and 19 days, respectively. At Cuddalore, in 2019, the number of days with satisfactory and good NAQI was 220 and 76 days, respectively, while in 2020, the number of days with satisfactory and good NAQI was 241 and 61 days, respectively. At Manali, in 2018, the number of days with satisfactory and good NAQI was 23 and 32, respectively, while in 2020, the number of days with satisfactory and good NAQI was 64 and 33, respectively.

## 4. Conclusion

In this study, we reported air quality trends (between 2015 to 2020) in industrial clusters (Thoothukudi, Cuddalore, and Manail) of Tamil Nadu and compared them with those in major Indian cities (Delhi, Mumbai, Kolkata, and Chennai). Our findings suggest no significant impact of coastal meteorology on the air quality of industrial cluster cities because the seasonal variations in the concentration levels of key air quality parameters were insignificant. The seasonal impact on air quality in Delhi is slightly more pronounced than that observed in other cities. The concentration levels of key air quality parameters, including, NAQI in Thoothukudi, Manali, and Cuddalore, were lower than those of Delhi, Mumbai, Kolkata, and Chennai. Most cities investigated in this study did not comply with the prescribed NAAQS for $PM_{10}$ and $PM_{2.5}$ All the cities complied with the prescribed NAAQS for $SO_2$, as its value is much higher than the observed $SO_2$ concentrations. This study noted that most key air quality parameters, including NAQI, have shown a declining trend over the years, with increasing good, satisfactory, and moderate NAQI days in all the cities. The improvement in air quality could be attributed to the air pollution reduction measures implemented by the Government. The results of this study could be a good reference for policymakers and air quality scientists for formulating air pollution control policies specifically targeted toward industrial clusters.

## CRediT authorship contribution statement

**Ram Lal Verma:** Overall responsibility of the manuscript including data analysis and drafting; **Lakshani Gunawardhana:** Data analysis and contribution in drafting the manuscript; **Jatinder Singh Kamyotra:** Data collection and contribution in drafting the manuscript; **Balram Ambade:** Contribution in drafting the manuscript; **Sudarshan Kurwadkar:** Contribution in drafting the manuscript.

## Declaration of Competing 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.

## Data availability

No data was used for the research described in the article.

## Acknowledgment

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