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Urban Air Quality of Residential, Commercial, Industrial, and Sensitive Areas in Srinagar City, Kashmir Himalaya

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ABSTRACT

Urban air quality deterioration has emerged as a major environmental concern worldwide due to its adverse implications for human health and its influence on local to regional weather and climate. In view of these concerns, the present investigation assessed the ambient air quality of Srinagar city, located in the Himalayan region, with particular emphasis on particulate and gaseous pollutants. Ambient air samples were collected for $PM_{2.5}$, PM_{10}, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) during winter and summer seasons across four areas, namely residential, commercial, industrial, and sensitive, from December 2014 to September 2015. $PM_{2.5}$ samples were collected using a fine particulate dust sampler (Envirotech APM 550 MFC), while PM_{10} and gaseous pollutants were monitored using a respirable dust sampler (Envirotech APM 460 DXNL) equipped with glass impingers. Spatial analysis revealed that mean $PM_{2.5}$ concentrations were highest in commercial areas (159±103 μgm^{-3}), followed by industrial (108±43 μgm^{-3}) and residential (69±43 μgm^{-3}), with the lowest levels recorded at sensitive area (61±32 μgm^{-3}). A similar spatial pattern was observed for PM_{10}, with maximum concentrations in commercial areas (291±190 μgm^{-3}) and minimum values in sensitive locations (78±81 μgm^{-3}). The mean concentrations of SO_2 and NO_2 also exhibited higher levels in commercial and industrial zones compared to residential and sensitive areas, although their values remained relatively low. Overall, concentrations of $PM_{2.5}$ and PM_{10} exceeded the Indian National Ambient Air Quality Standards, indicating a significant particulate pollution burden across the city. In contrast, SO_2 and NO_2 levels were consistently within the prescribed national limits. To integrate the combined effects of these pollutants, the Air Quality Index (AQI) was calculated for all sites and seasons using $PM_{2.5}$, PM_{10}, SO_2, and NO_2 as input parameters. AQI values varied widely, ranging from good to poor categories, with higher indices during winter and lower values in summer. On average, commercial areas exhibited moderately polluted conditions, residential and industrial zones showed satisfactory to moderately polluted air quality, and sensitive areas ranged from good to satisfactory. The overall AQI for Srinagar indicated satisfactory air quality, despite elevated particulate matter concentrations.

Keywords: *Air Pollution, PM_{10}, $PM_{2.5}$, NAAQS, AQI, Western Himalaya, Meteorology*

INTRODUCTION

Air pollution has emerged as one of the most serious environmental challenges worldwide, posing significant risks to human health, ecosystems, and climate systems (Manisalidis *et al.,* 2020; Orellano *et al.,* 2020; Wei *et al.,* 2023). Atmospheric pollution arises from both natural processes, such as wildfires, and human activities, including industrial emissions of particulate matter (PM), sulfur oxides, nitrogen oxides (NO_x), and volatile organic compounds (VOCs), as well as coal combustion for seasonal heating and heavy urban traffic that release PM, sulfur dioxide (SO_2), carbon monoxide (CO), and NO_x (Wei *et al.,* 2023). Rapid growth in motorized transport and industrial activity has increased reliance on fossil fuels such as oil, natural gas, and coal, whose combustion in air generates oxides of carbon, PM, sulfur, and nitrogen (Syrek-Gerstenkorn *et al.,* 2024). Air pollution is estimated to cause nearly 8 million premature deaths annually across the globe (WHO, 2014). Air pollutants adversely affect human and animal health, damage vegetation, reduce visibility and solar radiation, impair ecosystem functioning, and negatively influence agriculture and overall quality of life (Decker *et al.,* 2000; Mayer *et al.,* 2000; Vicente *et al.,* 2001; Molina and Molina, 2004). Beyond localized impacts, air pollution contributes to large scale environmental problems such as global warming, environmental acidification, photochemical smog formation, and stratospheric ozone depletion, thereby influencing regional and global climate systems (Kelessis, 2001; McMichael *et al.,* 2006; Sivakumar, 2007; Abrutzky *et al.,* 2012). Consequently, air pollution has become a major concern at ecological, climatological, epidemiological, and toxicological levels worldwide (McMichael *et al.,* 2006). Among various air pollutants, atmospheric particulate matter (PM) has received particular attention due to its widespread occurrence and pronounced health and environmental effects (Meo *et al.,* 2024). Particles between 0.1–10 µm pose significant health risks as they can be inhaled into the respiratory system with $PM_{2.5}$ reaching the alveoli and is linked to cardiovascular and respiratory diseases and premature death, while PM_{10} mainly deposits in upper airways, causing inflammation, asthma aggravation, and impaired lung functions (Pope and Dockery, 2006). Fine particles have longer atmospheric residence times and can be transported over large distances, while coarse particles settle more rapidly and tend to affect areas closer to their sources (Shin *et al.,* 2009; Rasheed *et al.,* 2015). Due to these characteristics, $PM_{2.5}$ poses a greater threat to human health and regional air quality than coarse particles.

Atmospheric particulate matter is recognized as a global environmental issue because of its adverse impacts on human health, climate, ecosystems, visibility, and atmospheric chemistry (Bhattarai *et al.,* 2024; Duan *et al.,* 2007; Gupta and Kumar, 2006; IPCC, 2007; Tsai and Cheng, 2004; Wallenborn *et al.,* 2009). PM influences climate through direct and indirect radiative effects, alters biogeochemical cycles, and participates in complex atmospheric chemical reactions (Kouyoumdjian and Saliba, 2006; Rinaldi *et al.,* 2007; Shin *et al.,* 2009; Bhaskar and Mehta, 2010; IPCC, 2013; Wang, 2013). In addition, particulate pollution contributes to the soiling of monuments and urban infrastructure, material degradation, and damage to terrestrial and aquatic ecosystems (Cobourn *et al.,* 1993; Tiwari *et al.,* 2009; Baker *et al.,* 2006). Along with particulate matter, gaseous pollutants such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) play an important role in determining ambient air quality. Nitrogen dioxide (NO_2) is a widespread urban air pollutant that adversely affects human health, contributes to ground level ozone formation, and participates in secondary particulate formation, with concentrations largely driven by fuel combustion and vehicular emissions (Chen *et al.,* 2018; Faustini *et al.,* 2014). Sulfur dioxide (SO_2), mainly emitted from fossil fuel combustion in power plants and industrial sources, transforms in the atmosphere into sulfuric acid and fine particulate matter, causing significant health, environmental, and economic impacts (Hasan *et al.,* 2018; McLinden *et al.,* 2016; Meo *et al.,* 2024).

Over the past few decades, air pollution has become a critical environmental challenge in Indian cities, largely due to accelerated urban expansion, population growth, increasing vehicular density, and industrial development (Dutta *et al.,* 2021). Urban air pollution in India is primarily driven by industries, automobiles, and domestic fuel combustion, while natural sources such as dust storms also contribute significantly to particulate loading (Bhasker and Mehta, 2010; Badarinath *et al.,* 2007). Among these, vehicular emissions, particularly from diesel powered vehicles, have been recognized as one of the most important contributors to urban $PM_{2.5}$ pollution (Morawska *et al.,* 1998; Weisel, 2002).

Despite the growing concern over air pollution in India, information on particulate and gaseous pollutants in Himalayan urban environments remains limited. Srinagar city, located in a topographically enclosed Himalayan basin, is particularly vulnerable to air pollution due to rapid urbanization, increasing vehicular density, restricted dispersion conditions, and seasonal meteorological influences. The lack of comprehensive data on $PM_{2.5}$, PM_{10}, SO_2, and NO_2 in this region represents a significant knowledge gap. In this context, the present study was undertaken to generate baseline information on ambient concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 in Srinagar city. By assessing spatial and seasonal variations across different zones, the study aims to improve understanding of air pollution characteristics in a Himalayan urban environment and provide scientific evidence to support air quality management and policy formulation in the region.

MATERIAL AND METHODS

Study area

Srinagar city is situated in the central part of the Kashmir Valley between 33°53′49′′N – 34° 17′14′′N latitude and 74°36′16′′E – 75°01′26′′E longitude (Nengroo *et al.,* 2017) at an elevation of about 1600 m above sea level in western Himalayan region. It represents the largest urban settlement in the Indian Himalayan region and is located along the banks of the Jhelum River within the valley's central plains (Nengroo *et al.,* 2017). The city covers an area of about 285 km^2 and supports a population of 1,236,829 with a density of 625 persons per km^2 (Census, 2011). Srinagar is a major administrative centre and a prominent tourist destination, surrounded by mountain ranges, lakes, and historic gardens.

Climate

Based on the revised Köppen-Geiger climate classification, Srinagar has temperate climate, defined by its temperature and precipitation characteristics, and exhibits four distinct seasons: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February) (Romshoo *et al.,* 2020). The region is characterized by predominantly sub-zero winter temperatures, moderate summer conditions with temperatures of about 25-35°C, and an average annual precipitation of approximately 840 mm occurring mainly as rainfall during spring, summer, and autumn, and as snowfall in winter (Zaz *et al.,* 2019). Autumn is marked by minimal precipitation and clear atmospheric conditions, while wind activity remains subdued in autumn and winter and intensifies during the other seasons (Ahmad *et al.,* 2017; Bhat *et al.,* 2022).

Sampling sites

Sampling sites were selected to capture the pollutant influences from different urban settings, including industrial, commercial, residential, and sensitive areas (Fig. 1). The location and key characteristics of the sampling sites are represented in Table 1.

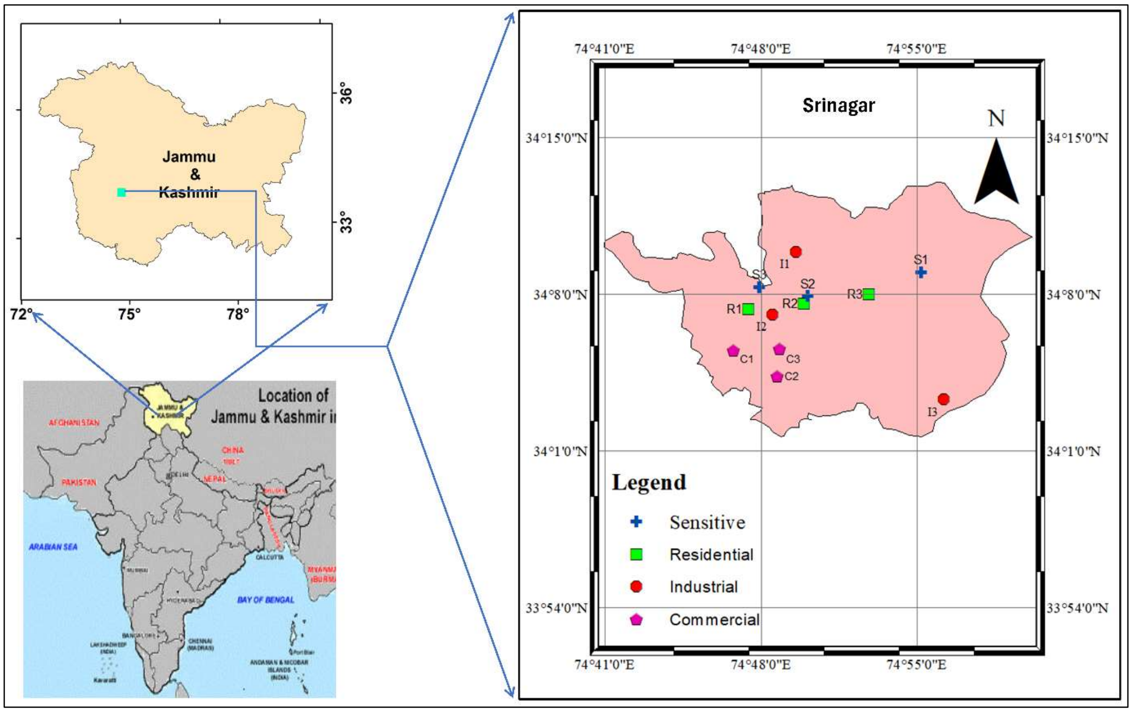

Fig.1. Location of the sampling sites in Srinagar city

Table 1. Sampling sites from different areas/zones of Srinagar city

Area/Zone	Sites	Location	Characteristics
Commercial	Qamarwari (C1)	34° 05.498' N; 74° 46.776' E (1601 amsl)	• General market place • 150 m away from the road having high traffic volume
	Lalchowk (C2)	34° 04.327' N; 74° 48.746' E (1586 amsl)	• Main commercial and business hub of the city characterized by high traffic density and high traffic volume • 70 m away from the road
	Khanyar (C3)	34° 05.544' N; 74° 48.826' E (1610 amsl)	• Located in Shehr-e-Khaas characterised by high traffic density and volume due to pilgrimage activity at the Dastgeer Sahib (R.A) shrine • 80 m away from the road
Residential	Achan (R1)	34° 07.334' N; 74° 47.446' E (1588 amsl)	• Close to the landfill site of the city surrounded by residential houses, and agriculture fields • 250 m away from the main road
	Nigeen (R2)	34° 07.602' N; 74° 49.918' E (1594 amsl)	• Located in the north of city surrounded by residential houses close to Nigeen lake • 100 m away from the main road
	Nishat (R3)	34° 08.000' N; 74° 52.826 E (1626 amsl)	• Located on the banks of the Dal Lake surrounded by residential houses • 500 m from the road.

Industrial	Zukura (I1)	34° 09.921' N; 74° 49.567' E (1612 amsl)	- Located in the industrial estate having an area of 1.28 Km^2 with activities like food processing, cement-based units, copper rolling mills, wooden furniture works, etc.
	Baghi-Ali-Mardan Khan (BAMK) Nowshera (I2)	34° 07.107' N; 74° 48.511' E (1606 amsl)	- An industrial estate of city with an area of $1.44Km^2$. Main activities include bakery, sweets, food processing, manufacture of PVC pipes, glass grinding and moulding, wood works, cement-based works, etc
	Khonmoh (I3)	34° 03.303' N; 74° 56.204' E (1655 amsl)	- Industrial estate with an area of 20.37 Km^2 characterised by the activities like stone crushing, manufacture of POP and wall putty, RCC pipes, cardboard manufacturing, aluminium utensils manufacturing, cement-based works, etc
Sensitive	Dachigam National Park (S1)	34°08.950' N; 74° 55.195' E (1709 amsl)	- An ecologically sensitive place with area of 141 Km^2, about 20 km away from the main city. - It is full of thick woods, steep rocky ridges, gentle grassy slopes and deep gullies.
	Kashmir University campus (S2)	34° 07.936' N; 74° 50.108' E (1591 amsl)	- The campus is spread over 247 acres of land flanked by the Dal Lake on its eastern side and Nigeen Lake on the western side. - Campus is housing the buildings of different departments.
	SKIMS, Soura (S3)	34° 08.352' N; 74° 47.921' E (1594 amsl)	- The tertiary care hospital of the valley surrounded by residential houses from the north and western sides - About 400 m away from the main road - Influenced by burning of hospital waste in the incinerator

Sampling and analysis

$PM_{2.5}$ and PM_{10}

$PM_{2.5}$ and PM_{10} samples were collected following an identical sampling protocol given by central pollution control board, India (CPCB, 2013). $PM_{2.5}$ was collected using a fine particulate sampler (Envirotech APM 550 MFC) onto Teflon® (PTFE) filters and operated at 16.7 L min^{-1}, while PM_{10} was collected using a high-volume respirable dust sampler (Envirotech APM 460 DXNL) at a flow rate of 1 m^3 min^{-1} on glass fiber (GF/A Whatman) filter. Both samplers were operated for 24-hour integrated sampling (10:00 AM–10:00 AM) over the period from December 2014 to September 2015, with one sampling event conducted in each season at the selected sites. Both Teflon® and GF/A filter substrates were inspected for any physical deformities prior to sampling. After sample collection, the filters were placed in petri dishes, properly sealed, and stored at 4 °C until further analysis. $PM_{2.5}$ and PM_{10} mass was determined gravimetrically by calculating the difference between pre- and post-sampling equilibrated filter weights (Eq. 1). All the weighing was performed using an electronic balance (SHIMADZU, Model AUW220D) with a sensitivity of 0.00001 g. Prior to each weighing, the filters were conditioned in a desiccator.

$$\text{PM mass} = \frac{(W_2 - W_1)}{V} \qquad [1]$$

w_2: post-sampling weight (µg)

w_1: pre-sampling weight (µg)

v: volume of air sampled (m^3)

Sulfur dioxide and nitrogen dioxide

SO_2 and NO_2 were sampled by passing ambient air through impingers attached with APM 460 DXNL containing appropriate absorbing solutions, namely potassium tetrachloro-mercurate for SO_2, and sodium hydroxide and sodium arsenite for NO_2. Sampling was carried out at a flow rate of 1 L min^{-1} for a duration of 8 hours. Following collection, the impinger solutions were immediately stored in ice boxes and later kept under refrigeration until chemical analysis. NO_2 concentrations were determined using the modified Jacob and Hochheiser method (1958), while SO_2 levels were quantified by the modified West and Geake method (1956).

Air Quality Index

An air quality index (AQI) integrates weighted concentrations of individual air pollutants into a single value to represent the overall air quality status of an area (Ott, 1978). AQI was calculated by using Eq.2 (Chauhan *et al.,* 2010). The overall AQI thus obtained is the mean of the four sub-indices, giving equal weight to PM_{10}, $PM_{2.5}$, SO_2, and NO_2.

$$AQI = \frac{1}{4}\left[\frac{PM_{10}}{sPM_{10}} + \frac{PM_{2.5}}{sPM_{2.5}} + \frac{SO_2}{sSO_2} + \frac{NO_2}{sNO_2}\right]\times 100 \qquad [2]$$

where, sPM_{10}, $sPM_{2.5}$, sSO_2, and sNO_2 represent the ambient air quality standards as prescribed by the Central Pollution Control Board (CPCB, 2009). PM_{10}, $PM_{2.5}$, SO_2 and NO_2 represent the observed values of pollutants during the study.

2.6 Meteorological parameters

Meteorological data was obtained from India Meteorological Department (IMD), Srinagar (http://www.imdaws.com). The parameters viz. temperature, rainfall, wind speed and wind direction are on hourly basis. So, daily, weekly and monthly mean time series of these parameters were prepared. Wind rose plots were generated using a WRPLOT View Software (Lakes Environmental, version 7.0.0).

Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) procedures were implemented to ensure the accuracy and reliability of sampling and chemical analyses of gaseous pollutants. All filter substrates were inspected for suitability prior to pre-weighing and use in sampling. Flow rate calibration and leak checks were performed for each sampler prior to sampling. Filters were pre- and post-weighed under controlled conditions, and reweighed to ensure measurement precision. Prior to weighing, the balance underwent a quality control (QC) check using working mass reference standards. Calibration with standard solutions was performed for SO_2 and NO_2 measurements, complemented by blanks and replicates to maintain analytical reliability.

RESULTS AND DISCUSSION

$PM_{2.5}$ and PM_{10} mass concentration

$PM_{2.5}$ concentration showed clear spatial and seasonal variability across different areas. In commercial areas, levels ranged from 60 μgm^{-3} at Khanyar (C3) during summer to a maximum of 304 μgm^{-3} at Qamarwari (C1) in winter (Fig. 2). Residential locations recorded comparatively lower values, varying from 24 μgm^{-3} at Nishat (R3) in summer to 132 μgm^{-3} at Nigeen during winter. In industrial zones, $PM_{2.5}$ concentrations ranged from 66 μgm^{-3} at BAMK, Nowshera (I2) in summer to 173 μgm^{-3} at the same site in winter. Sensitive areas exhibited concentrations between 27 μgm^{-3}

at SKIMS, Soura (S3) during summer and 114 µgm^{-3} at the Kashmir University campus (S2) in winter. Across all zones, seasonal mean $PM_{2.5}$ levels were consistently lowest in summer and highest in winter, with overall seasonal averages spanning from 33 µgm^{-3} to 248 µg m^{-3} (Fig. 3). For $PM_{2.5}$, a statistically significant difference was observed among areas (F = 15.85, p = 0.001). The one-way ANOVA model explained 85.60% of the total variance (R^2 = 85.60%; adjusted R^2 = 80.20%). Mean concentrations were highest in the commercial area (159±29 µg m^{-3}), followed by the industrial (108±11 µg m^{-3}), residential (69±18 µg m^{-3}), and sensitive zones (61±16 µg m^{-3}). Tukey's post hoc test indicated that the commercial area (group-a) differed significantly from the other three zones (group-b), while industrial, residential, and sensitive areas did not differ significantly from one another (Table 2). Notably, the mean concentrations across all areas exceeded the National Ambient Air Quality Standard (NAAQS) limit of 60 µgm^{-3} (CPCB, 2009) (Fig. 4). Elevated $PM_{2.5}$ levels in commercial sites can be attributed to high traffic volume, leading to increased vehicular emissions, frequent operation of diesel and kerosene driven generator sets during power outages, particularly in winter, and enhanced re-suspension of road dust. Contributions to fine particulate pollution arise from incomplete fuel combustion in diesel operated vehicles and two-stroke engines, which are recognized as major sources of $PM_{2.5}$ emissions (Srimuruganandam and Nagendra, 2012; Rasheed *et al.,* 2015). In addition, vehicular movement promotes the re-suspension of roadside dust, generating a substantial share of ambient $PM_{2.5}$ (Deshmukh *et al.,* 2011). Mean $PM_{2.5}$ concentrations in all zones exceeded the NAAQS limit of 60 µgm^{-3} (CPCB, 2009). In residential areas, biomass combustion, unpaved roads, waste burning, and exposed soil are major contributors, whereas comparatively lower levels in industrial areas are due to presence of only small scale units in these industrial estates which are mostly electricity driven, and also due to the location of the estates away from the city centre. The higher $PM_{2.5}$ values across all zones pose a significant health risk for the residents of the Srinagar city. Exposure to $PM_{2.5}$ is associated with adverse health effects, including respiratory disorders, cardiovascular disease, bronchitis, asthma, lung cancer, strokes, heart attacks, and increased risk of cognitive decline such as dementia (Abidin *et al.,* 2025; Southerland et al., 2022; Sangkham et al., 2024; Zambrano-Monserrate et al., 2024).) Owing to its smaller size, $PM_{2.5}$ can reach deep into the lungs and enter the bloodstream via the alveoli, whereas PM_{10} primarily deposits in the upper respiratory tract (Xing *et al.,* 2016).

PM_{10} concentrations exhibited marked spatial and seasonal variability. In commercial areas, concentrations ranged from 87 µgm^{-3} at Qamarwari (C1) during summer to 493 µgm^{-3} at Lal Chowk (C2) in winter (Fig. 2). Residential sites showed values between 43 µgm^{-3} at Achan (R1) in summer and 329 µgm^{-3} at the same location during winter. In industrial zones, PM_{10} levels varied from 48 µgm^{-3} at Zukura (I1) in summer to a maximum of 542 µg m^{-3} at BAMK, Nowshera (I2) during winter. Sensitive areas recorded the lowest concentrations, ranging from 40 µgm^{-3} at Dachigam National Park (S1) and SKIMS, Soura (S3) in summer to 242 µgm^{-3} at the Kashmir University campus (S2) in winter. Seasonally, mean PM_{10} concentrations were highest in winter, peaking at 460 µg m^{-3} in commercial areas, and lowest in summer, with a minimum of 44 µgm^{-3} at sensitive sites (Fig. 3). Across all locations, summer concentrations were consistently lower than winter values.

For PM_{10}, the differences among areas were also statistically significant (F = 5.59, p = 0.023), with an R^2 of 67.70% (adjusted R^2 = 55.59%). The commercial area again recorded the highest mean concentration (291±37 µg m^{-3}), followed by industrial (233±112 µg m^{-3}), residential (165± 22 µg m^{-3}), and sensitive areas (78±60 µg m^{-3}). Tukey grouping showed (Table 2) that the commercial area formed a distinct group (a), while the sensitive area was grouped separately (b). Industrial and residential areas fell within overlapping groups (a and b), suggesting intermediate concentrations without clear statistical separation. Nevertheless, mean concentrations at all sites, except those in sensitive areas, exceeded the NAAQS prescribed by the Central Pollution Control Board (CPCB, 2009) (Fig. 4). The high concentration of PM_{10} at commercial area is due to vehicular emissions and road re-suspension. Vehicular movements are major contributors of PM_{10} (Giri *et al.,* 2007; Sathaye *et al.,* 2010) because diesel fueled vehicles contributes major portion of PM_{10} mass (Gargava *et al.,* 2014). Vehicular movements on roads also increase the road resuspension which leads to increase in PM_{10} concentration in the ambient air (Dahl *et al.,* 2006; Ancelet *et al.,* 2014). Presence of industrial units which use mechanical processes like manufacture of POP, cement-based units, stone crushers and flour mills in these estates may contribute to PM_{10} concentrations (Begum *et al.,* 2006).

The high concentrations of $PM_{2.5}$ and PM_{10} are primarily associated with biomass burning and the widespread use of wood for domestic space heating during winter, along with the combustion of hard coke in offices for heating purposes (Huma *et al.,* 2016; Hakim *et al.,* 2018; Bhat *et al.,* 2021).

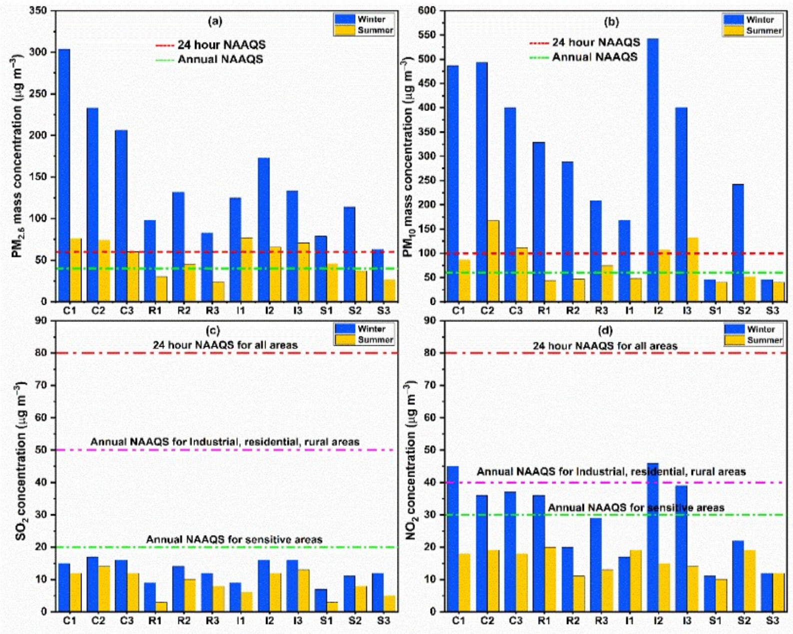

Fig. 2. Variation of (a) $PM_{2.5}$, (b) PM_{10}, (c) SO_2 and (d) NO_2 at different sites

Sulfur dioxide (SO_2)

SO_2 concentrations exhibited limited spatial and seasonal variability across the study areas. In commercial zones, levels ranged from 12 μgm^{-3} at Qamarwari (C1) and Khanyar (C3) in summer to 17 μgm^{-3} at Lal Chowk (C2) during winter (Fig. 2). Residential areas recorded values between 3 μgm^{-3} at Achan (R1) in summer and 14 μgm^{-3} at Nigeen in winter. Industrial sites showed concentrations from 6 μgm^{-3} at Zukura (I1) in summer to 16 μgm^{-3} at BAMK, Nowshera (I2) and Khonmoh (I3) in winter, while sensitive areas ranged from 3 $\mu g\ m^{-3}$ at Dachigam (S1) in summer to 12 $\mu g\ m^{-3}$ at SKIMS, Soura (S2) in winter. Mean SO_2 levels were highest in winter (16 $\mu g\ m^{-3}$) at commercial sites and lowest in summer (5 μgm^{-3}) at sensitive locations (Fig. 3). For SO_2, although mean concentrations varied spatially, the differences were not statistically significant at the 95% confidence level ($F = 3.37$, $p = 0.075$). The one-way ANOVA model accounted for 55.84% of the total variance (adjusted R^2 = 39.28%). The commercial area exhibited the highest mean concentration (15±2 $\mu g\ m^{-3}$), followed by industrial (12±4 $\mu g\ m^{-3}$), residential (9±4 $\mu g\ m^{-3}$), and sensitive areas (8±3 $\mu g\ m^{-3}$). Tukey grouping indicated substantial overlap among areas, suggesting no clear pairwise differences (Table 2). All values remained within NAAQS limits of CPCB (2009) (Fig. 4). The highest concentration of SO_2 was observed at commercial areas because of the vehicular emissions as diesel vehicles are the main sources of SO_2 emissions and also from burning of coal during winters for heating purposes (Koukouli *et al.,* 2018; Meng *et al.,* 2010; Romshoo *et al.,* 2020; Wójcik-Gront and Gozdowski, 2025).

Nitrogen dioxide (NO_2)

NO_2 concentrations varied modestly across zones and seasons. In commercial areas, levels ranged from 18 μgm^{-3} at Qamarwari and Khanyar during summer to 45 μgm^{-3} at Qamarwari in winter (Fig. 2). Residential sites recorded values between 11 μgm^{-3} at Nigeen in summer and 36 μgm^{-3} at Achan during winter, while industrial areas ranged from 14 μgm^{-3} at Khonmoh in summer to 46 μgm^{-3} at BAMK, Nowshera in winter. Sensitive locations showed the lowest concentrations, varying from 10 μgm^{-3} at Dachigam National Park in summer to 22 μgm^{-3} at the Kashmir University campus during winter. Seasonal means ranged from 14 μgm^{-3} at sensitive sites in summer to 39 μgm^{-3} at commercial sites in winter (Fig. 3).

In the case of NO_2, the overall difference approached statistical significance ($F = 4.01$, $p = 0.052$), with 60.04% of the variance explained (adjusted R^2 = 45.06%). The highest mean concentration was recorded in the commercial area (29±2 $\mu g\ m^{-3}$), followed by industrial (25±7 $\mu g\ m^{-3}$), residential (22±6 $\mu g\ m^{-3}$), and sensitive areas (14±5 $\mu g\ m^{-3}$). Tukey analysis showed that the commercial area formed group-a, while the sensitive zone was placed in group-b (Table 2). Industrial and residential areas overlapped between groups a and b, indicating partial but not definitive separation. All values were within NAAQS limits (80 μgm^{-3}) CPCB (2009) (Fig. 4). Vehicular emissions from the traffic congested areas are the contributing sources of NO_2 in commercial areas of the city as nitrogen dioxide is considered a well-recognized indicator of emissions from fuel combustion in motor vehicles (Artíñano *et al.,* 2004; Anenberg *et al.,* 2022; Dou *et al.,* 2021; Qian *et al.,* 2021; Smargiassi *et al.,* 2005; Stranger *et al.,* 2008; Sharma and Raina, 2015). Usage of diesel and kerosene driven generator sets during electricity failures may also be the cause of high NO_2 levels within the commercial areas. The lowest mean concentration was observed at Dachigam National Park because of the absence of pollutant sources in its vicinity and presence of forest area.

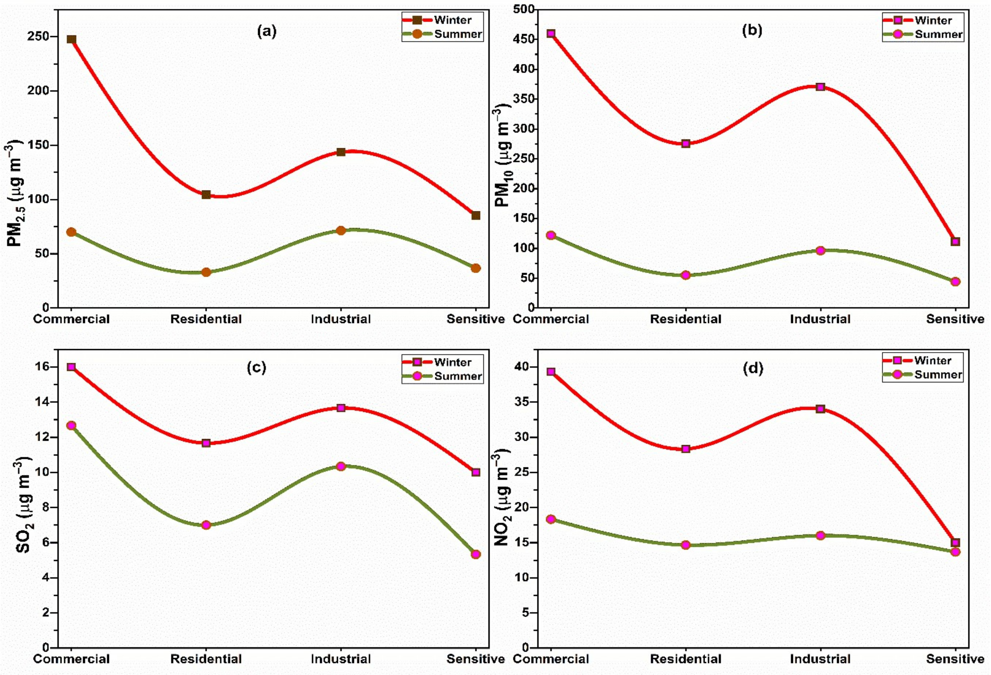

Fig. 3. Seasonal mean variation of (a) $PM_{2.5}$ (b) PM_{10}, (c) SO_2 and (d) NO_2 in different zones of Srinagar city

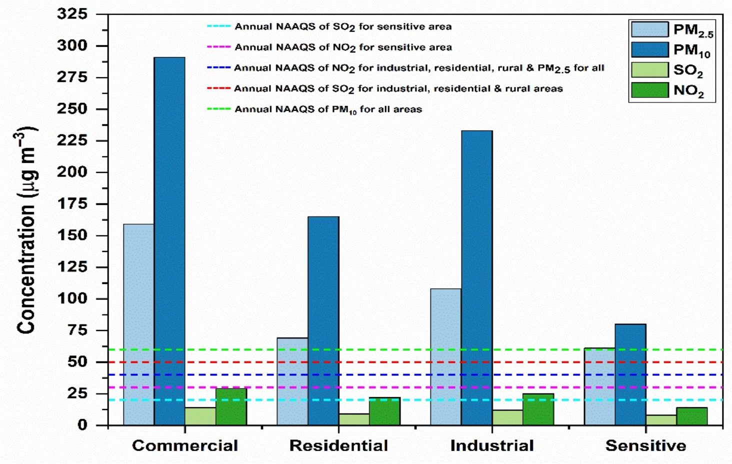

Fig. 4. Comparison of mean concentration of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 in different zones of Srinagar city with NAAQS, India

Table 2. One-way ANOVA and Tukey's HSD post-hoc test comparison of pollutant concentrations across different areas/zones

Pollutant	F (3,8)	p-value	R^2 (%)	Commercial	Industrial	Residential	Sensitive
$PM_{2.5}$	15.85	0.001	85.6	159±29^{a}	108±11^{b}	69±18^{b}	61±16^{b}
PM_{10}	5.59	0.023	67.7	291±37^{a}	233±112^{ab}	165±22^{ab}	78±60^{b}
NO_2	4.01	0.052	60.04	29±2^{a}	25±7^{ab}	22±6^{ab}	14±5^{b}
SO_2	3.37	0.075	55.84	15±2^{a}	12±4^{a}	9±4^{a}	8±3^{a}

Values are expressed as mean± SD (µg m^{-3}), n = 3 per area. Different superscript letters within a row indicate statistically significant differences among zones according to Tukey's HSD test at $p < 0.05$

Role of meteorology

Meteorological conditions during the study period showed marked seasonal variability in temperature, rainfall, and wind speed. The highest monthly mean temperature was observed in July (27.9°C), while the lowest monthly mean temperature occurred in December (-2.6°C) (Fig. 5). Weekly temperature data, presented in Fig. 5, indicate that the minimum weekly temperature of -6.0°C was recorded in January, whereas the maximum weekly temperature reached 33.8 °C in July. Monthly average rainfall peaked in July (12.9 mm), while the lowest rainfall (0.1 mm) was recorded in January and September; no rainfall was observed during December 2014 and the first half of January 2015. At the weekly scale, the highest rainfall event (99 mm) occurred during the second week of March, followed by substantial rainfall during the fourth week of June and the third week of August. Wind speed also exhibited temporal variation, with minimum monthly averages of 0.2 m s^{-1} recorded in December and February, and a maximum monthly average of 3.7 m s^{-1} in May, followed by 3.2 m s^{-1} in June. The highest weekly mean wind speed (1.58 m s^{-1}) was observed during the fourth week of May and the second week of June. Meteorological factors including temperature, rainfall, mixing height, relative humidity, and wind speed play a critical role in regulating ambient air pollution levels (Bhasker and Mehta, 2010; Guttikunda, 2012). In the present investigation, meteorological conditions were found to exert a strong influence on pollutant concentrations. The associations between air pollutants and meteorological variables were evaluated using Pearson's correlation analysis (Table 3).

Average temperature exhibited a clear negative relationship with $PM_{2.5}$, PM_{10}, SO_2, and NO_2, with correlation coefficients of -0.63, -0.64, -0.37, and -0.57, respectively, indicating a general decline in pollutant concentrations with increasing temperature. Wind speed also showed negative correlations with $PM_{2.5}$, PM_{10}, SO_2, and NO_2 (r = -0.26, -0.17, -0.30, and -0.03, respectively), suggesting that enhanced air movement facilitates pollutant dispersion and reduces their accumulation in the atmosphere. Rainfall was similarly negatively correlated with both particulate and gaseous pollutants ($PM_{2.5}$: -0.36, PM_{10}: -0.42, SO_2: -0.22, NO_2: -0.43). Elevated pollutant levels were associated with dry conditions, whereas increased precipitation contributed to reduced concentrations through wet deposition processes. Notably, rainfall exhibited stronger correlations with most pollutants than wind speed, highlighting its greater effectiveness in pollutant removal during the study period.

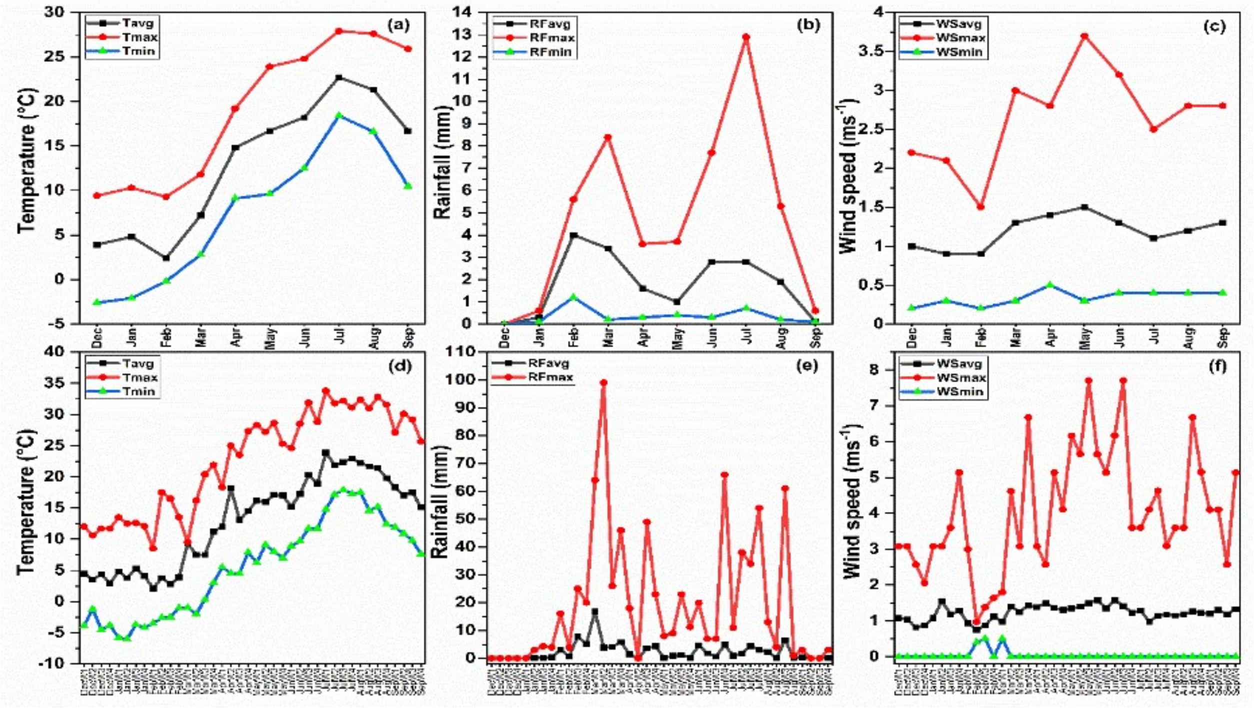

Fig. 5. Monthly (a-c) and weekly (d-f) average values of meteorological parameters from Dec -2014 to Sept -2015

Overall, the observed negative relationships of pollutants with temperature, rainfall, and wind speed resulted in comparatively lower concentrations during the summer season, largely due to precipitation driven washout effects (Sadiq and Qureshi, 2010; Tandon *et al.,* 2010). Conversely, winter conditions characterized by temperature inversions limited vertical mixing and hindered pollutant dispersion, leading to higher concentrations, while warmer conditions enhanced atmospheric mixing (Galindo *et al.,* 2011; Wang *et al.,* 2014). Increased wind speeds promoted turbulence and dispersion, further lowering pollutant levels (Vassilakos *et al.,* 2005; Galindo *et al.,* 2011; Alghamdi *et al.,* 2015; Kim *et al.,* 2009). In addition, the mountainous terrain of Srinagar constrains horizontal pollutant transport (Huma *et al.,* 2016), and the combined effects of low wind speeds, frequent temperature inversions, and orographic confinement further suppress dispersion (Berman *et al.,* 1995; Ellis *et al.,* 2000). The occurrence of winter fog additionally favours pollutant stagnation and secondary aerosol formation, exacerbating air quality deterioration during colder months (Biswas *et al.,* 2008).

Table 3 Correlation matrix between air pollutants and meteorological variables

	$PM_{2.5}$	**PM_{10}**	**SO_2**	**NO_2**	**Temp**	**WS**	**RF**
$PM_{2.5}$	1						
PM_{10}	.884**	1					
SO_2	.689**	.757**	1				
NO_2	.806**	.932**	.630**	1			
Temp	-.632**	-.646**	-0.374	-.574**	1		
WS	-0.26	-0.172	-0.303	-0.035	.406*	1	
RF	-0.361	-.426*	-0.229	-.437*	0.139	-0.074	1

$*p < 0.01$; $**p < 0.05$

Wind rose plots

Wind rose analysis (Fig. 6) reveals clear seasonal and annual patterns in wind direction and speed. During winter, the dominant wind direction was east-northeast (ENE), accounting for 18.6% of occurrences, followed by north-northeast (NNE) at 8.9% and northeast (NE) at 6.6%. Nearly half of the observed wind speeds (45.2%) were within the 1.0–2.0 m s^{-1} range, while calm conditions were pronounced, representing 36.57% of the total observations. In summer, the prevailing winds were primarily from the north-northeast (NNE) sector (14.5%), followed by east-northeast (ENE) (12.5%) and south-southwest (SSW) (4.2%). Calm conditions decreased to 29.61% compared to winter. Similar to winter, the most frequent wind speed class was 1.0–2.0 m s^{-1}, contributing about 50% of the observations.

On an annual scale, winds were predominantly from the east-northeast (ENE) direction (15.3%), followed by north-northeast (NNE) (12.4%) and south-southwest (SSW) (5.1%). Annual calm conditions accounted for 29.53% of the record, and the 1.0-2.0 m s^{-1} wind speed range remained dominant (48.8%). Overall, the city exhibited a persistent northeasterly wind regime across both seasons, with winter characterized by a higher frequency of calm conditions compared to summer. The northeasterly wind regime is likely to facilitate the movement of pollutants from the cement plants and brick kilns into the city. Coal and biomass burning constitutes the primary contributor to pollutant emissions in and around the Srinagar city (Bhat *et al.,* 2022; Hakim *et al.,* 2018).

Air quality index

The Air Quality Index in the present study was calculated using $PM_{2.5}$, PM_{10}, SO_2, and NO_2 as the input pollutants. Seasonal variations in AQI across Srinagar city during winter and summer are illustrated in Table 5 and Fig. 7. During the winter season, AQI values ranged from a minimum of 45 at SKIMS, Soura (sensitive area) to a maximum of 267 at Qamarwari (commercial area). In contrast, summer AQI values were substantially lower, varying from 27 at SKIMS, Soura to 83 at Lal Chowk, both representing the sensitive and commercial zones, respectively. Overall, the highest AQI values were consistently recorded in commercial areas, followed by industrial, residential, and sensitive zones. Zonal analysis showed that during winter, the highest mean AQI was observed in commercial areas (235), whereas the lowest was recorded in sensitive areas (71). A similar spatial pattern was evident in summer, with sensitive areas exhibiting the lowest AQI (32) and commercial areas showing the highest values (69). The seasonal average AQI values for different monitoring locations are presented in Fig. 7. Within commercial zones, Qamarwari registered the highest average AQI (161), while Khanyar recorded the lowest (132). In residential areas, the maximum average AQI was observed at Nigeen (88) and the minimum at Nishat (68). Industrial locations showed considerable variability, with BAMK, Nowshera recording the highest average AQI (145) and Zukura the lowest (77). Among sensitive sites, the Kashmir University campus exhibited the highest average AQI (77), whereas SKIMS, Soura showed the lowest value (36).

Based on the AQI classification, air quality in commercial areas was categorized as moderately polluted, while residential areas generally fell within the satisfactory category (Table 4). Sensitive areas ranged from good to satisfactory, whereas industrial zones varied between satisfactory and moderately polluted. Overall, the AQI status of Srinagar city remained within the satisfactory range. However, the relatively lower AQI values largely reflect the comparatively low concentrations of gaseous pollutants, which offset the influence of elevated particulate matter levels that would otherwise yield higher AQI values if considered independently.

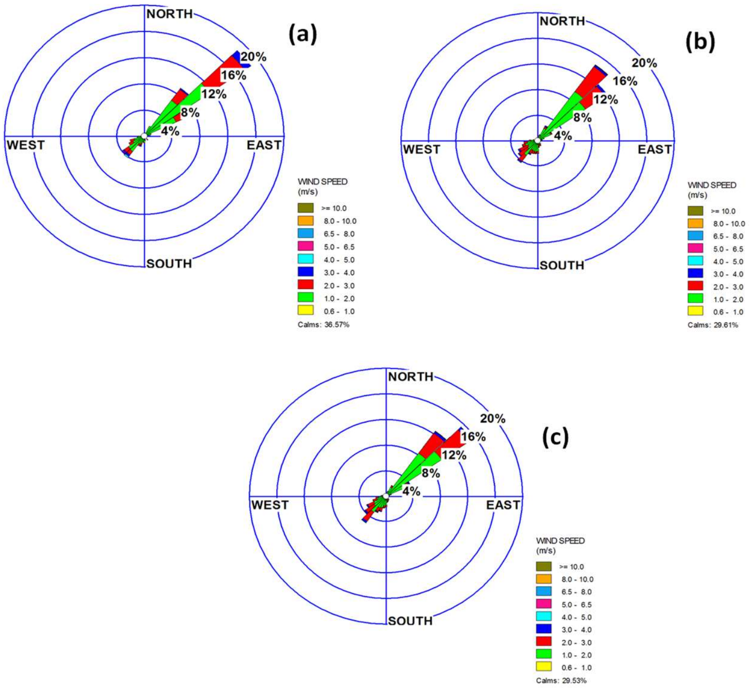

Fig. 6: Wind rose plots of Srinagar city for (a) winter, (b) summer and (c) annual

Table 4. IND-AQI category and range with colour code (CPCB, 2014-15)

AQI category	AQI range	Representing Colour
Good	0-50	🟩
Satisfactory	51-100	🟩
Moderately polluted	101-200	🟨
Poor	201-300	🟧
Very poor	301-400	🟥
Severe	401-500	🟥

Table 5. Average AQI at different sites of the Srinagar city during the study.

Site	Average AQI	AQI Category
C1	165	Moderately polluted
C2	160	Moderately polluted
C3	132	Moderately polluted
R1	83	Satisfactory
R2	88	Satisfactory
R3	68	Satisfactory
I1	77	Satisfactory
I2	145	Moderately polluted
I3	122	Moderately polluted
S1	42	Good
S2	77	Satisfactory
S3	36	Good

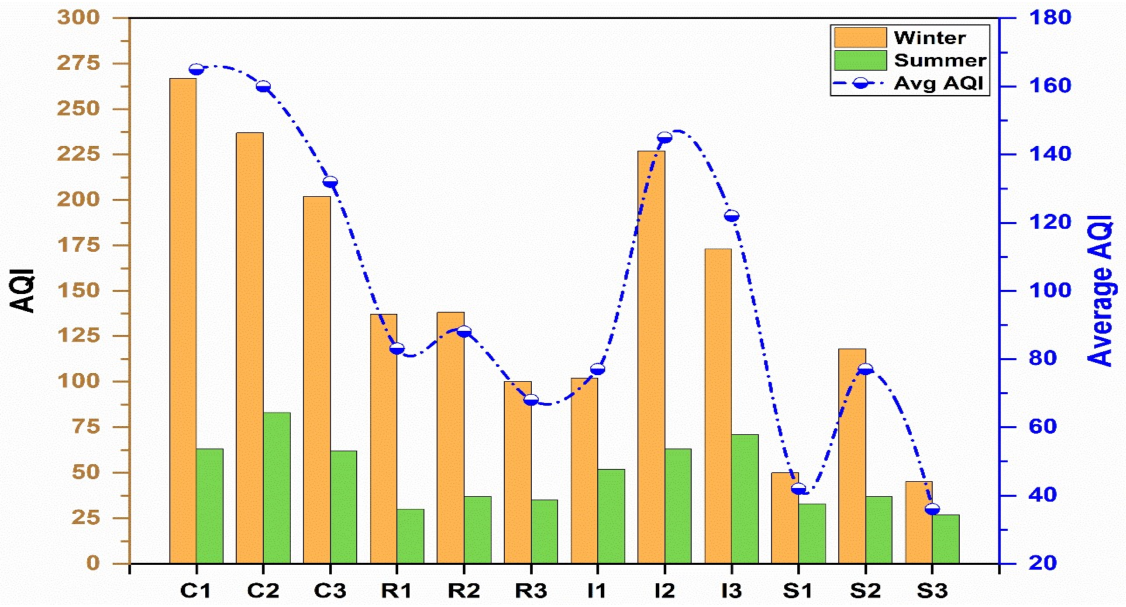

Fig. 7: AQI at different sites of Srinagar city during the study period

CONCLUSION

This study assessed ambient air quality in Srinagar city, Kashmir, from December 2014 to September 2015, focusing on $PM_{2.5}$, PM_{10}, SO_2, and NO_2 across four areas/zones: commercial, industrial, residential, and sensitive, with three monitoring sites in each zone. Sampling was performed using a Fine Particulate Sampler (Envirotech APM 550 MFC) and a High Volume Dust Sampler (Envirotech APM 460 DXNL). The results show that particulate matter was the dominant contributor to air pollution, with substantially higher concentrations during winter than summer. $PM_{2.5}$ levels ranged from 24 to 304 μgm^{-3}, with zonal mean concentrations between 61 and 159 μgm^{-3}, following the order commercial >industrial >residential > sensitive. Mean $PM_{2.5}$ concentrations in all zones exceeded NAAQS, India. PM_{10} concentrations varied from 40 to 542 μgm^{-3} and exhibited a similar spatial pattern, exceeding regulatory limits in commercial, industrial, and residential areas. In contrast, SO_2 (3-17 μgm^{-3}) and NO_2 (10-46 μgm^{-3}) remained well within prescribed standards despite showing comparable zonal trends.

Pollutant concentrations were negatively correlated with rainfall, temperature, and wind speed, underscoring the influence of meteorology on dispersion processes in the city. Air Quality Index analysis indicated good air quality during summer and poor conditions in winter, with average AQI values ranging from 52 in sensitive zones to 153 in commercial areas. Overall, Srinagar's air quality was generally satisfactory but showed a clear tendency toward moderate pollution, driven mainly by particulate emissions from biomass burning, vehicular traffic, and road dust. Further, continuous monitoring and source apportionment studies are required to quantitatively identify and distinguish the relative contributions of sources to ambient air pollution in Srinagar. Such studies would support targeted mitigation strategies and strengthen air quality management and policy decisions for the region.

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