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Estimation of Particulate Matter (PM₁₀) Over Middle Indo-Gangetic Plain (Patna) of India: Seasonal Variation and Source Apportionment

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Abstract: Despite extensive research on particulate matter (PM) pollution in India's Indo-Gangetic Plain (IGP), source apportionment remains challenging. This study investigates the effect of particulate matter (PM₁₀)-associated water soluble inorganic ions (WSIIs) on ambient air concentration across the middle IGP from January to December 2018. Moreover, the seasonal fluctuation and chemical characterization of PM₁₀ were assessed for the year 2018. The results revealed a high concentration of PM₁₀ (156 µg/m³), exceeding the WHO and National Ambient Air Quality Standard (NAAQS) limits. The highest PM₁₀ levels were observed during autumn, winter, summer, and the rainy season. The study identified SO₄^{2−} and NH₄⁺ as the most common WSIIs, constituting 46% and 23% of the total WSIIs. Source apportionment analysis indicated that street dust, biomass burning, and vehicle and industrial emissions together with secondary formation significantly contributed to IGP's PM pollution. Additionally, the investigation of air mass back trajectory suggests that air quality in IGP is largely influenced by eastern and western Maritime air masses originated from the Arabian Sea, the Bay of Bengal, Gujarat, Afghanistan, Pakistan, and Bangladesh.

Keywords: ambient air quality; quartz fiber filter; particulate matter; water-soluble inorganic ions; cations; anions



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1. Introduction

Global air pollution has become an urgent problem specifically for the large cities. It endangers human health, welfare, and the global climate system. Air pollution is known to have a variety of detrimental effects, ranging from upsetting the hydrological cycle to raising global temperatures [1–3]. Furthermore, air pollution poses serious health risks and causes of mortality as well as specific diseases [4]. It ranks fourth among risk factors for mortality and was the cause of 12% of deaths worldwide in 2019 [5]. Approximately 80% of the world's population lives in developing nations with middle- to low-income economies, where air pollution is the primary cause of 90% of illnesses and fatalities. India's rapid economic growth, high industrial rates, urbanization, population expansion, and increased automobile emissions have all significantly declined the country's air quality. This harms both the environment and human health. According to WHO [6], particulate matter (particles having an aerodynamic diameter of 10 µm or less) is considered as one of the primary indicators of air quality.

According to WHO [7], exposure to air pollution is thought to be the third leading cause of death worldwide, accounting for over 7 million premature deaths. Addressing air pollution, which is the second most significant risk factor for noncommunicable diseases, is a key to protecting public health [8]. In 2017, it was estimated that exposure to air pollution caused 1.24 million fatalities in India, with ambient particulate matter exposure accounting for 54% of these deaths [9]. An evaluation of air quality is necessary to comprehend the

effects of particulate matter (PM) on the environment and human health [10–12]. Because of its potential to harm human health, PM₁₀ has drawn much attention. It has been shown that the presence of water-soluble ions in the particles is responsible for a considerable amount of PM₁₀'s harmful health impacts [13,14]. PM₁₀, a combination of solid and liquid particles suspended in the atmosphere, is produced by both natural and manmade sources. These particles can come from a variety of sources, including natural dust, building sites, automobile emissions, and industrial activities. Major constituents of PM are WSIs, of which ammonium, nitrate, and sulfate are the predominant ions [15–17]. These ions are essential to atmospheric chemistry. Ionic species are important markers for determining the source characteristics of air quality.

The Indo-Gangetic Plain (IGP) of India, which hosts 9% of the world's population, is identified as one of the most heavily polluted regions worldwide. The IGP in South Asia is characterized by a huge and diversified aerosol load due to many emission sources, its distinct terrain and position, regional meteorology, socioeconomic development, and human behavior [18–22]. The increased aerosol loading over the area, which is attributed to various anthropogenic activities, shows substantial spatiotemporal variability and considerable seasonal heterogeneity in its characteristics [23–28]. The potential health risks of particulate matter for humans and the quality of the air have led to extensive study on the subject in recent years on all continents, including the IGP region [29–34]. Previous studies showed that the formation of secondary inorganic particles and other anthropogenic sources over the IGP, India, is caused by soil dust, agricultural activities, burning of biomass, vehicle emissions, and industries [31–33,35]. Few concurrent long-term measurements of PM's chemical characteristics have been conducted over a wide range of the IGP. Most of the published research on the chemical characteristics of aerosol over the IGP region is based on single-location observations and experiments. Variations in inorganic secondary particles are more relevant from the standpoint of human health and warrant more investigation [30,36,37]. The goal of the current research is to understand the molecular characteristics and sources of PM₁₀ over the middle Indo-Gangetic Plain (Patna). To further understand the pattern of PM-related air pollution in a highly populated area, seasonal variation in PM₁₀ was evaluated. This research may be useful in examining the long-term trends of PM₁₀ in the middle Indo-Gangetic Plain (Patna) and the resultant health impacts. The findings from this study will advance our understanding of the composition, sources, and potential health impacts of PM₁₀ in this specific urban environment. Furthermore, they will provide valuable insights to policymakers and public health experts for devising effective strategies to reduce PM₁₀ exposure and associated health risks in residential areas.

2. Materials and Methods

2.1. Study Area

More details about the study site and sampling of PM have been discussed elsewhere [38,39]. Patna, the capital city of the Indian state of Bihar, situated on the southern bank of the river Ganges, is one of the most polluted cities in India nowadays after Delhi and Kolkata (Figure 1) [38,40]. It lies on an average elevation of 53 m (174 ft) above MSL. It is a good representation of the metropolitan environment but it lacks distinct source points, such as a bustling junction, bus stop, or train station. The climate can be characterized by a sweltering and dry summer and freezing winter; the temperature during summer can reach 43 °C, and in winter can drop below 8 °C. The city's population is currently about 2 million; it is severely congested and overcrowded. There is a noticeable rise in PM₁₀ due to distressing rates of population and vehicle expansion as well as frequent traffic jams. Although vehicles and industries (such as brick kilns) are the two most significant contributors to Patna's ambient PM levels, contributions from other pollution sources, such as roadside dust, transboundary migrations, solid waste disposal, and local sources, are also common sources.

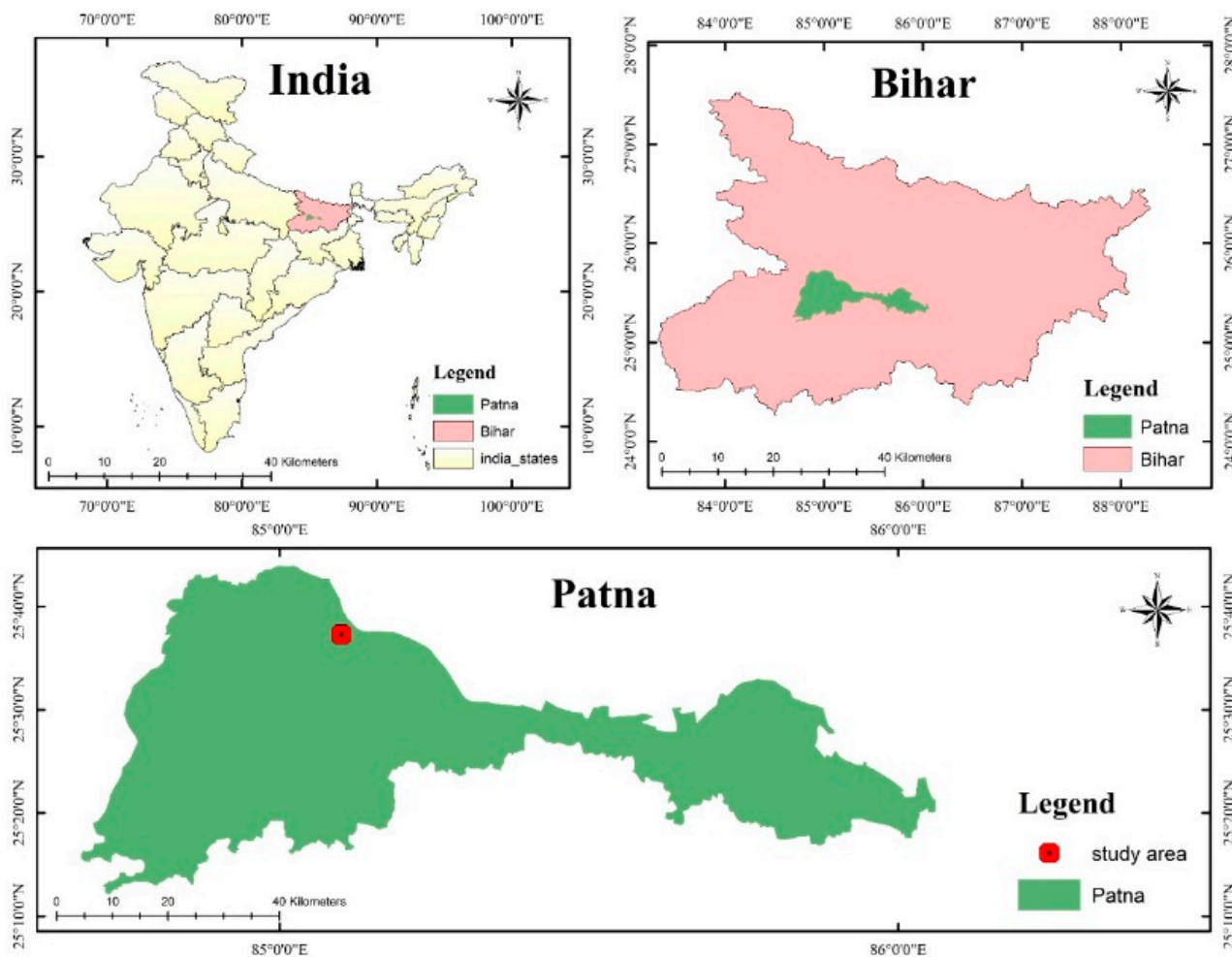


Figure 1. Map of India showing Patna and sampling site adapted from Devi et al. [40].

2.2. Sampling Strategy

The fate of PM in the air is highly variable and depends on several factors. Few sources of PM₁₀ are season- or time-specific, while others are space-specific. To capture the fate of PM₁₀ in the Patna region, we decided to conduct PM sampling for the period of one year. PM₁₀ samples (N = 120) were collected on a quartz fiber filter (QFF) (0.45 mm pore size and 47 mm diameter, make: Whatman, India) during January–December 2018 from Patna city, representing four seasons, i.e., winter (December–February), summer (March through May), rainy (June to September), and autumn (October through November). PM₁₀ samples were collected using a high-volume sampler (APM 550 M, Envirotech Pvt. Ltd., New Delhi, India) operated at a flow rate of 1.0 m³ h^{−1}. The QFF was prebaked in an oven at 350–400 °C for 6 h before sampling to avoid contamination. In order to remove the moisture, all QFFs were desiccated for 24 h before sampling. The mass concentrations of PM₁₀ were measured gravimetrically by weighing the QFF before (blank filter) and after (total filter) sampling using an analytical balance (Make-Sartorius AG, BS224 S, Goettingen, Germany) with a reading precision of 0.1 mg. Under standard circumstances (25 °C and 1 atm), each sample's air volume was calculated using the temperature and pressure measured during sampling. Then, the air samples were placed into plastic covers with aluminum foil and kept in a refrigerator at 4 °C until chemical analysis.

2.3. Chemical Characterization

Detailed procedures for the chemical characterization of PM₁₀ have been documented previously [39]. Briefly, a portion (2.8 cm²) of QFFs was cut and extracted with 50 mL of Milli-Q water (specific resistivity 18.2 MΩ) in an ultrasonication bath for 30 min. The

extract was filtered through a 0.2 μm pore size cellulose acetate filter (Make-Whatman, India). Later, ion chromatography analyzed the filtrate for WSIs (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , NH_4^+ , Cl^- , SO_4^{2-} , and NO_3^-) (Metrohm, 881 Compact IC). For anions (Column-Metrosep A sup 5–250 mm), 0.34 gm sodium carbonate and 0.084 gm of sodium bicarbonate were dissolved in 1 L Milli-Q water and the extract was filtered with the help of 0.42 μm filter paper and then transferred to the respective mobile phase bottle.

Similarly, for cations (Column-Metrosep C4-150 mm), 5.8 mL concentrated nitric acid (HNO_3) were dissolved in 100 mL Milli-Q water (1 Molar), and 0.117 gm pyridine dicarboxylic acid were dissolved in 100 mL of slightly hot water and mixed with 1.7 mL of 1M nitric acid, then made up to 1 L. The mobile phase extract was filtered with the help of 0.42 μm filter paper and transferred to the respective mobile phase bottle. Seven blank filters were also analyzed, and the ion concentrations were corrected for the respective blank concentrations. Therefore, the sample quantities that exceeded the detection limits were quantified, while the blank quantities were corrected by subtracting the mean blank amounts from the sample amounts.

2.4. Quality Assurance and Quality Control (QA/QC)

In order to minimize background contamination, five blanks samples were tested together with original samples. The blank samples were exposed and open at the sampling site in the same manner as the original QFF samples. The concentrations of WSIs in QFF sample were estimated by subtracting the blank values. The method detection limit (MDL) was estimated as means plus 3 times signal-to-noise ratio (S/N) obtained from the lowest spiked calibration standard. The measurements in this investigation were adjusted for background contamination.

2.5. Statistical Analysis

The statistical analysis of measured data was performed using SPSS software (version 21). Statistical summaries (mean, median, and range) of mass concentration and chemical species of PM_{10} were made using a Microsoft Excel sheet. The Spearman's rank correlation coefficient among chemical species of PM_{10} was performed to assess their relationship based on their rank.

2.6. Source Apportionment Study

Principal component analysis (PCA) and the molecular diagnostic ratio (MDR) are two significant methods frequently used for source assessment studies. MDRs, or the ratios of specific pairs of particular compounds, are frequently employed as organic tracers and WSII source category markers. However, the wide variety of combustion conditions and environmental degradation processes that are known to create substantial variability in the emission and degradation of certain compounds may pose a threat to the use of MDRs as reliable source apportionment methodologies. An additional method for source allocation research is principal component analysis (PCA). PCA is a widely used factor analysis technique for the purpose of source identification and apportionment of PM_{10} . PCA is a dimensionality reduction qualitative technique that is often used to reduce the dimensionality of large datasets, by transforming a large set of variables into a smaller one that still contains most of the information in the large set [41,42].

2.7. Air Mass Back Trajectory

The air mass trajectory-based approach is valuable for locating possible PM sources and obtaining crucial information about their origin. This technique tracks the flow of air masses using both forward and backward trajectories [43]. Examining these trajectories might identify the geographic origins of air masses and provide essential details about the sources of PM pollution. This work investigated long-range atmospheric and regional transport to the study area by generating air mass back trajectories using the HYSPLIT model and global data assimilation system (GDAS) global meteorological data. Five-day

isentropic air mass back trajectories were computed 500 m above sea level (AGL) to examine the influence of air masses originating from nearby or remote areas on PM concentration.

3. Results and Discussion

3.1. Concentration and Seasonal Variation of PM₁₀

In this study, the annual mass concentrations of PM₁₀ ranged from 90.4 to 238 µg/m³ (median 156 µg/m³). The average annual concentration of PM₁₀ measured in this study exceeded the annual recommended limit of the National Ambient Air Quality Standard (NAAQS) of India (60 µg/m³) and WHO (15 µg/m³). The mass concentration of PM₁₀ in this study was compared with previous studies reported globally (Figure 2 and Table 1). The average PM₁₀ mass in this study is consistent with those reported in Varanasi (168 ± 73 µg/m³) [44] and Kanpur (166.25 ± 58.00 µg/m³) [45,46]. The PM₁₀ concentration in Patna during sampling time showed a lower concentration than in Pakistan (Karachi), with mean concentrations of 437 µg/m³ [47] and Lahore (406 µg/m³) [47]. However, PM₁₀ concentration in this study was higher than in some of the Indian cities like Ahmedabad (171 µg/m³) and Mumbai (128 µg/m³) [48,49]. A box and whisker plot showing monthly and seasonal concentration of PM₁₀ in Patna during 2018 is shown in Figure 2. Winter season showed the highest PM₁₀ concentration followed by autumn, summer, and rainy season, and ranged from 113 to 238 µg/m³ (median 185 µg/m³), 130 to 193 µg/m³ (median 175 µg/m³), 127 to 213 µg/m³ (median 157 µg/m³), and 90 to 172 µg/m³ (median 121 µg/m³), respectively. The highest level of PM₁₀ measured in this study is consistent with those detected in most of the Indian cities (Table 1) [31,50]. The PM₁₀ concentration in this study is consistent with that reported in Islamabad, Pakistan (177 µg/m³) [51]. PM₁₀ concentration shows seasonal solid and monthly variation in Patna (Figure 2). The highest PM₁₀ concentration was observed (208 µg/m³) in December, and the lowest concentration (106 µg/m³) was observed in August. PM₁₀ concentrations were low from June through September because of high temperatures, high wind speed, long periods of solar radiation, and mixing height, which favors air pollution dispersion. Furthermore, the scavenging of aerosol particles by rainfall under the influence of monsoon can lower the PM₁₀ concentrations.

Table 1. Comparison of PM₁₀ concentration (µg/m³) in this study with previous studies reported worldwide.

Sampling Location	Sampling Periods	Winter	Summer	Rainy	Autumn	References
Patna	January 2018–December 2018	185	157	121	175	This study
Ahmedabad	December 2006–January 2007	171	-	-	-	[48]
Brahmaputra Valley	December 2010–October 2014	96.1	52.6	22.1	45.3	[52]
Chennai	October 2011–May 2012	170	150	158	-	[53]
Delhi	January 2010–December 2011	241	193	140	-	[54]
Hissar	December 2004	169	-	-	-	[31]
Prayagraj	October 2008	254	-	-	-	[55]
Kanpur	October 2008	-	-	-	243	[55]
Manali, India	November 2014–May 2016	131	107	103	115	[56]
Patna	January–December 2015	109	98.3	63	64.1	[57]
Varanasi	April–July 2011	-	210	131	-	[44]
Delhi	December 2008–November 2009	182	211	140	-	[58]
Islamabad	January–February 2016	177	-	-	-	[51]
Hong Kong	November 2000–February 2001	78.9	-	-	-	[59]
Guangzhou	August–September 2004	-	-	138	-	[60]

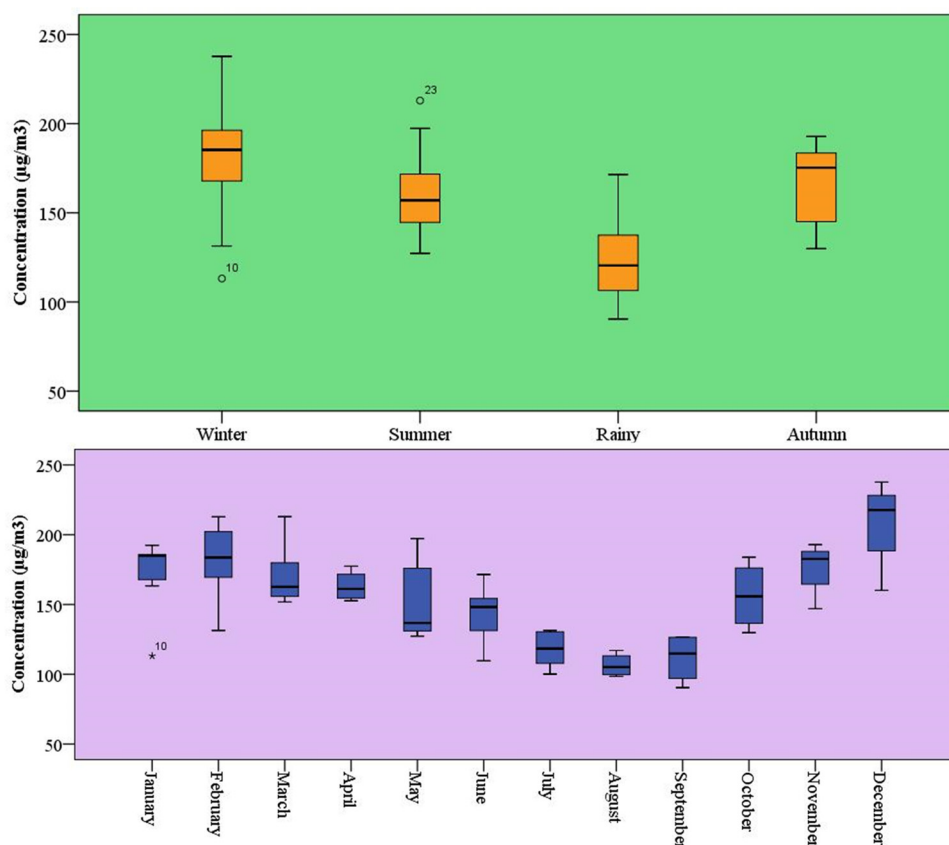


Figure 2. Box and whisker plot showing seasonal (**top**) and monthly (**bottom**) variation of PM₁₀ in Patna during 2018. The central box represents the concentration from 25th to 75th percentile. The middle bold line represents the median value. The asterisk/stars are extreme outliers that are >3-times beyond the interquartile range.

3.2. Concentration and Seasonal Variation of WSIs

Water-soluble inorganic species (mass concentrations of cations and anions) comprise a large part of aerosol particles and play an important role in the atmosphere. In this study, the WSIs ranged from 6.17 to 216 µg/m³ (median 26.6 µg/m³). The sum total of WSIs in PM₁₀ (26.6 µg/m³) measured in this study is consistent with WSIs reported in some of the Indian cities (Table 2) [31,52,56,61]. The monthly and seasonal variation of WSIs measured in PM₁₀ in this study is shown in Figure 3. Winter season had relatively higher levels of WSIs in PM₁₀, followed by autumn, summer, and rainy seasons. The chemical profile of the WSIs in PM₁₀ is shown in Figure 4. Among the WSIs, SO₄^{2−} was the most abundant chemical among WSIs and accounted for 46% of total WSIs and 9.20% of PM₁₀ mass. Next to SO₄^{2−}, NH₄⁺ was the second highest chemical among WSIs, followed by NO₃[−] and Na⁺, and these accounted for 23%, 13%, and 5% of total WSIs, respectively.

Table 2. Comparison of WSIs (µg/m³) in PM₁₀ measured in this study with previous studies reported worldwide.

Locations	Sampling Year	Season	K ⁺	Na ⁺	Ca ⁺²	Mg ⁺²	SO ₄ ^{−2}	NO ₃ [−]	NH ₄ ⁺	Cl [−]	References
Patna	January–December 2018	Winter	1.31	2.13	1.95	0.36	20.58	18.51	10.39	1.01	This study
		Summer	1.07	1.60	1.14	0.19	6.55	3.20	4.30	0.52	
		Rainy	0.97	1.21	0.84	0.53	10.55	1.38	4.65	0.29	
		Autumn	0.91	0.82	2.25	0.24	17.39	7.02	9.21	0.30	
Kanpur	April–July 2011	Summer	-	-	-	-	6.54	4.97	4.11	2.68	[61]

Table 2. Cont.

Locations	Sampling Year	Season	K ⁺	Na ⁺	Ca ⁺²	Mg ⁺²	SO ₄ ⁻²	NO ₃ ⁻	NH ₄ ⁺	Cl ⁻	References
Brahmaputra Valley	December–October 2014	Winter	2.1	2.14	0.66	0.09	5.02	2.14	2.20	1.10	[52]
		Summer	1.27	1.97	0.86	0.13	3.05	1.10	1.02	1.21	
		Rainy	0.66	1.47	0.38	0.05	1.15	0.49	0.43	0.84	
		Autumn	0.96	1.59	0.57	0.08	1.68	0.65	0.61	1.12	
Ahemadabad	December–January 2007	Winter	1.4	0.94	6.1	0.3	13.8	7.2	3.7	0.5	[48]
Hisar	December 2004	Winter	2.6	0.73	3.5	0.36	12.33	14.56	6.6	0.4	[31]
		Winter	2.4	0.66	5.7	0.6	17.66	9.26	6.23	0.16	
Manali	November 2014–May 2016	Winter	2.70	5.66	3.29	1.79	6.07	5.09	4.5	4.41	[56]
		Summer	2.51	3.56	3.07	1.26	5.94	3.24	3.51	3.44	
		Rainy	2.39	2.83	2.23	1.02	4.34	4.16	3.71	3.32	
		Autumn	2.93	4.38	2.32	1.27	5.56	5.27	4.24	3.53	
Delhi	January 2010–December 2011	Winter	1.7	2.3	4.8	0.7	11.6	14.1	9.6	5.0	[54]
		Summer	1.5	3.3	4.7	0.6	9.2	5.1	2.6	3.5	
		Autumn	1.7	4.2	5.2	0.6	8.8	4.9	2.5	2.5	
Chennai, India	October–November 2011 April–May 2012	Winter	1.70	3.85	3.90	0.19	10.57	5.92	6.54	3.59	[53]
		Summer	2.07	5.98	4.99	0.25	12.13	4.23	2.78	3.65	
		Rainy	0.87	3.22	3.35	0.33	9.96	5.90	7.53	3.18	
Varanasi, India	April–July 2011	Summer	2.35	2.2	3.6	0.55	5.3	4.5	1.21	1.8	[26]
		Rainy	1.15	2.7	2.8	0.45	4.3	2.6	0.7	2.4	

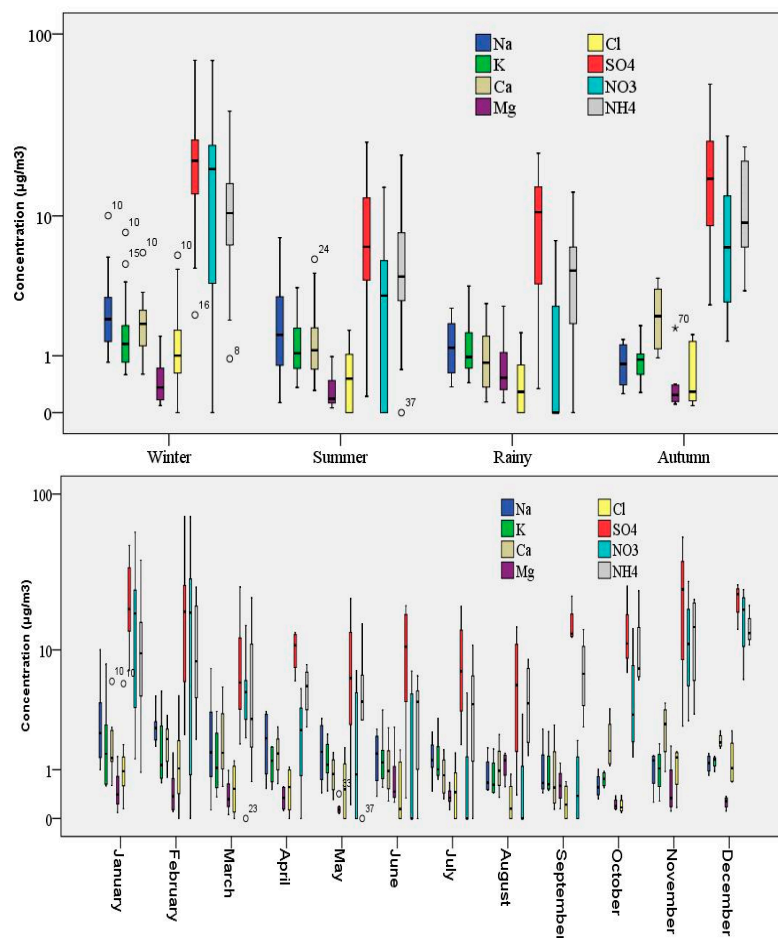


Figure 3. Box and whisker plot showing monthly and seasonal variation of WSIs in PM₁₀ from Patna. The central box represents the concentration from 25th to 75th percentile. The middle bold line represents the median value. The asterisk/stars are extreme outliers that are >3-times beyond the interquartile range. The concentration on the Y-axis is in logarithmic scale.

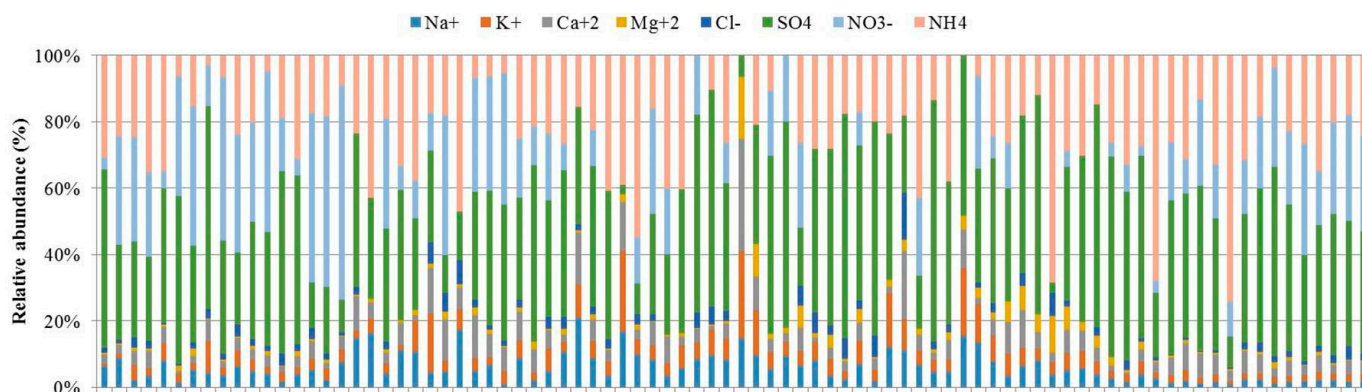


Figure 4. Relative abundance of WSIs in PM₁₀ samples from Patna.

3.3. Relationship between PM and WSIs

The interrelationship among WSIs constituents of PM₁₀ was tested using the SPSS software version 21 and is illustrated in Table 3. The strongly correlated WSIs suggest identical sources of emission, while poorly correlated WSIs specify different sources. The results showed that most WSIs were positively linked to each other. K⁺ and SO₄^{2−} were positively linked to each other ($r = 0.378$, $p < 0.05$) in PM₁₀, indicating a similar anthropogenic source, possibly from biomass burning; however, Mg²⁺ and SO₄^{2−} show a poor correlation between them. Similarly, NH₄⁺ and K⁺ showed a significant correlation ($r = 0.416$, $p < 0.05$), indicating emission from wood-burning activities [62,63] because K⁺ is mainly emitted from wood burning due to cooking or heating purposes. Ca²⁺ and Mg²⁺ were positively correlated ($r = 0.213$, $p < 0.05$), suggesting their emission from natural soil dust, especially in PM₁₀ (Table 3). A moderate correlation between NO₃[−] and SO₄^{2−} ($r = 0.494$, $p < 0.05$) indicated their similar sources from coal combustion. The ratios of NO₃[−]/SO₄^{2−} are commonly used to indicate the sources of these two ionic species. NO₃[−]/SO₄^{2−} ratios > 1 indicate the more significant contribution of NO₃[−] through mobile or vehicular emission, while a NO₃[−]/SO₄^{2−} ratio < 1 suggests ample contribution of SO₄^{2−} from industrial activity [64]. In this study, the NO₃[−]/SO₄^{2−} ratios ranged from 0 to 7.5 (1.2 ± 1.8) in the rainy season, indicating a mixture of mobile source and industrial emission. On the other hand, PM₁₀ shows a ratio range from 0 to 3.6. The NO₃[−]/SO₄^{2−} ratios in summer ranged from 0 to 70.5 (4.3 ± 15.6), autumn from 0 to 4.2 (0.7 ± 1.4), and winter from 0.3 to 1.33 (0.82 ± 0.42) in PM₁₀, respectively.

Table 3. Spearman's rank correlation coefficient analysis of WSIs in PM₁₀.

	PM ₁₀	Na	K	Ca	Mg	Cl	SO ₄	NO ₃
Na	0.11							
K	0.05	0.538 **						
Ca	0.31 **	0.486 **	0.412 **					
Mg	−0.14	0.12	0.332 **	0.21				
Cl	0.22	0.422 **	0.599 **	0.414 **	0.03			
SO ₄	0.35 **	0.335 **	0.378 **	0.378 **	0.19	0.597 **		
NO ₃	0.299 **	0.382 **	0.584 **	0.417 **	0.279 *	0.599 **	0.494 **	
NH ₄	0.10	0.523 **	0.416 **	0.428 **	0.06	0.536 **	0.467 **	0.458 **

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

3.4. Source Apportionment Study

The source apportionment of PM₁₀ in Patna was performed using multiple approaches, such as molecular diagnostic ratio (MDR) and principal component analysis (PCA), and these are discussed below.

3.4.1. Molecular Diagnostic Ratio (MDR)

The $\text{SO}_4^{2-}/\text{Na}^+$ ratio < 1 indicates the dust storms, while > 1 indicates the anthropogenic activities. In this study, $\text{SO}_4^{2-}/\text{Na}^+$ ratios in PM_{10} were high in the month of October (22.7), November (24.9), and December (18.3) (Table 4), suggesting anthropogenic source. A Cl^-/Na^+ ratio < 10 indicates the source of biomass and coal combustion burning. Cl^-/Na^+ ratios were observed to be predominantly low during November (1.06) and December (1.12). A K^+/Na^+ ratio < 10 indicates the source of dust, and > 10 indicates the burning of crop residues. In this study, K^+/Na^+ ratios were observed in October (1.25) and December (1.04). $\text{Ca}^{2+}/\text{Na}^+$ and $\text{Mg}^{2+}/\text{Na}^+$ ratios indicate the source of dust. Dust storms tremendously increase the Ca^{2+} concentration in the atmosphere [65,66]. In this study, $\text{Ca}^{2+}/\text{Na}^+$ and $\text{Mg}^{2+}/\text{Na}^+$ were observed during October (3.34), November (2.52), and December (1.71); and August (1.30) and November (0.61), respectively.

3.4.2. Principal Component Analysis (PCA)

PCA was performed on the WSIs dataset separately in each season to investigate the sources of PM_{10} . The results of PCA analysis irrespective of seasons are presented in Table 5. In winter, two principal components (PCs) were extracted with an eigenvalue greater than one and a cumulative variance of 75.65%. PC 1 accounted for 58.96% of the variation in WSIs data and was positively loaded with Na^+ (0.845), K^+ (0.728), Ca^+ (0.897), Cl^- (0.869), SO_4^{2-} (0.515), and NH_4^+ (0.839). K^+ is an indicator of biomass burning. A high contribution of SO_4^{2-} , NH_4^+ , and Na^+ are identified as secondary aerosol formation. High SO_4^{2-} and NH_4^+ are also released from an industrial source, such as a brick kiln [57–59]. PC 2 comprised 16.69% of the variance in data and was highly loaded with K (0.534), Mg (0.920), and NO_3^- (0.842). NO_3^- is associated with vehicle emissions, while high Mg is linked with soil and road dust [39].

In the summer, three PCs were extracted with an eigenvalue greater than 1, with a cumulative variance of 73.88%. PC 1 accounted for 36.87% and was highly loaded with Na^+ (0.872), SO_4^{2-} (0.525), and NH_4^+ (0.903). SO_4 and NH_4 in the atmosphere are generally assumed to be secondary fine particles produced from gas to particle conversion of NH_3 and SO_2 ; hence, this source can be identified as the secondary formation [67–69]. PC 2 explored 19.97% of the total variance in data and was positively loaded with Ca (0.838) and NO_3^- (0.907). PC 3 explained 17.05% data variation and was highly loaded with K (0.663) and Cl^- (0.857). Cl^- is believed to be associated with multiple sources, such as coal burning, biomass burning, and sea salts [70].

In the rainy season, three PCs were extracted with an eigenvalue greater than 1, with a cumulative variance of 70.80%. PC 1 contained 36.27% of the total variance and was loaded with Ca^{2+} (0.663), Mg^{2+} (0.829), and K^+ (0.894). High loading of Ca, Mg, and K demonstrate contribution from marine aerosols [71,72]. PC 2 accounted for 17.67% of data variance, with favorable loading on Na (0.747), K (0.528), and NO_3 (0.701). PC 3 explained 16.86% of data variance and was highly loaded with SO_4^{2-} (0.849) and NH_4 (0.685), suggesting secondary formation. SO_4^{2-} can also result from vehicular emission.

In autumn, only two main PCs were extracted with an eigenvalue greater than one and a cumulative variance of 76.96%. PC 1 accounted for 58.81% of data variation and was positively linked with Na^+ (0.942), K (0.795), Ca (0.527), Cl^- (0.817), SO_4^{2-} (0.677), and NO_3^- (0.762). The dominance of Cl^- and NO_3^- indicates secondary formation. The reaction of NOx with hydroxyl radicals leads to the formation of nitrate. PC 2 comprised 18.15% of data variation and was highly loaded with K^+ (0.533), Mg^{2+} (0.815), and SO_4^{2-} (0.715).

Overall, the principal causes of air pollution in Patna, according to the PCA analysis, are mostly emissions from mixed sources such street dust, coal combustion, biomass burning, vehicular emissions, and industrial emissions such as brick kiln and secondary aerosol formations. This finding is consistent with a previous study that identified similar sources in $\text{PM}_{2.5}$ from Patna [39].

Table 4. Molecular diagnostic ratios of WSIs utilized for source apportionment in Patna.

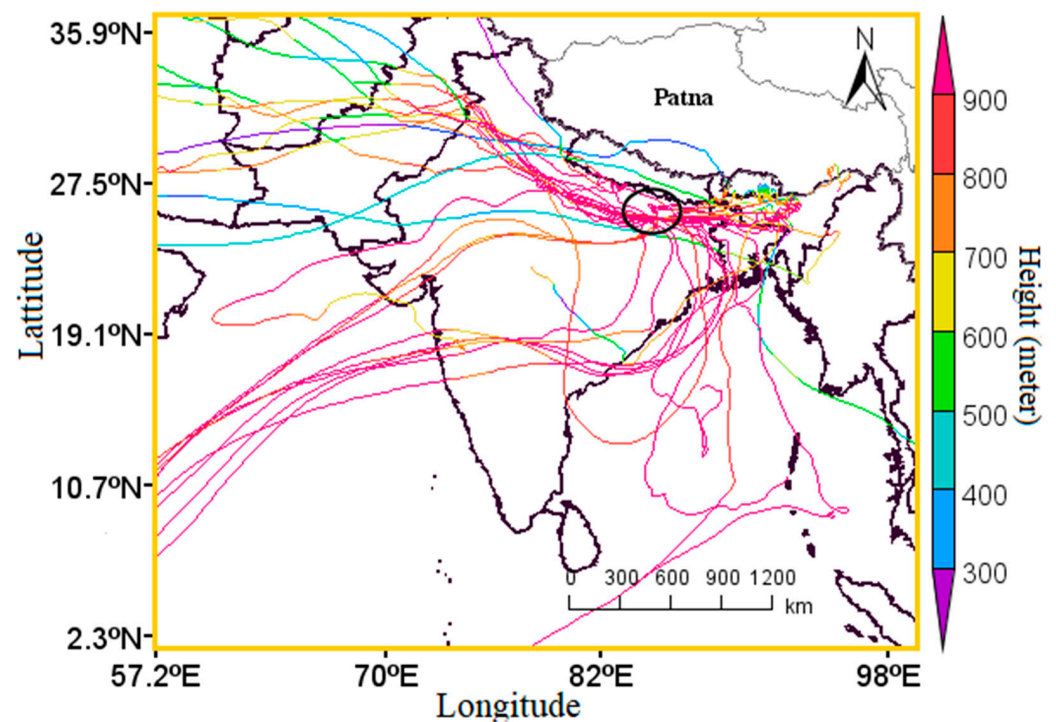
Months	Cl [−] /Mg ²⁺	SO ₄ ^{2−} /Mg ²⁺	Na ⁺ /Mg ²⁺	K ⁺ /Mg ²⁺	Ca ²⁺ /Mg ²⁺	Cl [−] /Na ⁺	K ⁺ /Na ⁺	Mg ²⁺ /Na ⁺	Ca ²⁺ /Na ⁺	SO ₄ ^{2−} /Na ⁺	SO ₄ ^{2−} /K ⁺	NO ₃ [−] /SO ₄ ^{2−}	Cl [−] /K ⁺	Na ⁺ /Ca ²⁺	K ⁺ /Ca ²⁺	Mg ²⁺ /Ca ²⁺	Cl [−] /Ca ²⁺	NO ₃ [−] /Ca ²⁺	SO ₄ ^{2−} /Ca ²⁺
January	2.53	41.3	5.91	3.95	3.67	0.43	0.67	0.17	0.62	6.98	10.4	0.85	0.64	1.61	1.07	0.27	0.69	9.56	11.2
February	2.83	42.3	5.23	3.69	3.85	0.54	0.71	0.19	0.74	8.08	11.4	0.96	0.77	1.36	0.96	0.26	0.74	10.5	10.9
March	1.46	21.3	5.98	3.71	5.61	0.24	0.62	0.17	0.94	3.58	5.77	0.59	0.39	1.07	0.66	0.18	0.26	2.24	3.81
April	1.63	29.1	6.17	3.51	4.54	0.26	0.57	0.16	0.74	4.73	8.30	0.25	0.46	1.36	0.77	0.22	0.36	1.63	6.42
May	4.00	51.8	10.7	8.31	5.69	0.37	0.77	0.09	0.53	4.82	6.23	0.30	0.48	1.89	1.46	0.18	0.70	2.74	9.11
June	0.65	12.1	1.77	1.71	1.37	0.37	0.97	0.56	0.77	6.83	7.07	0.21	0.38	1.30	1.25	0.73	0.48	1.83	8.85
July	1.46	21.4	3.84	3.78	2.43	0.38	0.99	0.26	0.63	5.58	5.66	0.15	0.39	1.58	1.56	0.41	0.60	1.36	8.81
August	0.26	5.71	0.77	0.73	0.98	0.33	0.94	1.30	1.28	7.42	7.86	0.13	0.35	0.78	0.74	1.02	0.26	0.74	5.81
September	0.45	23.6	1.69	1.64	1.58	0.27	0.97	0.59	0.94	14.0	14.4	0.05	0.28	1.07	1.04	0.63	0.29	0.72	14.9
October	0.95	62.8	2.77	3.45	9.27	0.34	1.25	0.36	3.34	22.6	18.1	0.40	0.28	0.30	0.37	0.11	0.10	2.72	6.77
November	1.74	41.0	1.65	1.63	4.15	1.06	0.99	0.61	2.52	24.9	25.1	0.50	1.07	0.40	0.39	0.24	0.42	4.93	9.87
December	5.12	83.8	4.58	4.77	7.81	1.12	1.04	0.22	1.71	18.3	17.5	0.78	1.07	0.59	0.61	0.13	0.66	8.40	10.7

Table 5. Principal component analysis (PCA) of WSIs in PM₁₀ from Patna.

WSIs	Winter		Summer			Rainy			Autumn	
	PC1	PC2	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC3
Na ⁺	0.845	0.002	0.872	0.179	0.251	0.367	0.747	0.337	0.942	−0.141
K ⁺	0.728	0.534	0.267	−0.099	0.663	0.663	0.528	0.185	0.795	0.533
Ca ²⁺	0.897	0.038	0.206	0.838	0.018	0.829	0.052	0.141	0.527	0.186
Mg ²⁺	0.009	0.920	0.453	0.710	−0.006	0.894	−0.004	−0.090	0.317	0.815
Cl [−]	0.869	0.358	−0.215	0.103	0.857	−0.406	−0.623	0.261	0.817	0.131
SO ₄ ^{2−}	0.515	0.305	0.525	0.358	0.426	−0.136	0.221	0.849	0.677	0.715
NO ₃ [−]	0.348	0.842	−0.171	0.907	0.039	−0.194	0.700	−0.037	0.762	0.475
NH ₄ ⁺	0.839	0.307	0.903	−0.004	−0.191	0.320	−0.282	0.685	0.072	−0.888
Eigenvalue	4.717	1.336	2.950	1.597	1.364	2.902	1.414	1.349	4.705	1.452
Variance (%)	58.96	16.69	36.87	19.96	17.05	36.27	17.67	16.86	58.81	18.15

3.5. Backward Air Mass Trajectory

In this study, a five-day air mass back trajectory analysis was performed to examine the influence of air mass originating from a nearby or remote area on aerosol composition. The trajectories were calculated for an air mass arriving at our study site at 500 m above ground level, as shown in Figure 5. The back trajectory analysis indicates that the air mass in Patna city primarily originated from marine sources and was transported from the Arabian Sea, Bay of Bengal, Gujarat, Afghanistan, Pakistan, and Bangladesh. Therefore, the influence of air mass from both land and sea may have contributed to this study's high levels of PM₁₀.

**Figure 5.** Five-day air mass back trajectories arriving at Patna.

4. Conclusions

The contamination and seasonal distribution of PM₁₀ in ambient air were investigated to understand the pollution level in Patna. The results indicated severe contamination of PM₁₀ in the air, exceeding the annual recommended limit of WHO and NAAQS India. The annual average PM₁₀ concentration in Patna was slightly higher than some of India's megacities but was consistent with class-II cities. The winter season had a relatively higher

level of PM₁₀ than the rest of the seasons. SO₄ was identified as the most prominent compound among WSIs. The outcome of the principal component analysis indicated that the combined sources of PM pollution in Patna include vehicle emissions, industrial emissions, street dust, burning of biomass, and coal combustion. The back trajectory analysis suggests that the air mass at Patna city mainly originated from marine settings and was transported from the Arabian Sea and Bay of Bengal, Gujarat, Afghanistan, Pakistan, and Bangladesh. The results obtained in this study can be used to prepare PM₁₀ profiling of the IGP. As the urban quality of Indian cities, including Patna, is deteriorating, continuous air quality monitoring of PM is warranted.

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