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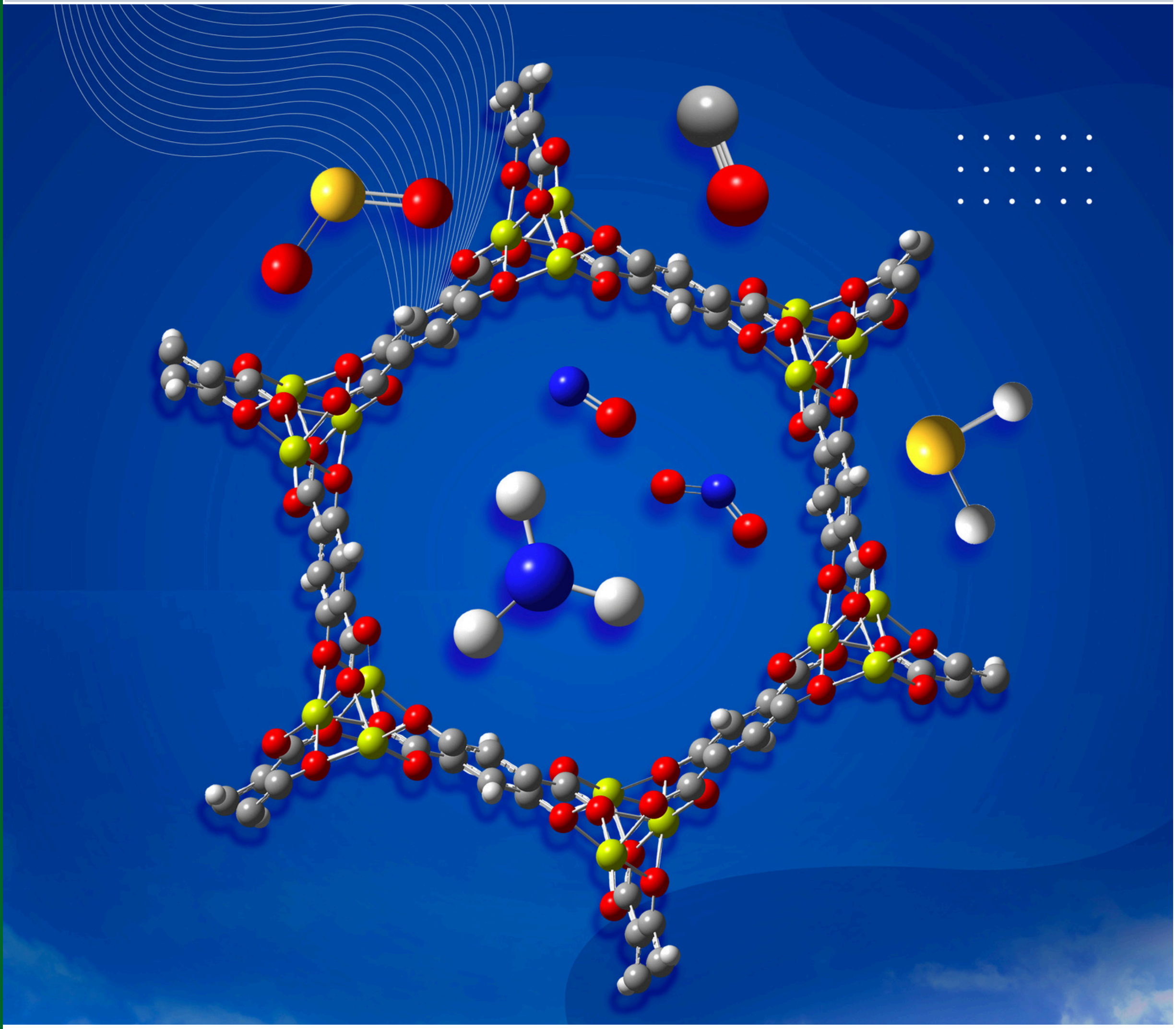

Department of Physics, Prithvi Narayan Campus, Pokhara
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Cover: Ball-and-stick model of selective separation of gases by Mg-MOF-74.
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Study and comparison of air pollution in three stations of Pokhara valley

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Abstract: In recent years, air pollution has become a pressing global challenge. Nepal is no exception, facing increasing air pollution as rapid urbanisation, a surge in vehicles, poor vehicle management, infrastructure development, and industrial growth have significantly degraded air quality across many cities. This review explores the escalating air pollution in Nepal by analysing recent trends in Pokhara Valley. Using available aerosol data from 2018 to 2020, this study provides a detailed assessment of air quality and its detrimental health impacts in Pokhara. The analysis draws on data from three monitoring stations to assess $PM_{2.5}$ and PM_{10} concentrations, evaluate compliance with air quality standards, and examine pollution distribution across the valley. In Pokhara, $PM_{2.5}$ over all three stations is found to be high during winter, especially during (January-February) when air quality exceeds (AQI>100) healthy levels. In contrast, the monthly average data for PM_{10} is seen (AQI<100) under safer limits despite some noticeable rise in winter seasons. Among these three stations, the DHM station recorded maximum and minimum Air quality index values of 243 in December 2019 and 11 in August and September 2018, respectively. The objectives include identifying key pollution sources and their impact on air quality and offering insights into the region's current state of air pollution. The findings of this study can play a crucial role in informing future planning and policy-making, offering data to help devise effective strategies to mitigate air pollution. These insights contribute to national and global efforts to improve air quality and reduce environmental pollution.

Keywords: Air pollution • $PM_{2.5}$ • PM_{10}

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I. Introduction

Air pollution is a critical global challenge, with the World Health Organization (WHO) estimating it contributes to approximately 7 million premature deaths annually. Nepal is not immune to these challenges. Kathmandu, once celebrated for its pristine environment and rich cultural heritage, is now ranked as one of the most polluted cities globally [1]. This stark transformation underscores a critical environmental crisis that poses serious risks to public health and economic development in the region.

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These alarming statistics highlight the urgent need for comprehensive policy interventions and global efforts to mitigate air pollution. The overexploitation of natural resources, driven by the pursuit of economic growth and development, has resulted in significant environmental degradation. This process often neglects ecological concerns, leading to escalating pollution from industries, factories, vehicular emissions, population growth, unchecked urbanization, power generation, and the extensive use of fossil fuels [2].

Understanding the causes and consequences of air pollution is crucial, as it directly impacts human health, economic productivity, and environmental sustainability. Many countries, including Nepal, are facing severe air quality challenges due to rapid urbanization, industrialization, and the uncontrolled exploitation of natural resources. Urban and industrial centers such as Kathmandu, Chitwan, and Pokhara are experiencing hazardous levels of air pollution, with far-reaching consequences for public health, economic stability, and the environment.

The primary objective of this study is to assess air quality in Pokhara Valley by evaluating compliance with established air quality standards, analyzing pollution distribution patterns, and identifying the key factors contributing to air quality degradation. This research also aims to compare current pollution levels with historical data to discern trends and understand the broader impact on the region. Through a thorough analysis of primary pollution sources, this study will examine their environmental effects and public health implications, contributing valuable insights for the formulation of future air quality management strategies. Air pollution in Nepal, particularly in urban areas, has reached critical levels. The Kathmandu Valley, recognized as one of Asia's fastest-growing metropolitan regions, ranks as the seventh most polluted city globally based on particulate matter (PM_{10} and $PM_{2.5}$) concentrations [3]. This severe pollution is driven by rapid population growth, unmanaged urbanization, and a substantial increase in vehicle numbers. Similarly, the Pokhara Valley is experiencing a significant rise in air pollution, primarily due to accelerated urbanization, industrial expansion, and increased vehicular emissions, all of which pose serious health risks and degrade the quality of life for residents. Air pollutants are substances in the air that can severely affect human health, other organisms, and ecosystems. They can be solid particles, liquid droplets, or gases and are categorized as either primary or secondary pollutants. Primary pollutants are emitted directly from sources such as factories and natural disasters, while secondary pollutants form in the atmosphere through reactions between primary pollutants [4].

Particulate Matter (PM): This includes a complex mixture of tiny particles and liquid droplets. It is often divided into two main groups:

- $PM_{2.5}$: Particles smaller than 2.5μm in diameter, primarily arising from combustion processes. They can penetrate deep into the lungs and enter the bloodstream, leading to serious health issues.
- PM_{10}: Particles between 2.5μm and 10μm in diameter, mainly from construction sites and poor-quality roads. They cause respiratory irritation and other health problems.

Other significant pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), lead (Pb), and carbon monoxide (CO), all contributing to cardiovascular and respiratory diseases [5]. Among these, $PM_{2.5}$ is particularly concerning due to its small size, which allows it to penetrate deep into the lungs, causing respiratory and cardiovascular diseases. Effective air pollution control measures are essential for protecting public health and the environment. Policies like the Clean Air Act have demonstrated that it is possible to reduce emissions significantly while maintaining economic growth, resulting in improved air quality and health outcomes for populations [6].

The Pokhara Valley, situated at an altitude of approximately 827 meters above sea level and located at a latitude of 28.2096° N and longitude of 83.9856° E, lies between the highly polluted Indo-Gangetic Plains to the south and the cleaner Himalayan-Tibetan regions to the north. This unique geographical setting exposes the valley to air pollutants transported from the IGP, adversely affecting the health of its vulnerable population, local ecosystems, and crop productivity [7]. Despite its environmental significance, this region remains under-researched, especially concerning aerosol properties and atmospheric observations. Moreover, vehicular emissions constitute a significant source of air pollution. Vehicle registrations increased from 34,199 in 2005 to 150,000 in 2018, driven by a rise in the number of automobiles, poor transport management, and inadequate vehicle maintenance [8]. Vehicles emit pollutants such as PM, volatile organic compounds (VOCs), NOx, CO, SO_2, and greenhouse gases. Diesel engines, in particular, are especially harmful due to their emission of fine particulate matter [9]. By 2013, the transportation sector was responsible for more than half of the CO and NOx emissions and about a quarter of hydrocarbon emissions [10]. Additionally, elevated CO2 levels, a major greenhouse gas, contribute to both global warming and ocean acidification [11].

Unplanned urbanization and the concentration of industrial activities within city areas further compromise Pokhara's air quality [12]. The valley's topography further exacerbates air pollution. Elevated Aerosol Optical Depth (AOD) during pre-monsoon months is linked to convective activity in the Indo-Gangetic Plain (IGP), which transports surface-level pollutants to higher altitudes and carries them northward toward the Himalayan foothills [13, 14].

Nepal's air quality has deteriorated significantly in recent years, placing the country among the lowest rankings globally. In 2016, Nepal ranked 177^{th} out of 180 countries on the Environmental Performance Index (EPI), and by 2020, it had dropped to the last position [10, 15]. Major urban centers such as Kathmandu, Chitwan, Biratnagar, Butwal, and Pokhara face severe air pollution challenges, primarily driven by vehicular emissions, industrial activities, and construction dust. Rapid urbanization has contributed to a sharp rise in both population and motor vehicle numbers, particularly in densely populated areas such as Kathmandu Valley, Pokhara Valley, and the Inner-Terai valleys [3]. In 2015/2016 alone, over 90,000 vehicles were added to the nation's roads, significantly worsening air pollution. Diesel emissions are of particular concern due to their toxic and carcinogenic properties [11].

Kathmandu Valley, Asia's fastest-growing metropolitan region, is among the most polluted cities in terms of particulate matter (PM_{10} and $PM_{2.5}$) concentrations [16]. Similarly, in Pokhara, poor transportation management, rapid urbanization, and ongoing construction activities have further exacerbated air quality deterioration. This decline is most evident in congested areas, along highways, and in tourist hotspots, adversely affecting the health and well-being of residents and workers alike.

The health impacts of this pollution are severe. WHO guidelines on $PM_{2.5}$ levels are consistently exceeded across the country, contributing to an estimated 33,500 pollution-related deaths annually in Nepal—surpassing even the death toll from the 2015 earthquake, according to a survey of WHO, Nepal Urban Health Profile, 2017. The economic consequences are equally troubling. If current trends persist, the World Bank predicts that the financial cost to Nepal could rise to between $136 million and $256 million by 2030, up from $130 million in 2015. These costs include healthcare expenditures, decreased labor productivity, and a decline in tourism revenue. In Pokhara, the Environmental Protection Agency (EPA) warns that without effective mitigation strategies, the prevalence of diseases such as cancer, heart disease, and respiratory conditions will continue to escalate.

Air pollution is not merely an environmental issue; it is a significant public health crisis. More than 80% of people living in urban areas with air quality monitoring are exposed to pollution levels that exceed WHO guidelines. This exposure is hazardous for vulnerable groups like children, the elderly, and people with pre-existing health conditions. Nepal's rapid urbanization and economic development have exacerbated air quality problems, requiring immediate, coordinated action from the government, civil society, and international organizations.

The central argument of this article is that air pollution in Nepal has reached a critical point, necessitating urgent intervention to safeguard public health and economic stability. To combat this, comprehensive policy measures are required, including stricter vehicle emission standards, the promotion of cleaner energy sources, improved urban planning, and the expansion of air quality monitoring networks. Public awareness campaigns and international cooperation are also vital in addressing this escalating issue.

Effective mitigation strategies must target the primary sources of air pollution, such as vehicular emissions, industrial activities, and construction dust. In addition, secondary pollutants need to be controlled through better management of chemical reactions in the atmosphere. A multi-faceted approach involving government regulations, technological innovations, and community engagement is essential to bring about meaningful change. Air pollution in Nepal is a growing threat with significant health, economic, and environmental implications. The deteriorating air quality in cities like Kathmandu and Pokhara serves as a stark reminder of the urgent need for action. Addressing this issue is crucial for protecting public health, promoting economic growth, and ensuring a sustainable future for all.

Air Quality Index (AQI)

The Air Quality Index (AQI) [17] measures daily air quality, indicating whether the air is clean or polluted and highlighting potential health effects. It covers five major pollutants: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. Ground-level ozone and airborne particles pose the most significant health risks. The AQI scale ranges from 0 to 500, with higher values indicating worse air quality and greater health risks. An AQI below 100 is considered satisfactory, while values above 100 can be harmful, especially to sensitive groups. The AQI is divided into six categories to help people understand how air quality affects their health.

Air Quality Index (AQI) values	Level of Health Concerns	Colors
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for sensitive groups	Orange
151 to 200	Unhealthy	Red
201 to 250	Very unhealthy	Purple
251 to 300	Hazardous	Maroon
301 to 500	Very Hazardous	Maroon

Figure 1. Air quality index values.

Each category corresponds to a different level of health concern. Risk evaluation is given based on the calculated data with a color scale. The problem of air pollution has become so important that timely information about differences in the air pollution levels in urban as well as rural areas is required.

II. Dataset and Methodology

In Nepal, there are currently 16 operational air quality monitoring stations, with three of these explicitly located in the Pokhara Valley, where the study was conducted at varying distances (Table 1). These stations, run by the Department of Hydrology and Meteorology (DHM), Pokhara University, and Gandaki Boarding School, are part of a national network aiming to monitor and manage air quality across various regions in the country. This monitoring network supports the efforts by Nepal's Ministry of Forests and Environment to provide real-time air quality data for effective environmental management and public awareness. The study was conducted at three Pokhara Valley sites—Pokhara University, DHM station, and Gandaki Boarding School—all located away from urban areas Fig. 2.

Table 1. Study areas' location, latitude and longitude.

Station	Location	Latitude	Longitude
1	Gandaki Boarding School (GBS)	28.2580° N	83.9680° E
2	Department of Hydrology and Meteorology (DHM)	28.2058° N	83.9736° E
3	Pokhara University (PU)	28.1431° N	84.0855° E

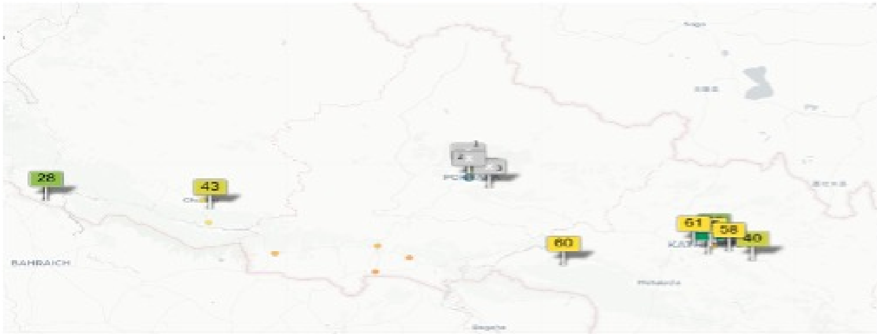

Figure 2. Map of study area, Pokhara.

Instrumentation & Method of Data Collection

Each monitoring station in the study used the Grimm Electronic Dust Monitor (EDM) 180 (Fig. 3) to measure particulate matter (PM_{10} and $PM_{2.5}$) using light-scattering technology. The GRIMM EDM 180 is a stationary ambient dust monitor that simultaneously measures PM_{10}, $PM_{2.5}$, and PM1 using advanced laser light scattering technology. It features an integrated data logger for remote access, includes environmental sensors for temperature and humidity, and is designed for low maintenance.

Figure 3. Grimm 180 ambient dust monitor.

The stations provide real-time data, which is downloaded daily from the official website [18] for analysis. Monthly averages were calculated from days with complete data, though data collection was challenging due to server issues, maintenance, and technical problems. The study relied on the available data, which was continuously recorded and transmitted to a server at the National Information Technology Center (NITC). Data from the Department of Transport Management (DoTM) was also used to assess vehicular impact on air quality [19]. This monitoring is crucial for planning future strategies to control air pollution. Data was directly collected from the government website [18], and relevant reviews were conducted for assessment.

III. Result and Discussions

Air Quality

A comparative analysis of available air quality data from three monitoring stations in Pokhara Valley—Pokhara University, Gandaki Boarding School (GBS), and the Department of Hydrology and Meteorology (DHM)—reveals distinct seasonal and spatial patterns in PM2.5 and PM10 concentrations (Fig. 4). The AERONET site does not have complete data, so our study is limited to the currently accessible data.

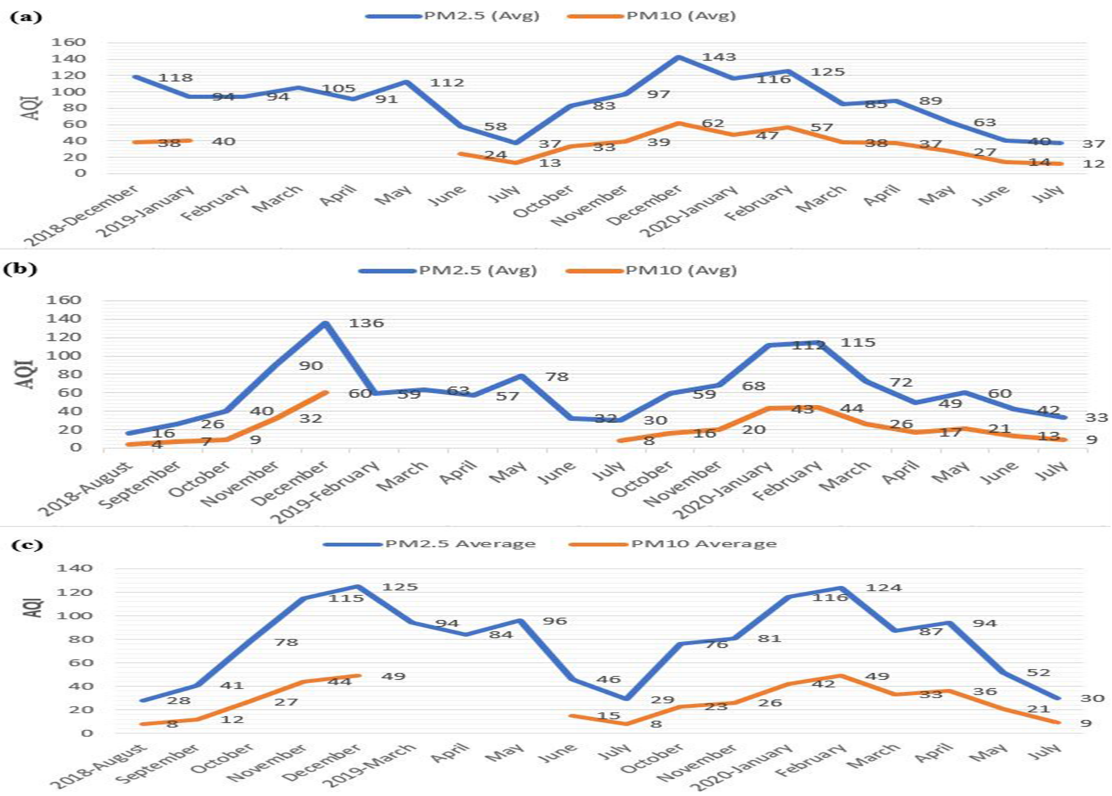

Figure 4. Average AQI at (a) DHM, (b) GBS, and (c) PU stations of Pokhara

Data from the DHM station (Table 2) indicated monthly average $PM_{2.5}$ levels ranging from 37 to 143 µg/m$^{\mathbf{3}}$. The highest concentration was 168 μg/m^{3}in February 2020, considered unhealthy by international standards. The lowest concentration of 15 μg/m^{3}was recorded in June and July 2020, indicating very good air quality. Similar to the other stations, PM_{10} levels at DHM were generally within safe limits, although concentrations rose noticeably during the winter months.

Table 2. Monthly AQI data of DHM station.

Month	$PM_{2.5}$			PM_{10}		
	Avg	Max	Min	Avg	Max	Min
2018-December	118	150	58	38	59	24
2019-January	94	150	58	40	-	-
February	94	150	58	-		-
March	105	155	61	-	-	-
April	91	146	54	-	-	-
May	112	154	76	-	-	-
June	58	83	31	24	40	11
July	37	76	21	13	35	8
October	83	109	20	33	44	6
November	97	112	84	39	45	29
December	143	165	124	62	80	52
2020-January	116	165	29	47	76	12
February	125	168	53	57	84	18
March	85	119	62	38	57	26
April	89	158	37	37	75	12
May	63	89	33	27	42	14
June	40	71	15	14	28	5
July	37	61	15	12	24	4

The GBS station's data (Table 3) for 2018 reflected similar seasonal variations, with $PM_{2.5}$ concentrations ranging from 16 μg/m^{3}in August to 136 μg/m^{3}in December. The highest $PM_{2.5}$ level recorded at this station was 245 μg/m^{3}in December 2018, significantly exceeding national air quality standards. However, the station recorded its lowest $PM_{2.5}$ value of 11 μg/m^3 in August, highlighting the seasonal variability. PM_{10} levels at the GBS station remained within safe limits, likely due to its location in a less densely populated area, resulting in lower pollution levels compared to more urbanised stations.

At the Pokhara University station (Table 4) , PM2.5 levels varied significantly, ranging from a low of 28 µg/m$^{\mathbf{3}}$ in August to a high of 125 µg/m$^{\mathbf{3}}$ in December 2018. The highest PM2.5 concentration recorded was 176 µg/m$^{\mathbf{3}}$ in April 2020, while the lowest was 15 µg/m$^{\mathbf{3}}$ in July 2020. PM10 levels at this station remained within moderate and generally safe limits, although air quality showed notable deterioration during winter.

Overall, air quality data from all three stations demonstrate a consistent decline during the winter months, with significant increases in both $PM_{2.5}$ and PM_{10} concentrations. The Pokhara University and DHM stations displayed pronounced deterioration during this period. In contrast, the GBS station, while recording high $PM_{2.5}$ levels, generally maintained safer PM_{10} concentrations due to its geographical location and lower urbanization.

Table 3. Monthly AQI data of GBS station.

Month	$PM_{2.5}$			PM_{10}		
	Avg	Max	Min	Avg	Max	Min
2018-August	16	26	11	4	6	2
September	26	62	11	7	23	3
October	40	57	20	9	14	6
November	90	163	36	32	67	8
December	136	245	100	60	124	37
2019-February	59	102	33	-	-	-
March	63	113	31	-	-	-
April	57	83	31	-	-	-
May	78	117	49	-	-	-
June	32	55	12	-	-	-
July	30	41	12	8	14	3
October	59	80	55	16	25	4
November	68	78	56	20	25	15
2020-January	112	114	75	43	61	22
February	115	159	52	44	66	13
March	72	103	43	26	42	11
April	49	51	47	17	18	16
May	60	88	32	21	42	11
June	42	72	15	13	26	4
July	33	51	16	9	16	4

This seasonal variability in air pollution can be attributed to several key factors. During the winter months, haze, reduced precipitation, dust particles, biomass burning from rural areas, and transboundary pollution from the Indo-Gangetic Plain (IGP) significantly contribute to elevated aerosol concentrations. The lack of rainfall during the winter allows aerosols to remain suspended in the atmosphere for extended periods, leading to higher pollution levels. Conversely, during the monsoon season, increased rainfall effectively removes aerosols from the atmosphere, leading to improved air quality. Previous studies also support the correlation between higher Aerosol Optical Depth (AOD) values from pre-monsoon to post-monsoon seasons and the accumulation of aerosols from biomass burning and IGP pollution, further degrading air quality in the Pokhara Valley.

Given the significant impact of transboundary pollution and local emissions, this study underscores the need for further analysis of aerosol optical properties using multi-year aerosol data. Additionally, conducting back trajectory analysis of air masses will be crucial for identifying the sources of transboundary aerosols and understanding their contribution to air pollution in the Pokhara Valley.

Table 4. Monthly AQI data of PU station.

Month	$PM_{2.5}$			PM_{10}		
	Avg	Max	Min	Avg	Max	Min
2018-August	28	41	20	8	12	6
September	41	62	21	12	22	6
October	78	116	46	27	40	11
November	115	163	77	44	67	27
December	125	163	100	49	69	37
2019-March	94	147	57	-	-	-
April	84	141	53	-	-	-
May	96	142	62	-	-	-
June	46	70	26	15	25	7
July	29	67	15	8	22	5
October	76	80	64	23	27	19
November	81	101	62	26	34	16
2020-January	116	163	80	42	60	24
February	124	165	61	49	74	18
March	87	119	55	33	48	18
April	94	176	41	36	80	16
May	52	55	37	21	42	11
July	30	39	15	9	13	4

Seasonal variation in particulate matter concentrations

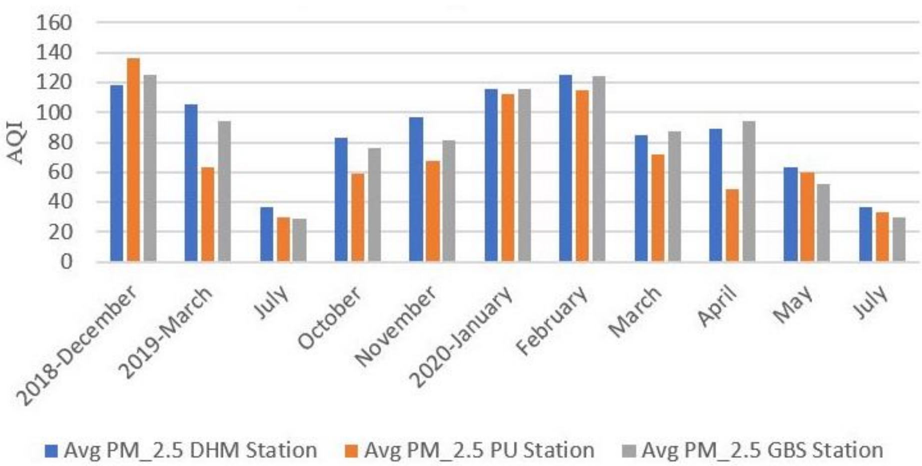

Figure 5. Analysis of $PM_{2.5}$ in 3 stations of Pokhara.

The data analysis reveals a distinct seasonal pattern in particulate matter ($PM_{2.5}$ and PM_{10}) (Fig. 5 & 6) concentrations across the Pokhara Valley. These concentrations begin to rise with the onset of the monsoon season (June/July), peak during the winter months (November to February), and gradually decrease as summer approaches. This seasonal variability is primarily driven by changes in meteorological conditions, local emission sources, and atmospheric dynamics.

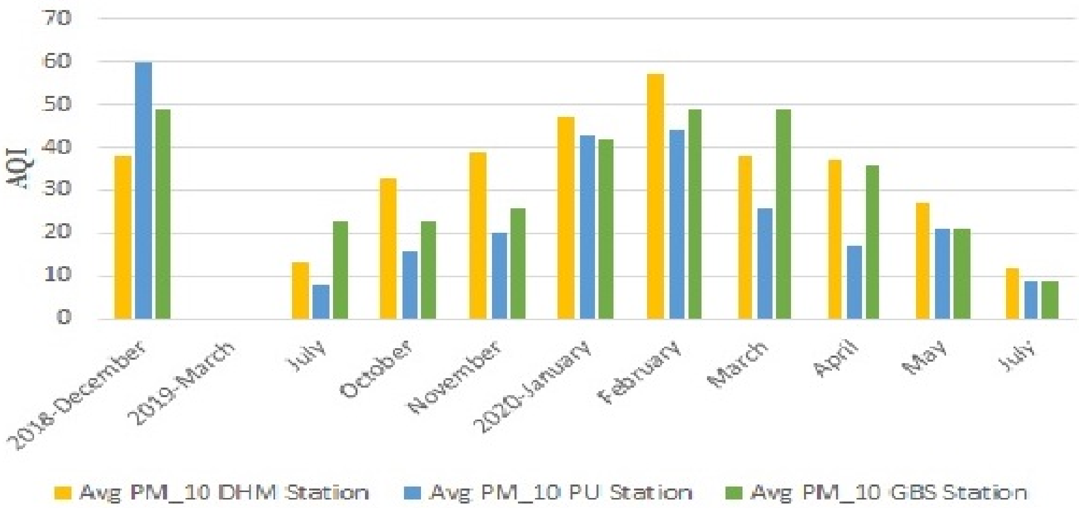

Figure 6. Analysis of PM_{10} in 3 stations of Pokhara.

Among the three monitored stations, the highest levels of particulate matter are consistently recorded within the urbanized areas of the valley, where vehicular traffic, industrial activities, and construction projects are concentrated. The Pokhara University station, situated near major highways and high-traffic zones, consistently reports elevated levels of $PM_{2.5}$ and PM_{10} compared to the GBS station, which is located in the less populated Lamachaur area. The GBS station's location results in lower pollution levels, reflecting the reduced influence of vehicular and industrial emissions. Seasonal variations significantly influence air quality, with monsoon rains helping to reduce particulate concentrations, while the winter months, with minimal rainfall, see a marked deterioration in air quality. The concentration of PM_{10} and $PM_{2.5}$ tends to be higher in Nepal during winter due to a combination of environmental and anthropogenic factors. Both types of factors play a crucial role in reducing air quality during this season. The dry climate and lack of rainfall increase anthropogenic activities like construction and biomass burning. Additionally, cooler temperatures lead to higher emissions of fine and coarse particulates from vehicle exhausts, especially from older, poorly maintained vehicles. Environmental factors such as decreased wind speeds, the region's natural topography, low winter precipitation, and temperature inversion—where a warm air layer traps cooler air below, preventing pollutants from dispersing—further exacerbate the accumulation of PM_{10} and $PM_{2.5}$, resulting in poorer air quality during winter.

IV. Conclusion

The data collected from three monitoring stations across Pokhara Valley reveal a critical insight: air pollution is notably severe in urbanized areas and along major highways, with consistently higher concentrations of $PM_{2.5}$ compared to PM_{10}. This predominance of fine-mode aerosols highlights a pollution profile driven largely by vehicular emissions, rapid urbanization, industrial activities, and poor vehicle maintenance. Such fine particulates ($PM_{2.5}$) pose elevated health risks as they penetrate deep into the respiratory system and bloodstream, contributing to cardiovascular and respiratory illnesses. Meteorological factors significantly impact air quality in Pokhara. During the monsoon season, high precipitation levels help cleanse the atmosphere by sweeping out airborne particulates, improving air quality. In contrast, the dry winter season, characterized by minimal rainfall, shows a substantial rise in aerosol concentrations. Data trends indicate that air quality deteriorates to near-unhealthy levels during winter, frequently surpassing both national and international standards, including those set by the WHO. Further analysis across the three stations shows pronounced pollution in urban and highway areas, particularly at the DHM (central urban) and PU (highway) stations, in contrast to nearby valleys (GBS station). This difference underscores the influence of high traffic density and industrial presence in urban zones, which generate primary pollutants such as PM1, TSP, $PM_{2.5}$, PM_{10}, SO_2, CO, CO_2, and NO_x. These pollutants not only degrade air quality but also contribute to the formation of secondary pollutants, exacerbating the pollution problem within the valley. These findings underscore an urgent need for targeted mitigation efforts focused on high-traffic and industrial zones to safeguard public health in Pokhara Valley. Addressing seasonal variations in pollution levels requires immediate policy interventions, enhanced public awareness, and stronger regulatory measures. Without swift action, air quality is likely to deteriorate further, posing long-term health risks to residents. Comprehensive mitigation strategies, especially during peak pollution seasons, will be crucial in promoting cleaner air and ensuring the well-being of the community.

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