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RESEARCH ARTICLE

Seasonal Trend Analysis of Major Air Pollutant ($PM_{2.5}$ and PM_{10}) Concentration in Visakhapatnam During 2020 – 2022: A Case Study

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Abstract

Objective: The main objective of the present study is to analyze the seasonal variations of major particulate air pollutants ($PM_{2.5}$ and PM_{10}) from January 2020 to December 2022 in the industrially developed Visakhapatnam City and its comparison with previous existing studies from January 2018 - December 2020. **Methods:** The real-time daily mass concentrations of air pollutants in Visakhapatnam recorded by the Central Pollution Control Board (CPCB) are collected for the present study. The monthly average observations of pollutants such as $PM_{2.5}$, $PM_{10,}$ and $PM_{2.5}/PM_{10}$ in each season are considered for the present study, and pollutants trends are studied from January 2020 - December 2022. The fine particles below 100μm (RSPM) and coarse particles > 100μm (TSPM) are treated as primary pollutants and pollutant concentration is determined based on prevailing meteorological and topographic factors. In the present study, the pollutant intensity is analyzed using the Pearson correlation coefficient for various seasons. Similarly, statistical analysis is also implemented on particulate air pollutants ($PM_{2.5}$ and PM_{10}) from January 2020 to December 2022. **Findings:** From Table 1 $PM_{2.5}$ levels fall within the range of 16 - 96 $\mu g/m^3$ and the minimum $PM_{2.5}$ level is in April 2020 and maximum in December 2020. According to AQI standards, moderate pollution indicates the fall of the PM_{10} levels within the range of 53-196 $\mu g/m^3$ during 2020-2022 minimum in April 2020 and maximum in December 2020. The present study recorded high pollutants of $PM_{2.5}$ and PM_{10} in Visakhapatnam in the winter season during 2020-2022. The obtained result reveals that high $PM_{2.5}$ and PM_{10} mass concentrations in winter exceed the NAAQS limit and better air quality is observed especially in summer and during monsoon season. The ratio between $PM_{2.5}$ and PM_{10} is minimal in May 2020 and almost similar maximum values from November - 2020 to December 2020. This indicates that PM_{10} concentration is maximum in May 2020 and minimum during November - 2020 to December 2020. The ratio between $PM_{2.5}$ and PM_{10} is maximum in November 2021 and minimum in September - 2021. This indicates that PM_{10} concentration is less in November 2021 and maximum in September – 2021. The ratio between $PM_{2.5}$ and PM_{10} is maximum in December 2022 and minimum in April - 2022. This indicates that PM_{10} concentration is less in December 2022 and maximum in April – 2022. The Pearson correlation coefficient between PMs over the period 2020-2022 is especially high in the summer season (r = 0.9711) and is negative (r= -0.7039) in the winter season which indicates that traffic-related emissions are the main sources of pollution at this site. **Novelty:** Air pollutants from January 2018 - December 2020 for nine monitoring stations in Visakhapatnam were observed by numerous authors and concluded that maximum $PM_{2.5}$ levels fall within the range of 61-90 $\mu g/m^3$. Similarly, PM_{10} falls within the range of 101-250 $\mu g/m^3$ in 2019 and 2020. The maximum PM_{10} concentration was 195$\mu g/m^3$ in December 2020 and the minimum value was 53$\mu g/m^3$ in April 2020. The decrease in PM_{10} concentration is probably due to the prevailing pandemic situation in 2020. The major harmful air pollutant is particulate matter ($PM_{10}$and $PM_{2.5}$) in Visakhapatnam city due to rapid industrialization and its variations are analyzed during January 2020 - December 22. The data analyzed from CPCB reveals that the maximum PM_{10} concentration was 166.5 $\mu g/m^3$ in January 2021 and the minimum value was 74.92 $\mu g/m^3$ in May 2021. The maximum $PM_{2.5}$ concentration is 83.38 $\mu g/m^3$ in January 2021 and the minimum value is 20.2 $\mu g/m^3$ in April 2022. The decrease in P.M concentrations is probably due to the prevailing post-pandemic situation.

Keywords: Particulate matter; Dispersion; Pollution; Anthropogenic

1 Introduction

The atmosphere of Earth is a dynamic system that takes a variety of gases, liquids, and solids from both natural and man-made sources. These materials spread through the air, interact physically and chemically with other materials, and travel together. Most of these eventually wind up in an interceptor, such as a person, object, animal, or plant, or a depository like the ocean. A wide range of pollutants are released into the atmosphere through man made and natural activities. Man has designated the portion of these compounds as pollutants that interact with the environment to create toxicity, sickness, aesthetic distress, impacts, or environmental degradation. Air pollutants can also be broadly classified into two general groups a) Primary Pollutants and b) Secondary pollutants. The Primary pollutants emit into the atmosphere directly but the secondary pollutants are produced by chemical and photochemical reactions of primary pollutants.

At the beginning of the 21st century, industrialization and modernization are at their peak around the world. As a result, catastrophic levels of air pollution are on the rise. Air pollution is a major environmental problem affecting people and biodiversity in both developed and developing countries. Particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NO and NO_2), sulfur dioxide (SO_2), Ozone (O_3), carbon monoxide (CO), volatile organic compounds (VOCs), and NH_3 are the most common air pollutants encountered in our daily lives [1]. The main anthropogenic sources of these particles are vehicle emissions, industry, fossil fuel combustion, and power plants.

Sulfur dioxide is released into the atmosphere by both natural and anthropogenic emissions. Natural sources are mainly volcanic eruptions, while anthropogenic sources include the combustion of all sulfur-containing fuels such as oil, coal, and diesel used to generate electricity for industrial activities. Air pollution adversely affects all life on earth. Poor air quality has become a global concern. According to one report, about 4.2 million people die prematurely every year due to exposure to poor air quality, which causes lung cancer, heart disease, asthma, and other chronic respiratory diseases [2]. In addition to health, air pollution also has negative impacts on the environment, climate, vegetation, and the economy.

Air pollution can be categorized based on its origin, chemical composition, size, and whether it originates from indoor or outdoor sources [3]. In terms of origin, air pollution can be classified into two main types: natural and man-made pollution, as well as stationary and mobile pollution. Natural pollutants are emitted directly from natural sources, such as forest fires, volcanic eruptions, dust storms, pollen grains, and radon gas [4]. On the other hand, man-made pollution is a result of human activities. Man-made sources of air pollution can be further divided into three categories: point source, area source, and line source. Point sources are localized and stationary, typically associated with large facilities or locations where significant amounts of air pollutants are released during manufacturing processes [5]. These point sources usually release pollutant substances into the atmosphere through chimneys at a sufficient height to allow for substantial dilution before reaching the ground surface. However, certain weather conditions, such as low temperatures, winds, and a stable atmosphere, can hinder the dispersion of pollutants, leading to poor air quality near the point source [6]. In contrast to point sources, area sources are smaller in scale but can still contribute significantly to air pollution when their cumulative effects are considered. Stationary sources of air pollution include manufacturing facilities, power plants, oil refineries, chemical plants, and other industrial utilities [7]. In contrast to point sources, area sources are smaller in scale but can still contribute significantly to air pollution when their cumulative effects are considered. Stationary sources of air pollution include manufacturing facilities, power plants, oil refineries, chemical plants, and other industrial utilities [7].

The current COVID-19 outbreak has been reported to have a positive impact on the environment. Various workers reported that the COVID-19 lockdown showed a significant decrease in the concentrations of SO_2 (6.76%), NO_2 (5.93%), $PM_{2.5}$ (13.66%), and PM_{10} (24.67%) over 44 cities in northern China [8–10]. In urban areas of Malaysia, the COVID-19 lockdown has shown reductions in NO_2 and SO_2, $PM_{2.5,}$ and PM_{10} concentrations [11].

In Barcelona, Spain, air pollution was significantly reduced by the closure of COVID-19 [12]. In India, air pollution levels have decreased significantly due to a massive reduction in vehicular traffic and industrial activity, resulting in cleaner and fresher air [13,14]. COVID-19 lockdown has been reported to improve air quality in 22 Indian cities [15]. The impact of COVID-19 lockdown measures on air pollution levels has been analyzed in six mega cities in India and China, and the analysis showed a drastic reduction in air pollution [16]. In this context, the present study was envisaged to evaluate the influence of the COVID-19 lockdown in the year 2020 on the concentrations of air pollutants such as $PM_{2.5}$ and PM_{10} at the selected locations of Visakhapatnam city, Andhra Pradesh [17]. The values of these parameters were compared with the same parameters obtained at the same locations of the city in 2018 and 2019, to document the impact of the lockdown on the evaluated parameters [17,18].

Visakhapatnam is not meeting National Ambient Air Quality Standards (NAAQS) as identified by the Central Pollution Control Board (CPCB) and it is one of the leading industrial centers in southern India. The major industries such as Coromandel fertilizers, Visakhapatnam Port Trust, Hindustan Zinc Limited, Hindustan Petroleum Corporation Limited, LG polymers, and Essar Steel are responsible for contributing to significant air pollution. Particulate matter and gaseous emissions are identified as pollutants due to industrial and domestic activities from NAAQS. Fine particulate matter is generally in the lower portion of the atmosphere in the winter season due to the condensation process. The particulate matter is one of the major pollutants in Visakhapatnam several studies [17] reported that particulate pollutants are emerging as critical air pollutants in the winter season which is unhealthier. The average PM_{10} mass concentrations at the Jogannapalem and Parawada sites in Visakhapatnam exceeded the CPCB annual limit (60 mg/m^3). Air pollutants from January 2018 - December 2020 for nine monitoring stations in Visakhapatnam observed that maximum $PM_{2.5}$ levels fall within the range of 61-90 μg/m3 [18] and PM_{10} falls within the range of 101-250 $\mu g/m^3$ in 2019 and 2020. The present paper aims to analyze the seasonal trend in particulate matter from January 2020 to December 2022.

Studies on Particulate Matter (PM) and Health have demonstrated a connection between PM and detrimental health outcomes, with an emphasis on either acute or chronic short-term PM exposure. Typically, chemical reactions between the various pollutants result in the formation of particulate matter (PM) in the atmosphere. Particle size has a direct impact on how well they penetrate [19]. The United States Environmental Protection Agency categorized particulate matter (PM) as particles [20]. PM_{10}, or particles having a diameter of 10 micrometers (μm) or less, and extremely fine particles, which typically have a diameter of 2.5 micrometers (μm) or less, are included in the category of particulate matter (PM) pollution.

Tiny liquid or solid droplets included in particulate matter can be ingested and have detrimental effects on one's health [21]. PM_{10} (particles smaller than 10 microns in diameter) can enter the circulation and infiltrate the lungs following inhalation. $PM_{2.5}$, or fine particles, are more harmful to health [22,23]. Numerous epidemiological research on PM's effects on health have been conducted. A positive correlation was seen between acute nasopharyngitis and both short- and long-term exposures to $PM_{2.5}$ [22]. Furthermore, it has been discovered that years of prolonged exposure to PMs are linked to cardiovascular illnesses and neonatal mortality.

In addition, respiratory diseases and immune system disorders have been documented as long-term chronic consequences [24]. It is important to highlight those individuals with asthma, pneumonia, and diabetes, as well as respiratory and cardiovascular conditions, are particularly susceptible and prone to the impacts of PM. $PM_{2.5}$, followed by PM_{10}, exhibits a strong association with various respiratory ailments [25], as their small size enables them to penetrate indoor spaces [26]. These particles induce toxic effects based on their chemical and physical characteristics. These particles induce toxic effects based on their chemical and physical characteristics.

The COVID-19 pandemic is typically associated with remote areas and low population densities, and some authors [27] have suggested that the spread of the virus to high latitudes or poles is an unlikely event. However, other studies [28] have raised concerns about the virus's potential to spread to Antarctic wildlife.

Researchers and environmentalists are referring to this outbreak as a "blessing in disguise" because lockdowns have significantly decreased air pollution. Globally, air pollution caused by human activity is typically one of the main factors contributing to health crises, inequality, and fatalities [29–31]. We now have the chance to breathe in low-carbon air because of the pandemic's reduction in air pollution, which was brought on by the cancellation of additional highway transportation, the suspension of public transit, and the closure of aeroplanes [32]. Lockdowns and restricted movement greatly enhance the quality of the environment around us, with the greatest benefit being a decrease in air pollution.

Particulate Matter (PM), which is particles of varying but extremely small diameters, enters the respiratory system through inhalation and can lead to cancer, reproductive, cardiovascular, and central nervous system disorders, as well as other health issues [33]. Ozone protects against UV radiation in the stratosphere, but when it is concentrated too much at ground level can be hazardous and negatively impact the cardiovascular and respiratory systems. Fine particles have been linked lung cancer death rate [34] in China.

Air pollution refers to the contamination of the surrounding atmosphere due to the presence of chemical substances, gases, or particulate matter. These pollutants have the potential to cause discomfort, diseases, and even millions of deaths annually. Additionally, they can have detrimental effects on vegetation, animals, and food crops. The emission of these pollutant materials can lead to the formation of smog and acid rain, which in turn can result in respiratory and cancer-related illnesses. Furthermore, the accumulation of these pollutants over time can contribute to the depletion of the ozone layer, exacerbating global warming. The harmful impact of pollutants is influenced by factors such as the duration and intensity of exposure, the specific type of pollutants, and the overall accumulation of pollutants over time. Commonly referred to as "criteria air pollutants" or "basic pollutants," these include nitrogen oxides, sulfur oxides, carbon monoxide, ground-level ozone, lead, volatile air compounds (VOCs), and particulate matter.

Airborne particulate matter is a prevalent type of air pollution found in the atmosphere. These particles can be categorized based on their aerodynamic diameter. Coarser particles, with a diameter of 10 μm or less, are referred to as PM_{10}, while fine particles, with a diameter of 2.5 μm or less, are known as $PM_{2.5}$. Ultra-fine particles, on the other hand, have a diameter lower than 0.1 μm [35]. Particulate matter can originate from both natural and human activities. Natural sources include volcanic eruptions, mineral dust, sea salt, and wildfires. Anthropogenic sources, such as fuel combustion, industrial emissions, biomass burning, road dust, and combustion in vehicles and heating boilers, are the main contributors to particulate matter in the atmosphere [35,36]. The World Health Organization (WHO) has highlighted the health effects of particulate matter, particularly those with aerodynamic diameters of less than 2.5 μm and 10 μm. PM_{10} particles can reach the bronchi and alveoli in the lungs, while $PM_{2.5}$ particles can penetrate the bronchial capillary wall and interfere with gas exchange in the lungs. In 2014, the WHO reported that outdoor and indoor particulate matter was responsible for over 7 million deaths. Inhalation of PM_{10} and $PM_{2.5}$ particles has been linked to acute and chronic health issues and damage to the respiratory system [37,38]. Additionally, particulate matter can affect visibility and have impacts on crops and ecosystems. PM is a major contributor to reduced visibility due to its ability to scatter and absorb light [39].

On the other hand, NO_2 exhibited a significant impact on children, particularly those under the age of 15. Moreover, an increase of approximately 10 $\mu g/m^3$ in ambient air pollution levels resulted in a rise of approximately 2.8%, 3.6%, and 7.7% in emergency room admissions for PM_{10}, SO_2, and NO_2, respectively. These results were reported by [40]. Furthermore, the association between respiratory disease mortality and lung cancer mortality with the major air pollutants (SO_2, NO_2, and PM_{10}) was examined. The study found that a 10 $\mu g/m^3$ increase in SO_2, NO_2, and PM_{10} levels led to a respective increase of approximately 7.69%, 4.38%, and 1.55% in respiratory disease mortality. Notably, only SO_2 showed a significant association with lung cancer mortality, as reported by [41].

2 Materials and methods

The real-time daily mass concentrations of air pollutants in Visakhapatnam city are recorded by the Central Pollution Control Board (CPCB). It is a single recording station that records real-time precise air pollution data of Visakhapatnam used for the present study. This real-time air pollution data (https://cpcb.nic.in) is maintained by the Greater Visakhapatnam Municipal Corporation (GVMC, Ramnagar). The monthly average observations of major pollutants such as $PM_{2.5}$, $PM_{10,}$ and the ratio of $PM_{2.5}/PM_{10}$ in each season are considered for the present study. The trends of major harmful air pollutants such as $PM_{2.5}$, $PM_{10,}$ and the ratio of $PM_{2.5}/PM_{10}$ are analyzed seasonally from January 2020 - December 2022. The present data analyzed and results were compared with previously available data. The conclusions are made based on seasonal variations of major pollutants and also prevailing pandemic situation at that time. The trends of harmful pollutants ($PM_{2.5}$, PM_{10}) are measured using the Pearson correlation coefficient. The present data is analyzed statistically from January 2020 - December 2022 and conclusions are made based on obtained results.

3 Results and Discussions

Air pollutants from January 2018 - December 2020 for nine monitoring stations in Visakhapatnam are observed that maximum $PM_{2.5}$ levels fall within the range of 61-90 μg/m3 [18]. Similarly, PM_{10} falls within the range of 101-250 $\mu g/m^3$ in 2019 and 2020 which indicates moderate pollution according to AQI [18].

Typically, chemical reactions between the various pollutants result in the formation of particulate matter (PM) in the atmosphere. Particle size has a direct impact on how well they penetrate. The US Environmental Protection Agency identified particles as part of the category known as particulate matter (PM) [20].

PM_{10}, or particles having a diameter of 10 micrometers (μm) or less, and extremely fine particles, which typically have a diameter of 2.5 micrometers (μm) or less, are included in the category of particulate matter (PM) pollution. Particulate matter is made up of microscopic solid or liquid droplets that are harmful to the lungs when inhaled. After inhalation, particles with a diameter less than 10 μm, or PM_{10}, can penetrate the lungs and potentially enter the bloodstream. $PM_{2.5}$, or fine particles, are more harmful to health.

The studies conducted rely on $PM_{2.5}$ monitors and have limitations in terms of the area they cover, either restricted to a specific study area or city due to the absence of detailed daily $PM_{2.5}$ concentration data. Consequently, these studies cannot be considered representative of the entire population. A recent epidemiological study conducted by the Department of Environmental Health at Harvard School of Public Health (Boston, MA) [42] highlighted that the spatial variation in $PM_{2.5}$ concentrations leads to an exposure error (known as Berkson error) and the complete understanding of the short- and long-term effects is still lacking. To address this, the team developed a $PM_{2.5}$ exposure model utilizing remote sensing data, enabling the assessment of both short- and long-term human exposures across different spatial resolutions for the entire population [42].

In addition, long-term chronic consequences include immune system affection and respiratory illnesses. It is important to remember that persons who have diabetes, asthma, pneumonia, or other respiratory or cardiovascular conditions are particularly vulnerable to the negative effects of PM's. Because $PM_{2.5}$ and PM_{10} are small enough to penetrate interior spaces, they are strongly linked to a variety of respiratory system disorders. The chemical and physical characteristics of the particles cause harmful effects.

It has been determined how environmental contamination contributed to the COVID-19 pandemic's spread and severity. Particulate matter (PM) in the atmosphere has the potential to transmit several viruses. Inhaled particles, particularly those smaller than 2.5 μm (PM2.5) and their associated microorganisms, can enter the deep lung and facilitate the growth of viruses that cause infections in the respiratory tract [43].

Since fine and ultrafine PM ($PM_{2.5}$ and $PM_{0.1}$) are thought to be responsible for several million fatalities annually worldwide, they are currently regarded as one of the most significant environmental risk factors [44,45]. In addition to compromising immunological functions, atmospheric pollution can cause pro-inflammatory and oxidative pathways in the lungs and other organs. These data suggest that air pollution may have a detrimental impact on COVID-19 patients' prognosis. Additionally, in Italy during the early stages of the COVID pandemic, noticeably higher death rates were noted in the northern regions, which are known to be more polluted than the other regions which suggest a possible role for pollution in the pandemic's spread [46]. India exhibits geographic heterogeneity, whereby regions with disparate climatic conditions, populations, and educational attainment levels produce varying indoor air quality. North Indian states have been shown to have higher $PM_{2.5}$ levels (557–601 $\mu g/m^3$)

in comparison to the Southern States (183–214 μg/m^3) [47,48].

The present paper aims to analyze the trend in particulate matter from January 2020 - December 2022. Table 1 shows air pollutants from January 2020 - December 2022 in Visakhapatnam and $PM_{2.5}$ levels fall within the range of 16 - 96 μg/m^3. The minimum $PM_{2.5}$ level is in April 2020 and the maximum in December 2020. Similarly, PM_{10} levels fall within the range of 53-196 μg/m^3 during 2020-2022. The minimum PM_{10} level is in April 2020 and maximum in December 2020 which indicates moderate pollution according to AQI. This study plays a vital role because the detailed trend analysis of major pollutants like $PM_{2.5}$ and PM_{10} is not made from January 2020 to December 2022.

Table 1. Monthly variations in $PM_{2.5}$ and PM_{10} (μg/m^3)

Year	Month	$PM_{2.5}$	PM_{10}	Year	$PM_{2.5}$	PM_{10}	Year	$PM_{2.5}$	PM_{10}
2020	January	59.18	120.04	**2021**	83.38	166.55	**2022**	63.73	126.99
	February	44.95	95.12		64.52	153.76		55.63	134.76
	March	29.89	78.34		47.24	136.36		53.24	140.27
	April	16.76	53.16		34.47	98.70		20.22	78.76
	May	17.92	68.89		24.46	74.92		33.35	97.64
	June	23.71	81.91		31.86	94.40		36.01	98.40
	July	25.39	75.04		25.1	77.82		29.65	91.80
	August	35.47	93.41		30.83	87.17		29.34	94.38
	September	28.96	75.77		25.22	81.06		29.83	87.23
	October	48.66	107.58		44.05	108.24		40.41	91.31
	November	59.94	121.70		49.37	85.74		69.32	151.44
	December	95.98	195.57		61.43	121.60		80.33	159.79
Mean		40.567	97.210		43.494	107.193		45.088	112.730
Standard deviation		22.855	37.179		18.623	30.800		18.911	28.0115

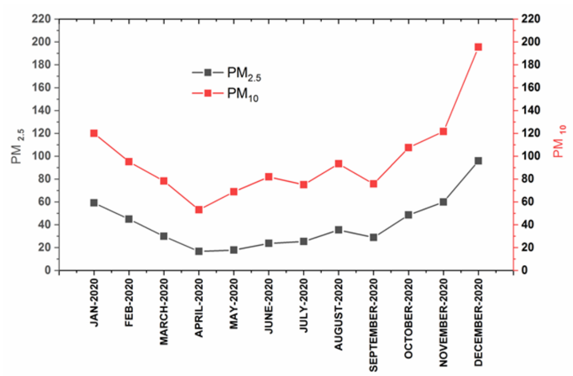
Table 2 shows monthly variations of $PM_{2.5}/PM_{10}$ from 2020-22. The most prominent pollutant at the study site is PM_{10} which is more intense in December 2020. $PM_{2.5}$ is also a more intense pollutant in December 2020. The maximum intensity of PM_{10} decreased by 26% in December 2021 and the maximum intensity of $PM_{2.5}$ decreased by 27% in December 2021. The maximum intensity of PM_{10} increases by 20% in December 2022 and the maximum intensity of $PM_{2.5}$ increases by 21% in December 2022. The ratio of $PM_{2.5}/PM_{10}$ is minimum (0.260) in May 2020 (Figure 4) and the ratio of $PM_{2.5}/PM_{10}$ is minimum (0.311) in September 2021 (Figure 5) and $PM_{2.5}/PM_{10}$ is minimum (0.257) in April 2022 (Figure 6). The gradual decrease of $PM_{2.5}/PM_{10}$ shows that PM_{10} is a significant pollutant. A low ratio of $PM_{2.5}/PM_{10}$ indicates the dominance of dust, and a high ratio denotes anthropogenic aerosols during the season. The ratio of $PM_{2.5}/PM_{10}$ less than 0.5 for the entire study period indicates the existence of higher coarse particle masses.

The average monthly variations of particulate matter (PM_{10} and $PM_{2.5}$) are shown in Figure 1**a, b,** and **c** for 2020-2022. The average PM_{10} concentration exceeded the national air quality standard from October to December 2020. The highest average value of 195.57μg/m^3 was recorded in December 2020, and the second-highest was registered in January 2021 (166.5 μg/m^3). The PM_{10} concentration was lower than national air quality standards from April - October for almost all the years, with a minimum average value of 70μg/m^3. The low values of PMs in the summer months can be attributed to dispersion conditions, and higher values in winter were due to inversion conditions and condensation of fine particulate matter in the lower atmosphere.

Seasonal variations of PMs are displayed in Figures 2 and 3. Seasonal average mass concentrations of PMs clearly show that air quality is clearest in summer. Season-wise variations exhibited a linear trend from summer to winter (2020 - 2022). In 2020, the particulate matter mass concentrations show a fluctuating trend, and changes in the meteorological conditions also affect the annual changes in pollutant levels. There is a decrease in particulate matter concentrations in the 2020 summer season when compared to the 2020 winter season due to the stringent lockdown imposed in March 2020 because of the COVID-19 pandemic. The ratio of $PM_{2.5}/PM_{10}$ decreases from January to May 2020 and increases afterward as shown in Figure 4. The ratio of $PM_{2.5}/PM_{10}$ decreases from January to March 2021 becomes uniform up to September 2021 and increases afterward as shown in Figure 5. The ratio of $PM_{2.5}/PM_{10}$ decreases up to April 2022 and has an irregular trend up to December 2022 as shown in Figure 6. The ratio of $PM_{2.5}/PM_{10}$ is maximum in the post-monsoon period in November 2021 and minimum in the summer period (April 2022) as shown in Figure 7.

Table 2. Monthly variations in $PM_{2.5}/PM_{10}$

Year	Month	$PM_{2.5}/PM_{10}$	Year	$PM_{2.5}/PM_{10}$	Year	$PM_{2.5}/PM_{10}$
	January	0.493		0.501		0.502
	February	0.473		0.420		0.413
	March	0.382		0.346		0.380
	April	0.315		0.349		0.257
	May	0.260		0.327		0.342
2020	June	0.289	**2021**	0.338	**2022**	0.366
	July	0.338		0.323		0.323
	August	0.380		0.354		0.311
	September	0.382		0.311		0.342
	October	0.452		0.407		0.443
	November	0.493		0.576		0.458
	December	0.491		0.505		0.503
Mean		0.3956		0.3964		0.3866
Standard deviation		0.0838		0.0869		0.0779



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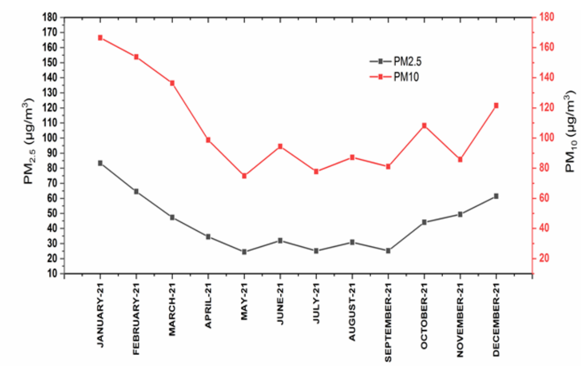

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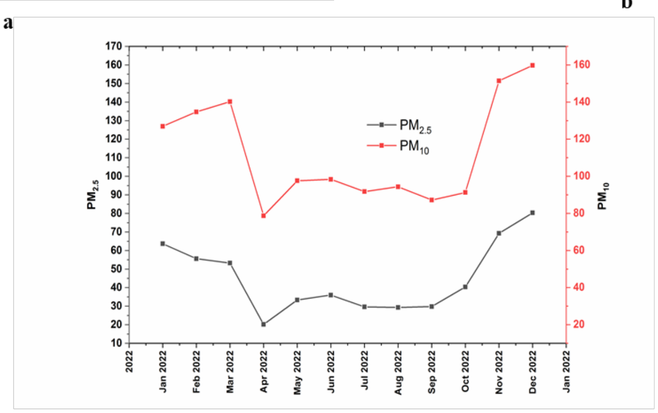

c

Fig 1. a. Average daily variation of PM concentrations for various months in 2020, b. Average daily variation of PM concentrations for various months in 2021, c. Average daily variation of PM concentrations for various months in 2022

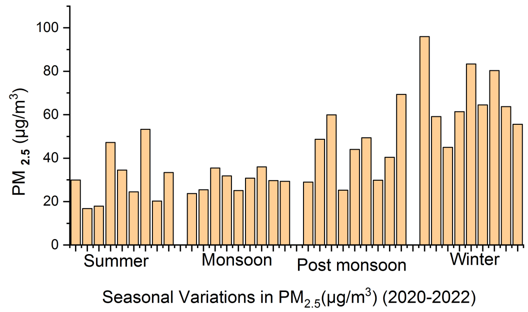

Fig 2. Seasonal variations in $PM_{2.5}$ (μg/m^3) during 2020-22

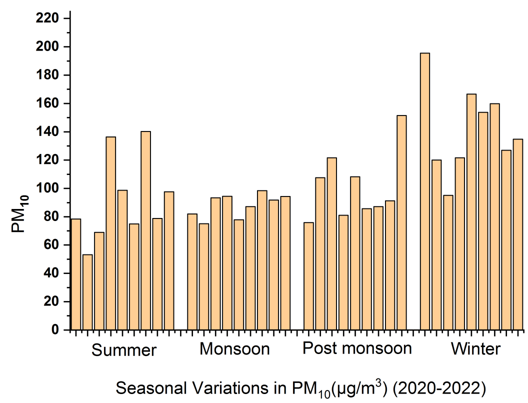

Fig 3. Seasonal variations in PM_{10} (μg/m^3) during 2020-22

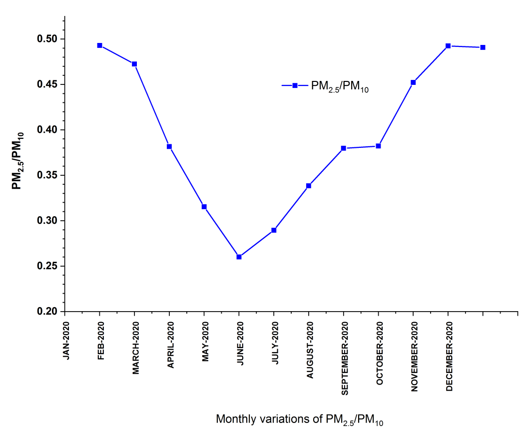

Fig 4. Monthly variations of $PM_{2.5}/PM_{10}$ in 2020

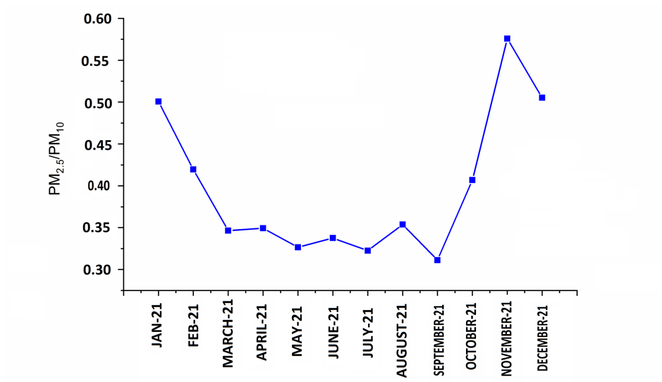

Fig 5. Monthly variations of $PM_{2.5}/PM_{10}$ in 2021

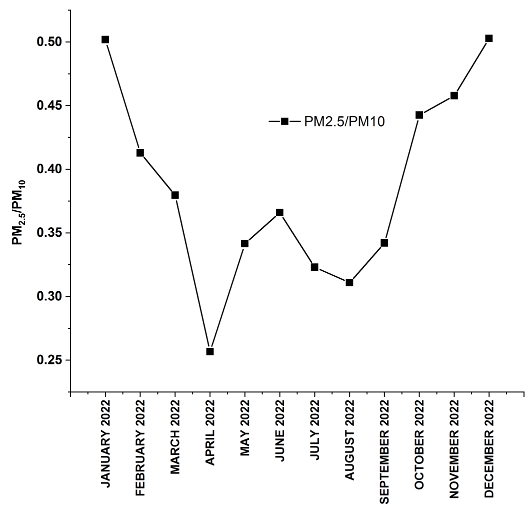

Fig 6. Monthly variations of $PM_{2.5}/PM_{10}$ in 2022

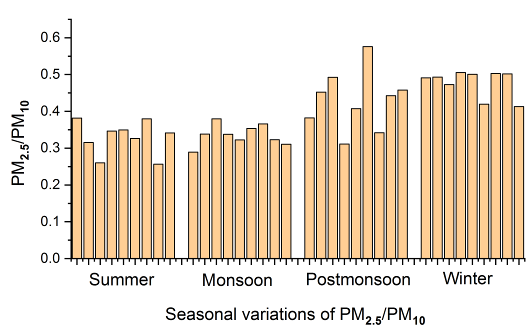

Fig 7. Seasonal variations of $PM_{2.5}/PM_{10}$ from 2020-2022

The meteorological parameters (relative humidity, wind speed, temperature, and precipitation) influence the air pollutants (particulate matter and gaseous pollutants). The distribution and spread of air pollutants were significantly influenced by meteorological parameters in Visakhapatnam city. The Pearson correlation coefficient results suggest that meteorological parameters influence the concentration of air pollutants. The temperature had the strongest negative effect on pollutant concentrations, and all other meteorological parameters investigated had both negative (decreased) and positive (increased) effects on air pollutant concentrations.

4 Conclusions

The low values of PMs in the summer months can be attributed to dispersion conditions, and higher values in winter were due to inversion conditions and condensation of fine particulate matter in the lower atmosphere. The Pearson correlation coefficient during January 2020-December 2022 is especially high in the summer season and negative in the winter season which indicates traffic-related emissions. It can be concluded that Visakhapatnam recorded high pollutants of $PM_{2.5}$ and PM_{10} in the winter season from Jan 2020 to Dec 2022 due to traffic-related emissions when compared to January 2018- December 2019. Due to the increased moisture storage capacity during non-monsoon summers, particles become larger and are deposited on the ground through dry deposition processes. In winter, water storage capacity decreases, leaving water vapor suspended along with air pollutants, further deteriorating air quality. High wind speeds promote dispersion and dilution, but high wind speeds can add dust particles and increase pollutant levels. The variation of $PM_{2.5}/PM_{10}$ showed that the cumulative effect of relative humidity was stronger in $PM_{2.5}$ than in PM_{10} (winter season).

The highest standard deviation of 37. 17 occurred in 2020 which indicates that the data points deviate from the average with low contamination. Conversely, a lower standard deviation indicates a lower variance and more tightly clustered datasets occurred in 2021 and 2022 which indicates high contamination. Numerous authors have already examined the diurnal variations in harmful PM concentrations ($PM_{2.5}$, PM_{10}) and other gaseous pollutants in Visakhapatnam City between 2018 and 2020 and concluded the study that residents of Visakhapatnam City are at high health risk due to fine particulate matter.

According to the previous study, air pollution levels for NO_2, SO_2, and NH_3 fall between 0 and $40\mu g/m^3$. While NH_3 levels fall between 0 and $200\mu g/m^3$, the minimum $PM_{2.5}$ levels in 2019 and 2020 fall between 0 and $30\mu g/m^3$, and the minimum PM_{10} levels fall between 0 and 50 $\mu g/m^3$, indicating a good air pollution status according to the AQI. However, in 2019 and 2020, the highest $PM_{2.5}$ levels were found to be between 61 and $90\mu g/m^3$ and 101 and 250 $\mu g/m^3$, respectively, indicating that the AQI classifies air pollution as moderately polluted. They identified that the concentration levels of NH_3, $PM_{2.5}$, and PM_{10} did not significantly decrease throughout the lockdown period, which may due to the sources of these parameters were not impacted by the COVID-19 lockdown. Prior research indicates that all monitoring sites of Visakhapatnam had acceptable levels of air quality; however, from January 2018 to December 2020, the only metric that showed a decrease across all monitoring stations was NH_3.

However, the current study analyzed the data for seasonal variations of dangerous pollutants like $PM_{2.5}$ and PM_{10} for the years 2020–2022. This study had a favourable impact on improving air quality, particularly during the COVID season which met AQI norms. The present study may be improved effectively if blood samples of living people in the polluted areas corresponding to industrial and seashore areas of Visakhapatnam were collected seasonally and analysis is carried out corresponding to sensitive biodiversity variations. Air pollution may cross AQI standards due to man made activities arising due to the failure of solid waste management policies in moderate economic countries like India. This present study may help policymakers and environmentalists to reduce air pollution in the future by strategically enacting lockdowns at pollution hotspots that cause the least amount of economic damage. The pollution prevention methods and current challenges in reducing air pollution also need to be elaborated. This study may not provide a proper reason if air pollution occurs from nonpoint sources. This study may be improved drastically if various pollution due to point and nonpoint sources were measured using remote sensing techniques.

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