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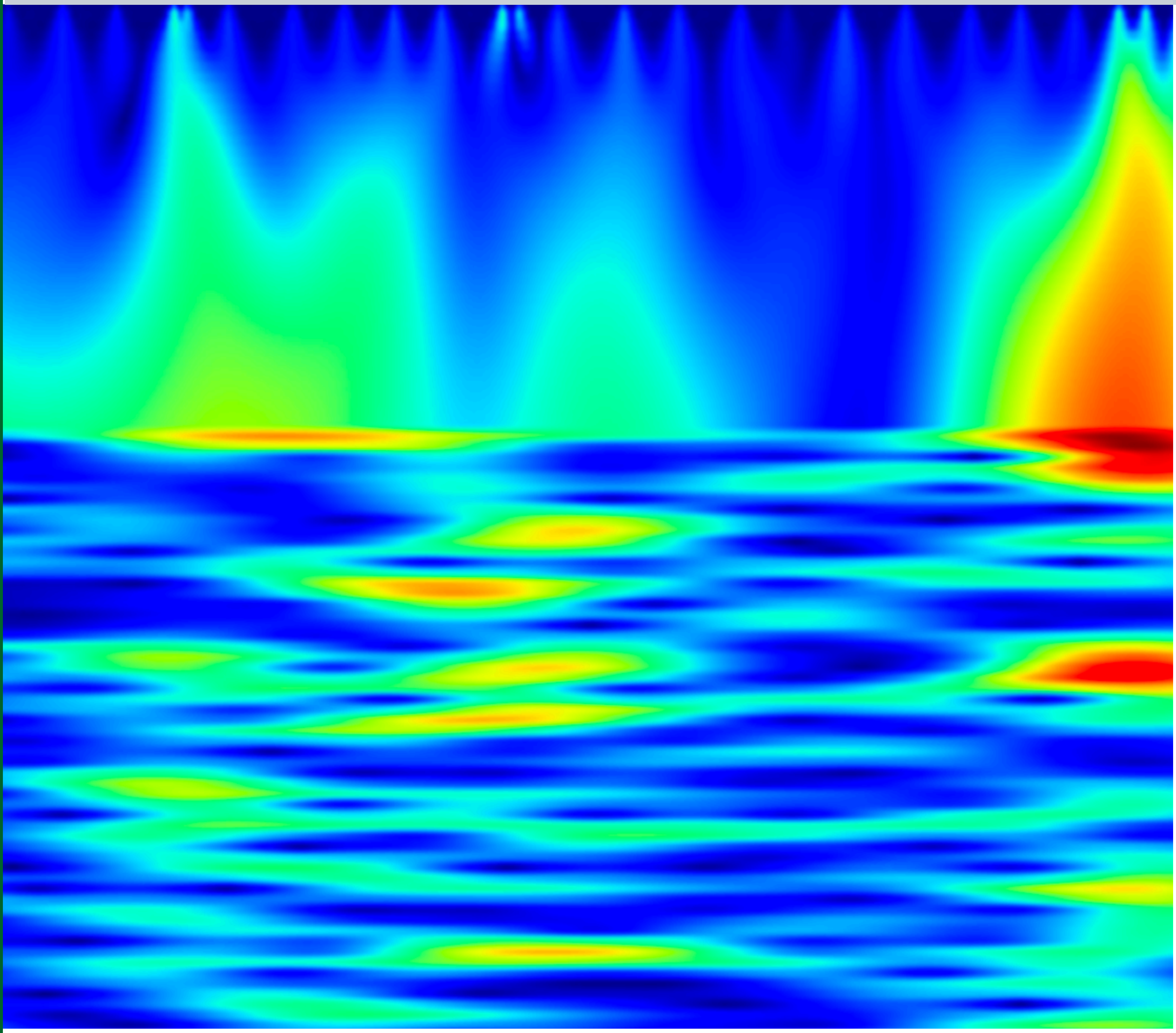

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Cover: Wavelet time–frequency representation for the NEAR condition. The figure shows stronger low-frequency activity over time, suggesting greater mental effort and engagement when surrounding stimuli are close to the target. (Figure 3(a), Himalayan Physics 12, 1-14, (2025))

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Himalayan Physics

Seasonal variation of $PM_{2.5}$ and PM_{10} in urban and remote regions of Nepal

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Abstract: Air pollution is a serious environmental problem that affects the health of people, animals, and the natural environment. It is mainly caused by human activities such as vehicle emissions, industrial work, waste burning, and construction dust. Breathing polluted air can lead to asthma, lung problems, heart disease, and other serious health issues. In cities like Kathmandu, air pollution is increasing due to rapid urban growth and traffic, while remote areas often have cleaner air. This study compares air quality between an urban site (Ratnapark, Kathmandu) and a remote site (Rara Lake, Mugu) in Nepal using $PM_{2.5}$ and PM_{10} measurements for 2023. Ratnapark exhibited much higher pollution, with peak $PM_{2.5}$ of 97.97 $\mu g/m^3$ and PM_{10} of 137.33 $\mu g/m^3$ in February, while Rara Lake remained relatively clean, with most $PM_{2.5}$ and PM_{10} values below 20 $\mu g/m^3$. The lowest pollution at both sites occurred during the rainy season. The $PM_{2.5}/PM_{10}$ ratio analysis revealed that finer particles were more dominant at the urban site, whereas coarser particles prevailed in the remote area. These results highlight the significant contrast in air quality between urban and remote regions and the influence of seasonal weather and human activities on pollution levels.

Keywords: Air pollution • Air quality index • $PM_{2.5}$ • PM_{10} • Nepal

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I. Introduction

Air pollution is a serious environmental issue that humans face worldwide, especially in rapidly growing urban areas of developing countries. This problem is mainly caused by increasing population, urbanization, industrialization, and rising vehicle use [1]. According to the World Health Organization (WHO), around seven million people die each year due to air pollution-related diseases, and 9 out of 10 people globally breathe air that contains high levels of harmful pollutants [2]. Ambient air pollution is

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responsible for an estimated 4.2 million deaths annually due to health problems such as stroke, heart disease, lung cancer, and chronic respiratory conditions [3].

Continuous air quality monitoring is essential to understanding and controlling air pollution. Many countries have started air monitoring programs that record the concentration of pollutants such as Suspended Particulate Matter (SPM), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulfur Dioxide (SO_2), and others [2]. According to the 2024 EPI report, Nepal ranked 165^{th} out of 180 countries, scoring 33.1, among the lowest-performing nations globally in terms of Environmental Performance Index [4]. Nepal's low Environmental Performance Index (EPI) score reflects its poor environmental performance. Kathmandu, the capital city, is one of the most polluted cities in South Asia due to high population density (32,978 people per km^2), a growing number of vehicles, road construction, brick kilns, and poorly managed urban infrastructure [5]. For example, according to the Department of Transport Management, Nepal, 203,552 new vehicles were registered in 2024. Many of these and many older and diesel-powered vehicles already on the roads contribute significantly to the country's worsening air pollution [6].

The Air Quality Index (AQI) is a numerical scale designed to describe the level of air pollution and its potential impact on human health. It simplifies complex air pollution data into a single value that indicates whether the air is clean or harmful to breathe. The AQI is essential because it focuses on short-term health effects, often experienced within hours or days of exposure to poor air quality [7]. According to the U.S. Environmental Protection Agency (EPA), the key pollutants used in calculating AQI include ground-level ozone (O_3), particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2).

AQI values are categorized into six levels based on the potential health effects:

- Good (0–50): Air quality is considered satisfactory, and air pollution poses little or no risk to health.
- Moderate (51–100): Air quality is acceptable; however, there may be a concern for some people who are unusually sensitive to air pollution.
- Unhealthy for Sensitive Groups (101–150): People with lung or heart diseases, older adults, and children are more likely to be affected.
- Unhealthy (151–200): Everyone may begin to experience health effects, while sensitive groups may experience more serious effects.
- Very Unhealthy (201–300): This level triggers health alerts. Serious health effects may affect the entire population.
- Hazardous (301 and above): This represents emergency conditions. The air is very dangerous, and serious health effects are likely for everyone [8, 9].

Among all air pollutants, particulate matter (PM) is considered especially dangerous due to its ability to penetrate deep into the respiratory system. PM consists of a complex mixture of tiny solid particles and liquid droplets suspended in the air [10]. These particles can react with other atmospheric substances and vary in size and origin. PM is usually classified into two main categories:

- Fine particles ($PM_{2.5}$): Particles with diameters less than or equal to 2.5 micrometers. Because of their small size can be inhaled deeply into the lungs and even enter the bloodstream. Familiar sources include vehicle exhaust, power plants, residential burning, forest fires, and industrial processes.

- Coarse particles (PM_{10}): These particles range in size from 2.5 to 10 micrometers and are often generated by mechanical processes like construction, mining, agricultural activities, road dust, and crushing operations [3, 11].

Earlier studies have shown that air quality in Kathmandu is poor, especially during the winter and spring seasons [12, 13]. Karki et al. found that NO_2, CO, and $PM_{2.5}$ concentrations were highest in winter and lowest during the rainy season [14]. Also, Kharel et al. reported that in Kathmandu Valley, mean TVOC and formaldehyde (HCHO) levels in high-risk indoor workplaces ranged from 1.5–8 mg/m^3 and <0.01–5.5 mg/m^3, respectively, with indoor-to-outdoor (I/O) ratios often exceeding 1.5 [15]. Shrestha et al. noted that vehicular emissions, particularly from in-use diesel vehicles with prolonged service life, were Kathmandu's dominant source of urban air pollution [16]. Likewise, Gurung and Bell highlighted a steady rise in ambient air pollution, with PM_{10} levels frequently surpassing national and WHO standards in major urban areas [17].

Most of these studies focus on urban and industrial regions. However, few studies have compared air quality between Nepal's urban and remote natural areas. Therefore, in this study, we analyze and compare the AQI of $PM_{2.5}$ and PM_{10} in Ratnapark (Kathmandu) and Rara Lake (Mugu), using data from 2023. This comparison helps us understand the differences in pollution levels and seasonal trends between an urban center and a clean, remote region. The results can support future policies and actions to control air pollution and protect public health.

II. Methodology

Data source, equipment, and parameters

The data used in this study were obtained from the Government of Nepal, Department of Environment website (http://doenv.gov.np/). The ministry operates 11 air quality monitoring stations nationwide, each with the Grimm Electronic Dust Monitoring (EDM 180) device. This instrument employs semiconductor laser-based light-scattering technology to detect and count airborne particulate matter in real time. It can simultaneously measure PM_{10} and $PM_{2.5}$ while also providing particle number concentrations across 31 size channels [18]. The system is fully automated and energy-efficient, requiring no consumables or radioactive sources, which makes it highly cost-effective and safe for long-term operation. Certified by US-EPA, UK-MCERTS, and CN-CMA, and recognized as equivalent in over 20 countries, it ensures reliable and comparable data for regulatory and scientific applications. Advanced features such as purge air to protect the laser and detector, built-in temperature and humidity sensors, and self-testing optical and pneumatic components guarantee consistent accuracy even under challenging environmental conditions. In addition, the instrument supports remote data access and GSM-based communication, enabling seamless integration into national and regional air quality monitoring networks. Its robust design, insensitivity to vibrations, and high reproducibility at low and high dust concentrations make it suitable for fixed stations and mobile monitoring platforms [19, 20]. It measures particle concentration directly in counts per liter and estimates mass concentrations through extrapolation.

Figure 1. Study area map showing air quality monitoring sites at Ratnapark (Kathmandu) and Rara Lake (Mugu).

The study specifically focused on two particulate pollutants:

- $PM_{2.5}$ (particles smaller than 2.5 micrometers) can penetrate the lungs deeply.
- PM_{10} (particles smaller than 10 micrometers) also poses health risks.

Data were recorded on the 28th day of each month throughout 2023. This study centers on two contrasting locations in Nepal (Fig. 1):

- Ratnapark, Kathmandu (27.7061° N, 85.3148° E; elevation 1324 m)
- Rara Lake, Mugu (29.5239° N, 82.0788° E; elevation 2975 m)

The primary objective was to compare the Air Quality Index (AQI) between these two sites using the $PM_{2.5}$ and PM_{10} values recorded on the 28^{th} of each month in 2023. The analysis aimed to identify which site had more favorable air quality and to observe how pollutant levels varied throughout the year.

Table 1. Monthly $PM_{2.5}$ and PM_{10} concentrations on the 28^{th} day of each month in 2023 for Ratnapark, Kathmandu, and Rara Lake, Mugu.

Date (2023)	Ratnapark, Kathmandu		Rara Lake, Mugu	
	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)	PM_{10}(μg/m^3)
Jan 28	35.9917	49.7792	4.3732	4.6619
Feb 28	97.9708	137.325	12.0742	16.2583
Mar 28	63.0917	91.3667	5.5843	7.8638
Apr 28	86.5667	118.9208	17.0934	21.9179
May 28	28.0458	37.625	13.4505	18.4334
Jun 28	11.0750	15.1083	6.3009	7.6278
Jul 28	13.3458	15.0333	4.6328	5.6596
Aug 28	12.1833	14.2083	14.8108	19.9538
Sep 28	16.3875	18.9500	6.2025	7.5861
Oct 28	11.4333	11.8333	7.5169	9.4501
Nov 28	28.8417	30.3250	4.7341	8.9692
Dec 28	63.10	115.4375	7.88069	12.2105

III. Results and Discussion

The data for $PM_{2.5}$ and PM_{10} concentrations at Ratnapark throughout 2023 show distinct monthly variations with notable trends (Fig. 2). Both $PM_{2.5}$ and PM_{10} levels are relatively low during the summer months of June, July, and August, with concentrations generally below 20 μg/m^3, reflecting the cleansing effect of monsoon rains. The highest pollution peaks occur in February, where $PM_{2.5}$ reaches around 98 μg/m^3 and PM_{10} peaks near 137 μg/m^3, likely due to wintertime temperature inversions and increased emissions from heating and vehicular activities. Elevated concentrations are also observed in March and April, with $PM_{2.5}$ around 63–87 μg/m^3 and PM_{10} near 91–119 μg/m^3, indicating ongoing pollution before the monsoon onset. After May, particulate levels drop sharply but rise again in November and December, with December showing a notable increase—$PM_{2.5}$ at approximately 63 μg/m^3 and PM_{10} at 116 μg/m^3-suggesting seasonal factors like biomass burning and colder weather contribute to pollution buildup. The

$PM_{2.5}$ at Ratnapark is 39.0 ± 31.0 $\mu g/m^3$, and for PM_{10} it is 54.7 ± 47.5 $\mu g/m^3$, reflecting substantial monthly variability. The $PM_{2.5}/PM_{10}$ ratio ranges from 0.547 to 0.966 (mean 0.78 ± 0.12), indicating a high proportion of fine particulate pollution typical of urban combustion sources. Furthermore, $PM_{2.5}$ and PM_{10} concentrations are strongly correlated (r = 0.98), showing that increases in fine particles are closely associated with rises in coarser particulate matter. Overall, these results demonstrate that particulate pollution at Ratnapark is strongly influenced by seasonal meteorology and human activities, with low levels during the monsoon and pronounced peaks during dry, cold periods.

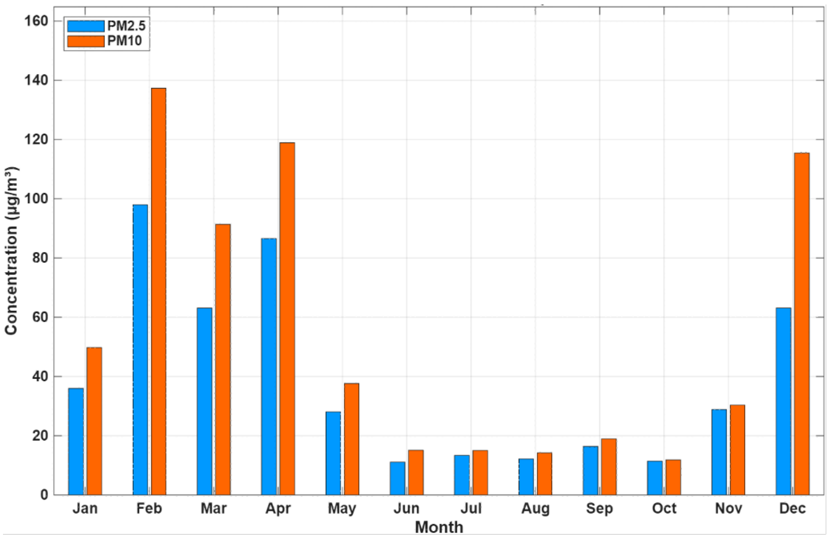

Figure 2. Particulate concentration ($PM_{2.5}$ and PM_{10}) vs month at Ratnapark, Kathmandu.

Fig. 3 shows the monthly variation of two types of particulate matter—$PM_{2.5}$ and PM_{10}—at Rara Lake, Mugu. It illustrates that PM_{10} concentrations are consistently higher than $PM_{2.5}$ throughout the year. The highest levels of both pollutants are observed in April and August, with PM_{10} peaking around 22 $\mu g/m^3$ and 20 $\mu g/m^3$, respectively. The lowest concentrations occur in January and July, where $PM_{2.5}$ and PM_{10} remain below 6 $\mu g/m^3$. Overall, $PM_{2.5}$ at Rara Lake is 8.7 ± 4.4 $\mu g/m^3$, and for PM_{10} it is 11.7 ± 5.9 $\mu g/m^3$, indicating generally low particulate pollution with moderate monthly variability. $PM_{2.5}$ and PM_{10} concentrations are strongly correlated (r = 0.98), demonstrating that increases in fine particulate matter are closely associated with rises in coarser particles. Independent t-tests comparing Ratnapark with Rara Lake confirmed that the differences in both $PM_{2.5}$ (t = 3.35, p = 0.0029) and PM_{10} (t = 3.11, p = 0.0051) were statistically significant. This indicates that the elevated particulate levels observed in Kathmandu are real and not due to random variation. Overall, these results highlight the significant impact of urban activities and seasonal meteorology on air quality, with Ratnapark experiencing much higher pollution levels and greater health risks compared to the relatively clean environment of Rara Lake. This pattern suggests that particulate pollution varies seasonally, with higher levels in spring and late summer, possibly due to environmental or human factors.

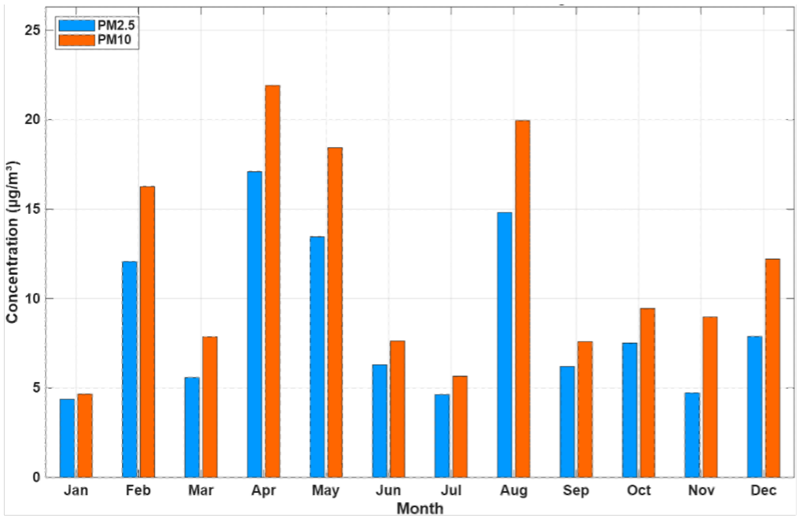

Figure 3. Particulate concentration ($PM_{2.5}$ and PM_{10}) vs month at Rara Lake, Mugu.

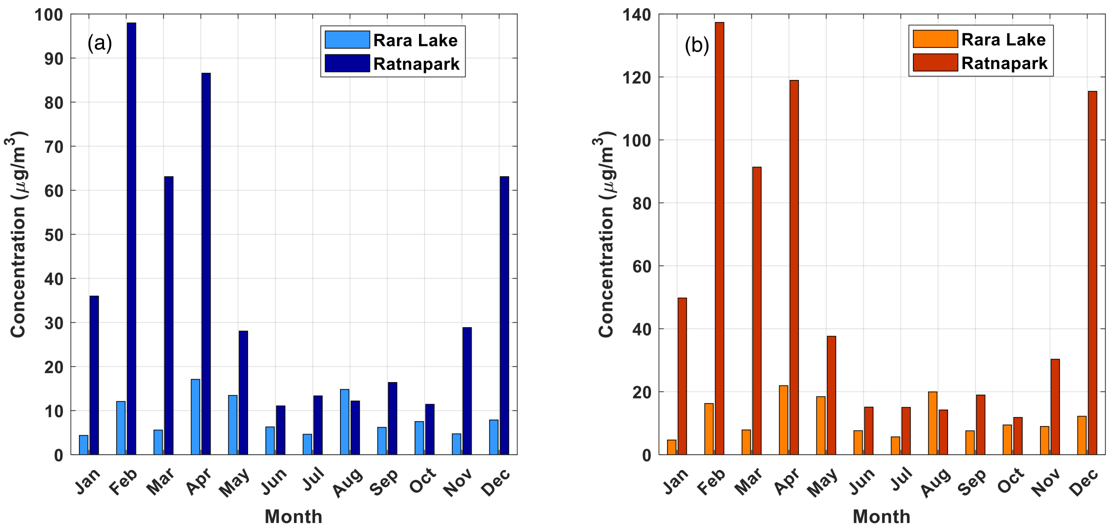

Figure 4. Comparison of particulate concentration (a) $PM_{2.5}$ and (b) PM_{10} at Rara Lake, Mugu, and Ratnapark, Kathmandu.

The comparison of $PM_{2.5}$ and PM_{10} concentrations between Ratnapark in Kathmandu and the remote Rara Lake in Mugu throughout 2023 reveals clear differences alongside some shared seasonal trends. Both locations show increased particulate levels in the early months (January to April) and late year (November to December), with a noticeable dip during the monsoon months of June and July due to rainfall reducing airborne particles. However, Ratnapark consistently experiences much higher pollutant levels, $PM_{2.5}$ peaks at approximately 98 $\mu g/m^3$ in February, and PM_{10} reaches around 137 $\mu g/m^3$—compared to Rara Lake's much lower peaks of about 12 $\mu g/m^3$ for $PM_{2.5}$ and 16 $\mu g/m^3$ for PM_{10} in the same period. Meanwhile, Rara Lake maintains a low and stable pollution baseline typical of clean mountainous regions. Fig. 4 shows these trends and the magnitude differences between the two sites. These patterns highlight the significant impact of urban activities and seasonal weather on air quality, with Ratnapark's elevated PM levels posing greater health risks. In contrast, Rara Lake benefits from its remote, less polluted environment.

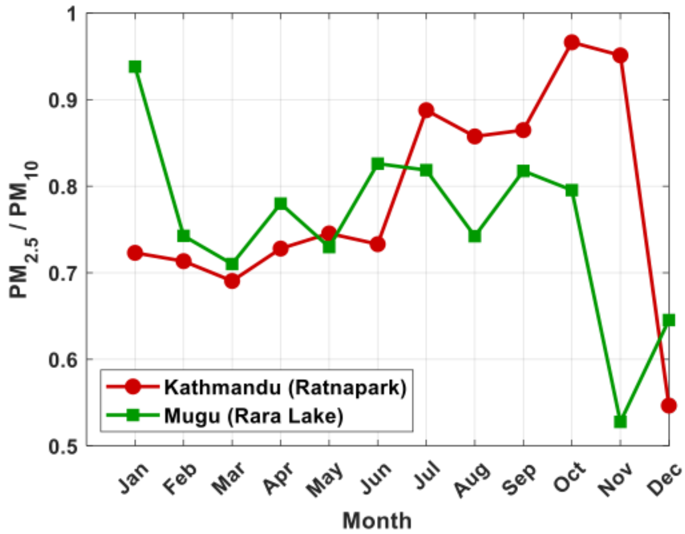

Figure 5. Monthly variation of $PM_{2.5}/PM_{10}$ ratio at urban (Ratnapark, Kathmandu) and remote (Rara Lake, Mugu) sites in 2023.

The $PM_{2.5}/PM_{10}$ ratio is a useful indicator of particulate pollution sources, where higher values (> 0.7) typically suggest dominance of fine particles from combustion-related urban sources, and lower values (< 0.5) indicate a greater presence of coarse particles, such as dust and soil [21, 22]. Fig. 5 shows the monthly variation of $PM_{2.5}/PM_{10}$ ratio values for Kathmandu (Ratnapark) and Mugu (Rara Lake) in 2023. The $PM_{2.5}/PM_{10}$ ratios calculated for Nepal show that Ratnapark, Kathmandu, ranges from 0.547 to 0.966, with a mean of 0.803 ± 0.126, indicating a high proportion of fine particulate pollution. In contrast, Rara Lake, Mugu, ranges from 0.528 to 0.826, with a mean of 0.795 ± 0.125, reflecting a mix of fine and coarse particles. Compared to India, where urban sites show seasonal mean ratios of 0.31–0.65 [23], China, with national ratios of 0.54–0.57, and Saudi Arabia, with ratios around 0.64–0.69 [24], Ratnapark exhibits higher fine particle dominance, likely due to urban activities. In contrast, Rara Lake's ratios are closer to rural or less urbanized conditions in these countries. Overall, Nepal's urban site shows more severe fine particulate pollution than comparable sites in India, China, and Saudi Arabia, while the rural site shows moderate pollution levels.

IV. Conclusions

The data show that air pollution levels in Ratnapark, Kathmandu, are much higher than in the remote Rara Lake, Mugu. Both places experience changes throughout the year, with cleaner air during the rainy monsoon season and more pollution in the colder, drier months. The high pollution in Kathmandu, especially during winter and late autumn, is mainly due to city-related activities and weather conditions. In contrast, Rara Lake stays relatively clean because it is far from urban pollution. This highlights how city life and the seasons affect air quality and health risks differently in urban versus rural areas. However, one limitation of this study is that sampling was conducted only on the 28^{th} of each month. This approach may miss short-term pollution events such as sudden traffic congestion, festival activities, industrial emissions, or unusual weather patterns, which could influence the overall representativeness of the results. Collecting samples more often, such as weekly or even daily, or using continuous monitoring stations, would be better for improving future work. This would help capture sudden spikes in pollution and give a more complete picture of how air quality changes over time. Adding real-time weather data and satellite information would also make the results more reliable and easier to apply to different places.

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