"Environmental Dynamics in Bengaluru and Mysuru: A Comprehensive Analysis of Rainwater and Aerosol Characteristics"

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Abstract: This article presents a comprehensive analysis of rainwater and aerosol characteristics in Bengaluru and Mysuru from June 2021 to May 2022, focusing on rainfall patterns, pH levels, trace metal concentrations, and environmental dynamics. The study reveals distinct seasonal variations in rainfall, highlighting the region's hydrological dynamics and seasonal trends crucial for water resource management. pH variations in rainwater reflect environmental influences, with stable pH during South-West Monsoon months and fluctuations in other seasons. Fluctuations in trace metal concentrations underscore seasonal and anthropogenic influences, emphasizing the need for pollution monitoring and mitigation strategies. Aerosol data comparison highlights atmospheric deposition sources, with seasonal variations influencing metal concentrations. Statistical analysis and correlation tests reveal strong relationships between pH and metal concentrations, guiding targeted pollution management strategies. Metal-to-metal ratios and scavenging ratios provide insights into elemental relationships and pollution dynamics, emphasizing the role of rainfall in mitigating atmospheric pollution. The findings have implications for environmental management, emphasizing the importance of continuous monitoring, targeted strategies, and further investigation into pollution sources and meteorological factors.

Keywords:

1. Introduction: Rainwater chemistry exhibits a remarkable degree of variability, influenced by both geographic factors and temporal variations driven by atmospheric circulation patterns (1). It contains particulates originating from local sources as well as those transported over long distances (2,3). The natural constituents of rainwater encompass sea salt and soil dust, whereas anthropogenic contributions include gases and particles associated with diverse sources such as traffic emissions, road dust resuspension, nonferrous metal production, fossil fuel combustion, and residential heating (4,5,6). These anthropogenic inputs significantly alter the chemical composition of rainwater, serving as indicators of air pollution levels across urban, rural, and industrial environments (7). Notably, the escalation in anthropogenic dust emissions has led to the prevalence of acid rain phenomena, extensively studied due to its detrimental effects on ecosystems, including human health impacts (8), even in remote areas. Furthermore, rainwater acts as a crucial vector for the transport of nutrients and contaminants, including metals, within the biogeochemical cycles of aquatic and terrestrial ecosystems (9,10,11,12). Its role extends beyond mere precipitation to influencing nutrient availability and contaminant dispersion, shaping the health and functioning of ecosystems. The intricate interplay between natural and anthropogenic factors in rainwater chemistry underscores its significance in understanding environmental dynamics and underscores the need for comprehensive monitoring and management strategies to safeguard ecosystems and human well-being.

The atmospheric budget of trace metals represents a complex interplay between emissions from both anthropogenic and natural sources and their subsequent deposition through wet and dry scavenging processes (13). Wet deposition, a significant pathway for trace metal deposition, operates through two primary mechanisms: in-cloud scavenging and below-cloud scavenging (14). These mechanisms are influenced by a multitude of factors, including air-mass origins, pollutant sources, transportation mediums, migration pathways, and the nature of aerosol particles, all of which collectively shape the concentrations of trace metals in rainwater (15,16). The presence of elevated levels of trace metals in rainwater poses substantial risks to terrestrial and aquatic ecosystems, given their inherent toxicity, potential for bioaccumulation and biomagnification, as well as carcinogenic properties. The global scientific community has increasingly focused on characterizing rainwater geochemistry since the 1970s, recognizing the importance of understanding the dynamics and implications of trace metal deposition in precipitation (17,18,19,20,21,22,23,24,25,26). These studies not only provide insights into the sources and pathways of trace metal contamination but also contribute to assessing environmental risks and formulating effective mitigation strategies. The comprehensive investigation of rainwater chemistry and trace metal dynamics is essential for safeguarding ecosystem health, preserving water quality, and ensuring human well-being in the face of ongoing environmental challenges.

In recent times, the global challenge of water scarcity has escalated, emphasizing the urgent need for sustainable water management strategies worldwide. Rainwater harvesting has emerged as a promising solution, particularly in urban settings, offering a potential source of water for various purposes including drinking, crop irrigation, and aquifer recharge (27). The implementation of rainwater collection and storage systems has become widespread, often serving as the primary source of drinking water in regions facing severe water scarcity. However, despite its potential benefits, the presence of dissolved contaminants in rainwater remains a significant concern (28,29,30,31,32,33,34). Of particular concern are trace metals in rainwater, which have been linked to various health disorders in humans, including atrial fibrillation, arterial hypertension, psoriasis, and angina pectoris (35). The presence of these contaminants underscores the importance of thorough monitoring and treatment measures in rainwater harvesting systems to ensure water quality and mitigate health risks. Additionally, the mystery surrounding the origin and composition of dissolved contaminants in rainwater highlights the need for comprehensive research and understanding to develop effective strategies for sustainable rainwater utilization while safeguarding public health.

Rainwater geochemistry serves as a valuable tool for discerning local and regional atmospheric emission patterns, offering insights into the source apportionment of trace metals (36,37,38). In the context of Mexico, particularly in Mexico City, one of the most polluted cities globally, extensive studies have been conducted to analyse the chemical composition of rainwater. These studies span nearly a decade and have focused on various regions within metropolitan Mexico City, examining the physicochemical parameters and dissolved geochemical elements present in rainwater (15,39,40,41). The findings from these studies consistently point to a common external and crustal origin of trace metals, highlighting the influence of both local emissions and natural geological processes on rainwater chemistry. The present study marks a significant advancement by directly measuring trace metals in rainwater collected from three different localities across Karnataka, encompassing diverse settings such as urban and industrial. This comprehensive approach allows for a nuanced understanding of how varying environmental contexts impact the composition of rainwater and the levels of trace metals present. By studying these different localities, the study aims to unravel the intricate interplay between anthropogenic activities, geological characteristics, and atmospheric processes that contribute to the observed variations in rainwater chemistry. Such detailed investigations are crucial for developing targeted mitigation strategies and enhancing our understanding of environmental dynamics in complex urban and industrial landscapes.

2. Experimentation: The rainwater chemistry analysis involved a thorough process combining field observations and laboratory tests, covering a wide spectrum of water quality parameters. Key aspects such as pH levels and trace metal concentrations were meticulously examined to gauge the overall composition of rainwater in the study area. This comprehensive approach aimed to provide a detailed understanding of the chemical makeup of rainwater and its potential implications for environmental and human health.

2.1 Location of Sampling: The selection of sampling locations was meticulously planned, prioritizing proximity to pollution sources to ensure data accuracy. This strategy was based on the understanding that air pollutant concentrations, such as SOx and NOx, typically decrease with distance from the emission point. By strategically siting the sampling stations near these sources, the study aimed to establish a direct link between pollutant emissions in urban areas and the resulting acidity levels in precipitation at the collection sites. However, the study also acknowledged potential complications arising from sampling too close to the source, including the influence of dust particles in emissions, which could impact the quality of both wet and bulk precipitation samples. To address this, the sampling stations were carefully positioned in the urban area, striking a balance between proximity to the source and minimizing the impact of dust contamination. Detailed coordinates, land-use types, collector placement heights, and longitude information for each station were documented in Table 1, ensuring a systematic and comprehensive approach. Figure 2 provided a visual overview of the study area, offering context for the strategic placement of sampling stations across the urban landscape.

Table 1: Coordinates, land-use types, roof heights for collector placement, and approximate longitudes for each station

SI NO	Sampling Site Location	Elevation (mts)	Land form type	Installation of Collectotrs and samplers	Altitude (mts)	Funnel Size (Cm)	Site Description
1	Peenya Bengaluru	945	Flat	Wet Collector, Bulk Collector High Volume Sampler	12.0	18.0	Surrounding by large no of Industries
2	Vidyaranyapura Bengaluru	945	Flat	Wet Collector, Bulk Collector High Volume Sampler	12.0	18.0	Surrounding by residential area with intensive road transport
3	Hebbal Mysuru	770	Flat	Wet Collector, Bulk Collector High Volume Sampler	12.0	18.0	Surrounding by large no of Industries

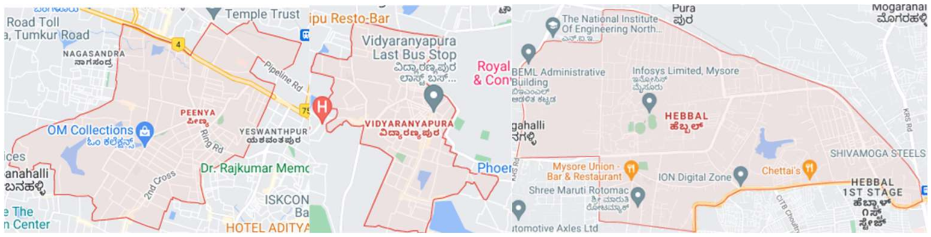


Fig 1: Peenya and Vidyaranyapura (Bengaluru) and Hebbal (Mysuru) location map

2.2 Process of Sampling: Between June 2021 and May 2022, a meticulous data collection strategy was executed, involving rigorous field and laboratory procedures to obtain wet and bulk precipitation samples alongside aerosols from four strategically chosen sampling stations. These stations were carefully selected to ensure geographical representation across the study area, as depicted in Figures 1 and 2. Given the region's distinct seasonal variations, ranging from summer to south-west and north-east monsoons, the sampling timeframe was crucial for capturing the dynamics of precipitation patterns. Using a manual sampling approach, samples were collected biweekly throughout the study period, resulting in 154 wet and 128 bulk precipitation samples. Each sample underwent thorough visual inspection to eliminate any potential contamination, with 12 bulk precipitation samples being discarded for this reason. Additionally, 45 aerosol samples were collected biweekly using a high-volume air collection system. Stricter rinsing and inspection protocols were adhered to, ensuring the reliability and integrity of the dataset. Furthermore, aerosol samples were transported to KSPCB for comprehensive chemical analysis, enhancing the depth of the study's findings.

The sampling program for wet and bulk precipitation samples was meticulously designed to ensure accuracy and representativeness in assessing the region's air pollution status. Biweekly collection of wet precipitation samples utilized collectors specifically designed to isolate wet precipitations and minimize contamination from dust fall and gas absorption during dry periods. Monthly aerosol sampling provided insights into atmospheric particulate matter composition. The wet precipitation collector, featuring an 18-cm polyethylene funnel connected to a 5-liter reservoir, excluded dry period influences and contributed to regionally representative sampling. Bulk precipitation, encompassing wet and dry components, was collected using purpose-designed collectors equipped with vapor traps and vapor barrier tubing to prevent gas exchange and evaporation, maintaining sample integrity. This meticulous sampling methodology facilitated a robust assessment of air and precipitation quality, crucial for understanding trace metal dynamics in the urban setting.

Fig 2: Collectors for wet and bulk precipitation samples and high-volume air sampler

3 Results and Discussion:

3.1 Data for Rainfall in the sampling period:

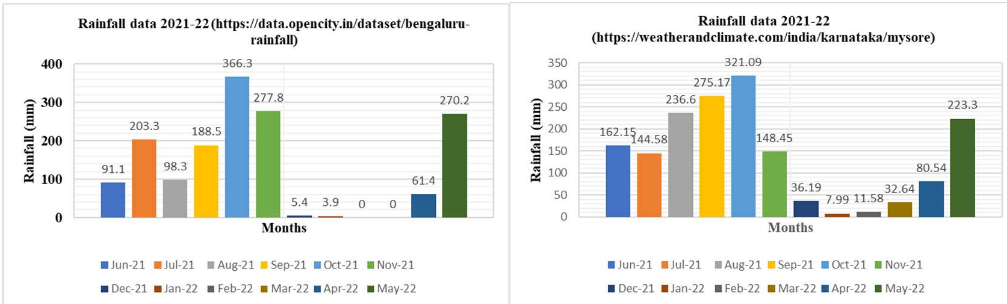


Fig 3: Data for rainfall in Bengaluru and Mysuru (2021-2022)

The first two sampling stations are situated in Bengaluru, the capital city of Karnataka, known for its diverse industrial landscape. Peenya, an industrial area established in the late 1970s, houses over 2,000 industries, making it one of Southeast Asia's oldest and largest industrial zones. However, it also faces severe pollution issues, with a Comprehensive Environmental Pollution Index (CEPI) score indicating significant pollution levels. Major contributors to pollution in Peenya include industries involved in engineering with surface treatment, spray painting, pharmaceutical research, electroplating, garment washing, and dyeing and printing. On the other hand, Vidyaranyapura, located in the north-west of Bengaluru, is known for its educational institutions and government sector factories like BEL and HMT. It is surrounded by various sub-blocks and layouts, making it a diverse locality within the city. The rainfall data for Bengaluru and Mysuru in the year 2021-22 depicts distinct seasonal variations. In Bengaluru, minimal precipitation is observed from March to May, indicating the summer season. The onset of the south-west monsoon in June brings a significant increase in rainfall, peaking in July and gradually decreasing towards September. This is followed by the north-east monsoon from October to January/February, characterized by variable rainfall patterns. Similarly, in Mysuru, minimal rainfall is recorded during the summer months, with a substantial increase during the south-west monsoon from June to September. The transition to the north-east monsoon from October to January/February is marked by variable rainfall, indicating the influence of monsoon seasons on both cities' climates.

3.2 pH Concentration Analysis:

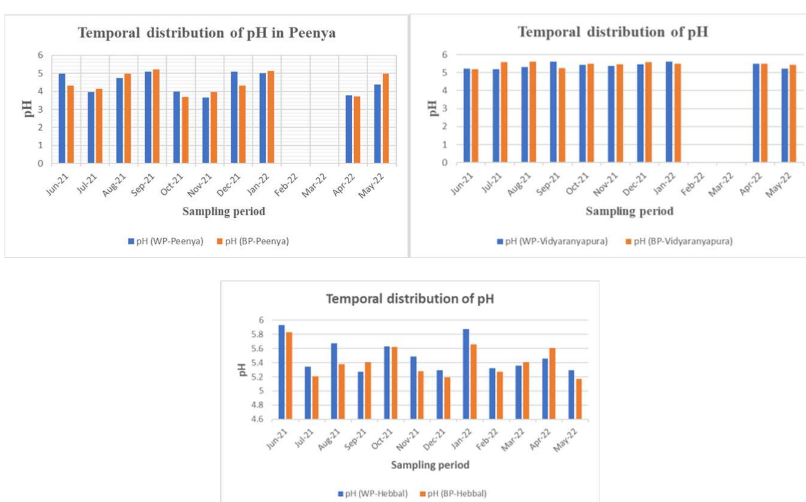


Fig 4: Temporal pH distribution in Peenya, Vidyaranyapura and Hebbal

The analysis of pH concentrations in rainwater across different sampling areas—Peenya, Vidyaranyapura, and Hebbal—reveals notable variations both temporally and seasonally. In Peenya, pH levels in wet precipitation (WP) varied from 3.67 to 5.1 and bulk precipitation (BP) from 3.7 to 5.21 over the sampling period from June 2021 to May 2022. This area exhibited moderate variability in pH, with aerosols showing the most stable pH levels. Vidyaranyapura displayed slightly higher pH values, with WP ranging from 5.2 to 5.61 and BP from 5.17 to 5.62. In contrast, Hebbal demonstrated a broader range of pH values, with WP varying from 5.29 to 5.93 and BP from 5.17 to 5.83, indicating more significant fluctuations across the months. Notably, February and March 2022 exhibited lower pH values across all areas, suggesting potential environmental changes during those periods.

Seasonally, Peenya during the South-West Monsoon (SWM) showed average pH values of 4.56 for WP and 4.48 for BP, reflecting the influence of increased moisture and atmospheric interactions. In Vidyaranyapura, pH levels during SWM averaged at 5.24 for WP and 5.46 for BP, indicating relatively stable pH conditions. Conversely, Hebbal during SWM had average pH values of 5.64 for WP and 5.47 for BP, showcasing higher pH values compared to the other areas. The North-East Monsoon (NEM) period showed further variations, with Vidyaranyapura recording an average pH of 5.46 for WP and 5.44 for BP. These variations across sampling areas and seasons underscore the dynamic environmental factors influencing pH levels in rainwater and aerosols, emphasizing the need for continuous monitoring and assessment.

3.3 Trace Metal Concentration Analysis in Wet and Bulk Precipitation (Temporal and Seasonal):

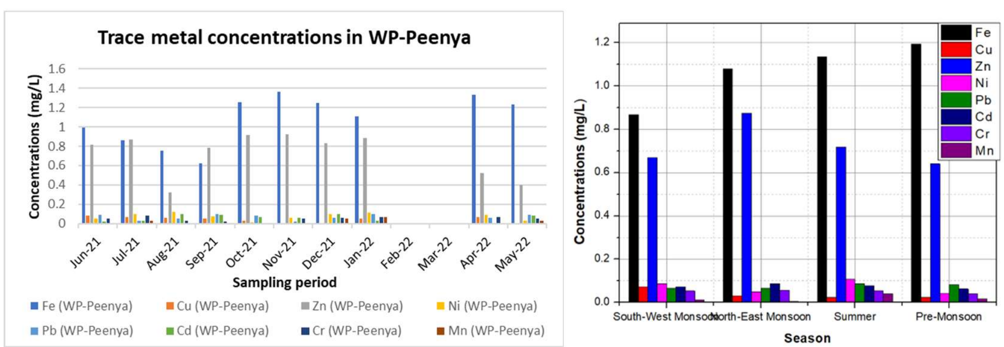


Fig 5: Temporal and seasonal trace metal concentration in wet precipitation Peenya

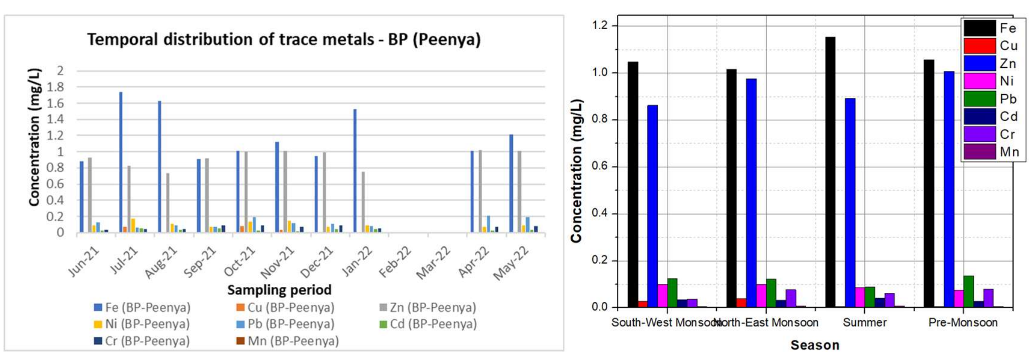


Fig 6: Temporal and seasonal trace metal concentration in bulk precipitation Peenya

The temporal and seasonal variations in trace metal concentrations in bulk precipitation at the Peenya sampling area from June 2021 to May 2022 reveal dynamic patterns influenced by environmental factors. Iron (Fe) concentrations ranged from 0.884 mg/L to 1.736 mg/L, with notable fluctuations across months, while copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and manganese (Mn) also exhibited varying levels. During the South-West Monsoon (SWM), most metals showed higher concentrations, notably zinc and cadmium, attributed to increased atmospheric activity. Conversely, the Pre-Monsoon period displayed lower metal concentrations, indicating potential washout effects. The trend analysis showed Pb > Zn > Fe > Ni > Cu > Cr > Cd > Mn in decreasing order of average concentrations, highlighting key pollutants and their seasonal dynamics for informed environmental management strategies.

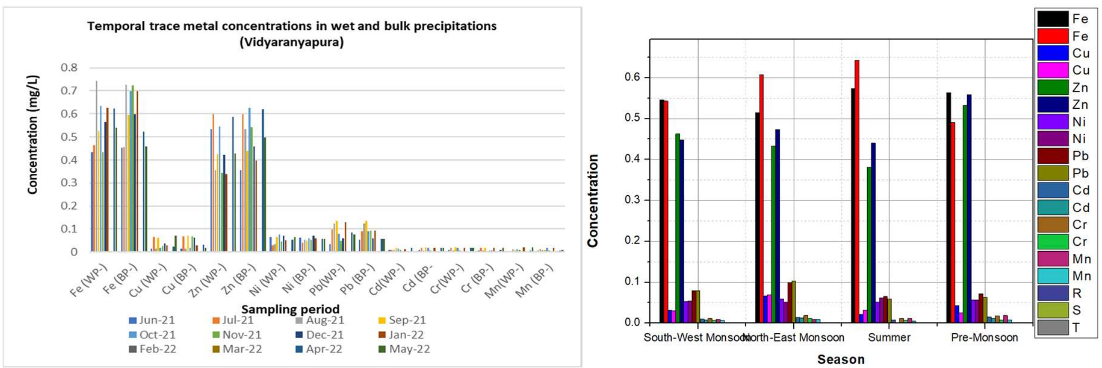


Fig 7: Temporal and seasonal trace metal concentration in wet and bulk precipitation Vidyaranyapura

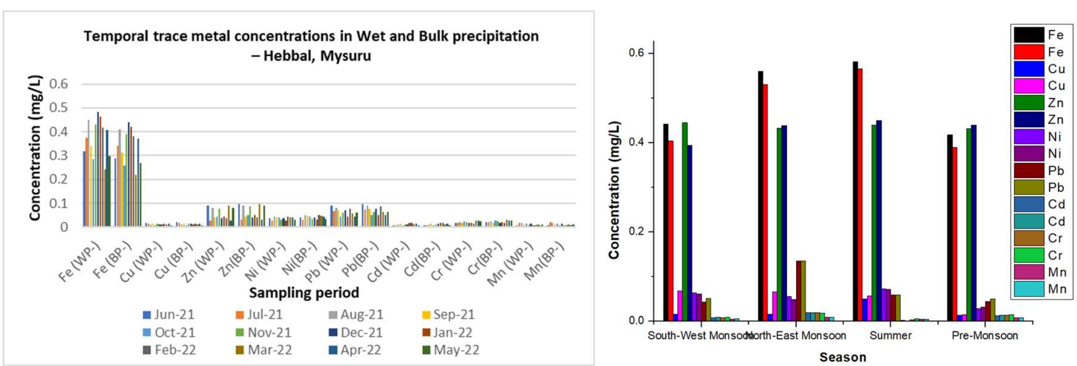


Fig 8: Temporal and seasonal trace metal concentration in wet and bulk precipitation Hebbal

The in-depth analysis of temporal and seasonal trace metal concentrations in both wet and bulk precipitation at Vidyaranyapura sampling area from June 2021 to May 2022 reveals dynamic trends. Iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and manganese (Mn) concentrations exhibited fluctuations over time, with Fe consistently showing the highest concentrations. Seasonally, the South-West Monsoon (SWM) exhibited lower average concentrations compared to other seasons, while the North-East Monsoon (NEM) showed slightly higher concentrations. Summer displayed fluctuations, with Fe and Zn concentrations decreasing, and Cu remaining stable. Pre-Monsoon exhibited similar trends to SWM and NEM. Wet precipitation consistently showed higher concentrations of trace metals compared to bulk precipitation, indicating a higher load in the liquid phase. Overall, the analysis underscores the importance of considering both phases for understanding trace metal distribution and transport in the environment, with Fe, Zn, and Cu being the predominant metals.

The analysis of temporal and seasonal trace metal concentrations in bulk precipitation at the Hebbal, Mysuru sampling area reveals significant variations and insights into environmental dynamics. Iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and manganese (Mn) concentrations fluctuate over time, reflecting influences from seasonal weather patterns, local industrial activities, and atmospheric deposition sources. During the South-West Monsoon (SWM) and North-East Monsoon (NEM) periods, metal concentrations tend to be higher, likely due to increased atmospheric deposition from rainfall and regional climatic factors. Summer months show fluctuations, with zinc concentrations notably higher, possibly linked to elevated industrial activities and atmospheric dust. Pre-Monsoon months exhibit varying concentrations influenced by dry deposition, local emissions, and atmospheric transport. Comparing with wet precipitation, bulk precipitation accumulates higher metal concentrations due to dry deposition and atmospheric particulates, highlighting different deposition mechanisms. The trend of trace metals in decreasing order in bulk precipitation is Pb > Zn > Ni > Fe > Cu > Cr > Cd > Mn, emphasizing the importance of understanding these patterns for effective environmental monitoring and management strategies to address metal pollution in the region.

3.3 Trace Metal Concentration Analysis in Aerosols (Temporal and Seasonal):

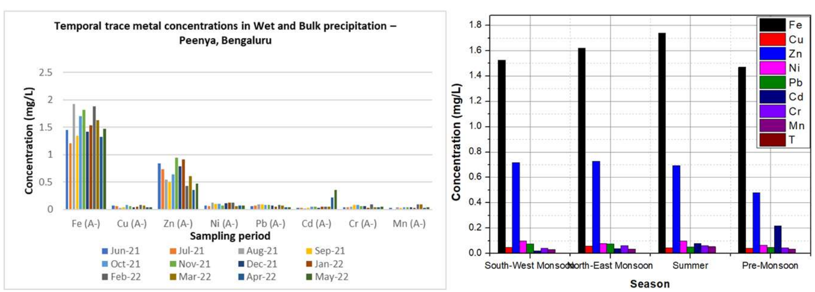


Fig 9: Temporal and seasonal trace metal concentration in Aerosols Peenya

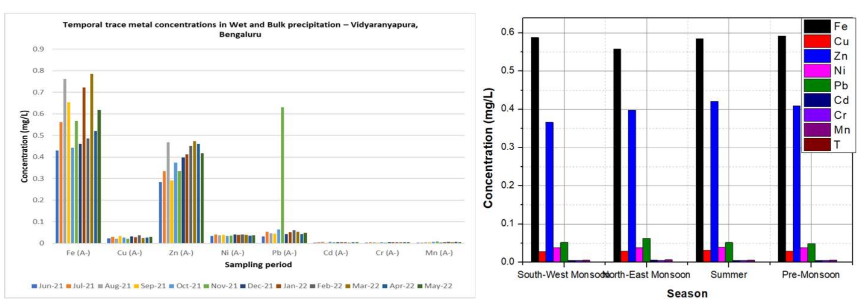


Fig 10: Temporal and seasonal trace metal concentration in Aerosols Vidyaranyapura

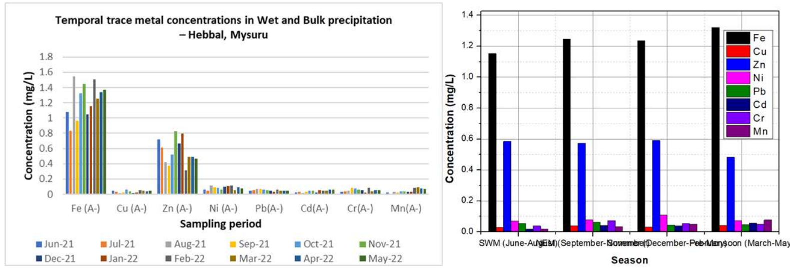


Fig 11: Temporal and seasonal trace metal concentration in Aerosols Hebbal

The analysis of temporal trace metal concentrations in Aerosols (A-Peenya), Bengaluru, for the specified sampling period in Peenya reveals notable variations across months. Iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and manganese (Mn) concentrations fluctuate, with each month showing different levels, reflecting atmospheric dynamics and potential sources. Seasonally, during the South-West Monsoon (SWM) and North-East Monsoon (NEM) periods, Cd and Zn concentrations are relatively higher, while Fe dominates during summer and Cd in the Pre-Monsoon season. Comparing with Wet and Bulk Precipitations, Aerosols exhibit higher concentrations of Cd and Cr, suggesting potential atmospheric deposition sources.

These findings underscore the influence of seasonal variations and atmospheric dynamics on trace metal concentrations in aerosols, providing valuable insights into environmental processes and pollutant transport mechanisms. The temporal trace metal concentrations in Aerosols at Vidyaranyapura, Bengaluru, from June 2021 to May 2022 exhibit dynamic fluctuations across Fe, Cu, Zn, Ni, Pb, Cd, Cr, and Mn, indicating varying environmental influences and pollution sources. Seasonally, Fe, Zn, Ni, and Cr show higher concentrations during the South-West Monsoon (SWM) and summer seasons, while Pb peaks during the North-East Monsoon (NEM). Comparing wet and bulk precipitations reveals distinct patterns, with metals like Pb showing elevated levels in wet precipitation during NEM, suggesting potential contamination sources.

These findings underscore the importance of seasonal monitoring and pollutant source identification for effective environmental management in Vidyaranyapura, Bengaluru. The temporal trace metal concentrations in Aerosols at Hebbal, Mysuru, from June 2021 to May 2022, exhibit varying patterns across Fe, Cu, Zn, Ni, Pb, Cd, Cr, and Mn, indicating potential influences from atmospheric conditions and pollution sources. Seasonally, Fe, Zn, Ni, Cr, Pb, Cu, Mn, and Cd show consistent trends across the South-West Monsoon (SWM), North-East Monsoon (NEM), Summer, and Pre-Monsoon periods, with fluctuations in concentrations observed throughout the year. Comparing concentrations in wet and bulk precipitations would elucidate the mechanisms of trace metal transport and deposition in the environment, highlighting the impact of atmospheric deposition and pollution sources on Hebbal, Mysuru. This analysis contributes crucial insights into environmental monitoring and pollution assessment efforts in the region.

3.4 Statistical Analysis (Correlation): The Pearson's correlation test conducted on rainwater samples identified significant inter-dependencies among parameters, ranging from weak to strong correlations. Strong correlations with coefficients $r \geq \pm 0.60$ were particularly notable, revealing robust relationships and providing valuable insights into the dynamics of rainwater composition across various sampling sites.

Table 2: Pearson's correlations matrix for wet precipitation Peenya

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.764							
Cu	0.553	0.230						
Zn	0.774	0.753	0.400					
Ni	0.707	0.457	0.556	0.477				
Pb	0.813	0.558	0.474	0.560	0.357			
Cd	0.652	0.430	-0.054	0.369	0.376	0.438		
Cr	0.618	0.686	0.446	0.582	0.726	0.326	0.051	
Mn	0.438	0.428	0.005	0.444	0.519	0.387	0.151	0.639

Table 3: Pearson's correlations matrix for Bulk precipitation Peenya

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.858							
Cu	0.139	0.381						
Zn	0.876	0.713	0.323					
Ni	0.667	0.821	0.743	0.732				
Pb	0.568	0.428	0.256	0.805	0.453			
Cd	0.863	0.745	0.118	0.67	0.498	0.264		
Cr	0.757	0.506	0.237	0.871	0.511	0.697	0.662	
Mn	0.884	0.769	0.288	0.782	0.635	0.521	0.796	0.774

Table 4: Pearson's correlations matrix for wet precipitation Vidyaranyapura

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.930							
Cu	0.567	0.418						
Zn	0.879	0.786	0.542					
Ni	0.850	0.769	0.465	0.778				
Pb	0.758	0.827	0.564	0.577	0.493			
Cd	0.695	0.677	0.335	0.698	0.576	0.741		
Cr	0.658	0.605	0.664	0.715	0.539	0.732	0.801	
Mn	0.611	0.686	0.387	0.336	0.542	0.640	0.394	0.589

Table 5: Pearson's correlations matrix for bulk precipitation Vidyaranyapura

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.918							
Cu	0.576	0.526						
Zn	0.930	0.856	0.548					
Ni	0.937	0.878	0.445	0.812				
Pb	0.786	0.864	0.594	0.737	0.622			
Cd	0.638	0.506	0.328	0.672	0.465	0.583		
Cr	0.608	0.439	0.532	0.508	0.426	0.583	0.819	
Mn	0.659	0.720	0.266	0.659	0.560	0.660	0.771	0.572

Table 6: Pearson's correlations matrix for wet precipitation Hebbal

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.101							
Cu	0.181	0.216						
Zn	0.317	-0.390	-0.110					
Ni	-0.154	-0.117	-0.109	0.036				
Pb	0.032	0.124	0.547	0.280	0.322			
Cd	-0.082	0.515	0.044	-0.546	0.224	-0.161		

Cr	-0.003	-0.557	-0.533	0.405	0.015	-0.567	-0.492	
Mn	-0.197	0.122	-0.173	-0.190	0.071	0.244	-0.371	-0.104

Table 7: Pearson's correlations matrix for bulk precipitation Hebbal

	pH	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Fe	0.101							
Cu	0.181	0.216						
Zn	0.317	-0.390	-0.110					
Ni	-0.154	-0.117	-0.109	0.036				
Pb	0.032	0.124	0.547	0.280	0.322			
Cd	-0.082	0.515	0.044	-0.546	0.224	-0.161		
Cr	-0.003	-0.557	-0.533	0.405	0.015	-0.567	-0.492	
Mn	-0.197	0.122	-0.173	-0.190	0.071	0.244	-0.371	-0.104

Table 8: Pearson's correlations matrix for aerosols Peenya

	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Cu	0.304						
Zn	0.014	0.065					
Ni	0.469	-0.126	-0.047				
Pb	0.455	0.279	0.053	0.353			
Cd	-0.242	-0.281	-0.472	-0.363	-0.765		
Cr	0.369	0.355	-0.327	0.355	0.629	-0.195	
Mn	0.596	0.480	-0.286	0.166	0.147	-0.044	0.347

Table 9: Pearson's correlations matrix for aerosols Vidyaranyapura.

	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Cu	-0.260						
Zn	0.400	-0.031					
Ni	0.259	0.639	0.154				
Pb	-0.041	-0.363	-0.249	-0.181			
Cd	-0.196	-0.138	0.334	-0.274	-0.048		
Cr	0.134	0.425	0.566	0.559	-0.276	0.336	
Mn	0.086	-0.186	0.393	-0.323	0.569	0.262	0.033

Table 10: Pearson's correlations matrix for aerosols Hebbal.

	Fe	Cu	Zn	Ni	Pb	Cd	Cr
Cu	0.246						
Zn	-0.283	-0.184					
Ni	0.390	-0.293	-0.311				
Pb	0.267	-0.020	-0.589	0.122			
Cd	0.325	0.473	-0.003	-0.063	-0.372		
Cr	0.290	0.288	-0.585	0.300	0.690	0.141	
Mn	0.613	0.469	-0.503	0.122	-0.051	0.618	0.284

In Peenya, Bengaluru, the Pearson's correlation analysis for physio-chemical parameters in rainwater samples from wet precipitation (WP) revealed notable relationships. The pH exhibited strong positive correlations with Fe (0.764), Zn (0.774), Pb (0.813), Cd (0.652), Cr (0.618), and a moderate positive correlation with Ni (0.707). Fe showed strong positive correlations with Zn (0.753), Pb (0.558), Cr (0.686), and a moderate positive correlation with

Ni (0.457). Zn exhibited strong positive correlations with Pb (0.560), Cd (0.369), and Cr (0.582). Ni showed a moderate positive correlation with Pb (0.357) and a strong positive correlation with Cr (0.726). Overall, these findings suggest significant inter-dependencies among these parameters in Peenya's rainwater samples, especially with pH playing a pivotal role in influencing multiple parameters. Moving to Vidyaranyapura, Bengaluru, the Pearson's correlations in wet precipitation revealed strong positive correlations of pH with Fe (0.930), Zn (0.879), Ni (0.850), Pb (0.758), Cd (0.695), Cr (0.658), and Mn (0.611). Fe exhibited strong positive correlations with Zn (0.786), Ni (0.769), Pb (0.827), Cd (0.677), Cr (0.605), and Mn (0.686), indicating potential co-occurrence or shared sources. Cu displayed moderate positive correlations with Fe (0.418), Zn (0.542), Pb (0.564), Cr (0.664), and a weak positive correlation with Ni (0.465). These correlations suggest diverse inter-dependencies among physio-chemical parameters in Vidyaranyapura's rainwater samples, emphasizing the significant influence of pH and the complex relationships among other parameters. In Hebbal, Mysuru, the correlations in wet precipitation showed weaker associations compared to Peenya and Vidyaranyapura. pH exhibited weak correlations with other parameters, indicating minimal influence. Fe showed a weak positive correlation with Cd (0.515) and a strong negative correlation with Cr (-0.557), suggesting potential interactions and inverse relationships. Cu displayed a moderate positive correlation with Pb (0.547) and weak correlations with other parameters. Zn demonstrated weak correlations with most parameters, except for a moderate negative correlation with Cd (-0.546). Overall, these findings suggest less pronounced inter-dependencies in Hebbal's rainwater samples from wet precipitation, with some metals showing stronger correlations than others.

3.5 Statistical Analysis (Factor Analysis): Principal Component Analysis (PCA) is utilized with Varimax rotation to extract factor components from physical and trace metal analysis of rainwater samples. This technique aims to identify and explain sources of trace metals by reducing variance and simplifying the interpretation of factor loadings with Eigenvalues greater than 1.

Table 11: Results of factor analysis of physio-chemical parameters in rainwater samples and aerosols samples collected from Peenya

	Wet precipitation			Bulk precipitation			Aerosols		
Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 1**	**Factor2**	**Factor3**
pH	1.432	-0.981	-0.549	1.574	0.873	-0.193			
Fe	0.119	-0.455	-0.09	0.464	0.075	-0.28	0.122	0.043	0.192
Cu	0.019	-0.001	-0.009	0	0.004	-0.02	0.007	0.001	0.002
Zn	0.106	-0.195	-0.267	0.197	0.294	-0.112	0.033	0.18	-0.06
Ni	0.029	-0.012	-0.007	0.026	0.017	-0.036	0.011	0.001	0.008
Pb	0.026	-0.013	-0.007	0.012	0.054	-0.023	0.002	0.005	0.008
Cd	0.024	-0.011	-0.001	0.015	0.005	0	-0.017	-0.066	-0.011
Cr	0.008	-0.017	-0.006	0.014	0.025	-0.002	0.001	-0.003	0.009
Mn	0.005	-0.008	-0.005	0.002	0.001	0	0.002	-0.002	0.017
Variance	2.078	1.2089	0.3808	2.7344	0.8588	0.1303	0.07034	0.057188	0.041392
% Var	0.566	0.329	0.104	0.734	0.231	0.035	0.396	0.322	0.233

Table 12: Results of factor analysis of physio-chemical parameters in rainwater samples and aerosols samples collected from Vidyaranyapura

	Wet precipitation			Bulk precipitation			Aerosols		
Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 1**	**Factor 2**	**Factor 3**	**Factor1**	**Factor2**	**Factor3**
pH	1.263	-1.2	-1.175	1.356	1.329	0.959			
Fe	0.183	-0.138	-0.054	0.225	0.089	0.073	0.029	0.014	-0.12
Cu	0.004	-0.008	-0.013	0.01	0.009	0.008	0	-0.002	0.001
Zn	0.045	-0.173	-0.089	0.124	0.081	0.156	0.05	-0.002	-0.019
Ni	0.011	-0.013	-0.013	0.015	0.015	0.006	0.001	0	0
Pb	0.034	-0.017	-0.008	0.033	0.012	0.01	-0.045	0.161	0.015
Cd	0.002	-0.004	-0.002	0.002	0.003	0.004	0	0	0
Cr	0.002	-0.005	-0.002	0.001	0.004	0.002	0	0	0
Mn	0.005	-0.001	-0.001	0.004	0.001	0.002	0	0.001	0
Variance	1.6329	1.4891	1.3914	1.9061	1.781	0.9489	0.042005	0.026223	0.017131
% Var	0.362	0.33	0.308	0.411	0.384	0.205	0.482	0.301	0.196

Table 13: Results of factor analysis of physio-chemical parameters in rainwater samples and aerosols samples collected from Hebbal.

	Wet precipitation			Bulk precipitation			Aerosols		
Variable	**Factor1**	**Factor2**	**Factor3**	**Factor1**	**Factor2**	**Factor3**	**Factor1**	**Factor2**	**Factor3**
pH	-0.228	0.026	-0.024	-0.228	0.026	-0.024			
Fe	0.001	0.071	0.003	0.001	0.071	0.003	0.11	0.068	0.183
Cu	0	0.001	0	0	0.001	0	0.004	0.004	0.001
Zn	-0.007	-0.009	-0.022	-0.007	-0.009	-0.022	0.033	-0.16	-0.018
Ni	0.001	-0.001	-0.001	0.001	-0.001	-0.001	0.008	0.009	0.003
Pb	0.001	0.002	-0.009	0.001	0.002	-0.009	0.001	0.007	0
Cd	0	0.002	0.001	0	0.002	0.001	-0.001	-0.001	0.007
Cr	0	-0.002	0	0	-0.002	0	0.001	0.012	0.002
Mn	0.001	0	0	0.001	0	0	-0.002	0.012	0.018
Variance	0.052193	0.005794	0.001135	0.052193	0.005794	0.001135	0.074626	0.035559	0.034921
% Var	0.879	0.098	0.019	0.879	0.098	0.019	0.509	0.243	0.238

The factor analysis of physio-chemical parameters in rainwater and aerosol samples from Peenya, Bengaluru, reveals distinct patterns. In wet precipitation, Factor 1 indicates alkalinity (strong positive loading of pH), while Factor 2 suggests anthropogenic contributions (positive loadings of Fe, Zn, Pb, Cd, Cr), and Factor 3 reflects a mix of natural and anthropogenic sources (positive loadings of Mn). Similarly, in bulk precipitation, Factor 1 shows alkalinity, and Factor 2 indicates potential anthropogenic contributions. Aerosol samples mirror these patterns, indicating a mixed influence, industrial emissions, and contributions from natural and anthropogenic sources.

For Vidyaranyapura, wet precipitation factors show alkalinity (Factor 1), potential anthropogenic contributions (Factor 2), and a mix of sources (Factor 3). Bulk precipitation follows similar trends with alkalinity and anthropogenic influences. Aerosol samples also exhibit comparable patterns. Conversely, Hebbal's wet and bulk precipitation factors

demonstrate lesser influence from pH and trace metals, with no strong loading observed. Aerosols at Hebbal also show minimal impact compared to Peenya and Vidyaranyapura.
Comparing these areas, Peenya and Vidyaranyapura exhibit stronger anthropogenic contributions in both wet and bulk precipitation, as well as in aerosols. Hebbal shows minimal pollution impact based on factor loadings for pH and trace metals, indicating Peenya and Vidyaranyapura as the major polluted areas in Bengaluru.

3.6 Statistical Analysis (Elemental Ratios): Metal-to-metal ratios and heavy metal ratios were computed in this study to analyze elemental relationships and potential pollution sources in rainwater and aerosol samples from various sampling sites. These ratios, including Fe/Zn and Cu/Ni, were used to evaluate the relative concentrations of these elements, offering valuable insights into their origins and environmental interactions.

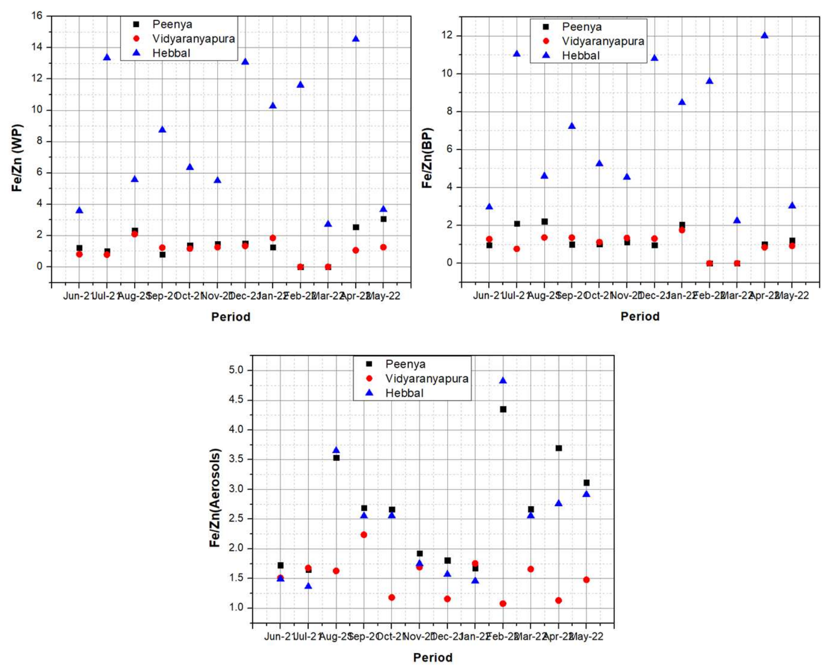
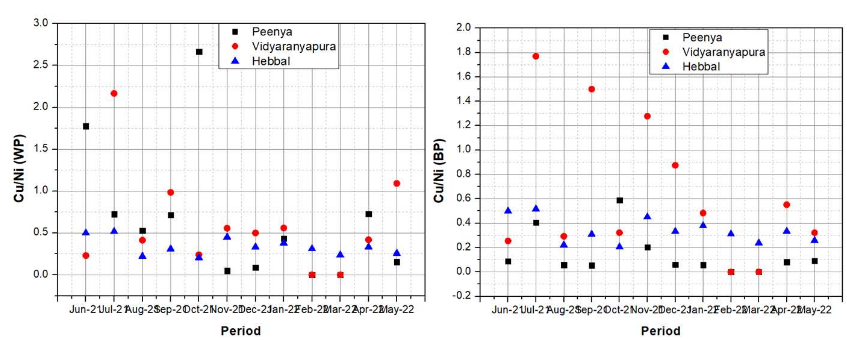


Fig 12: The Fe/Zn concentration ratio for rainwater samples collected from different sampling stations during the study period for wet and bulk precipitation and aerosols



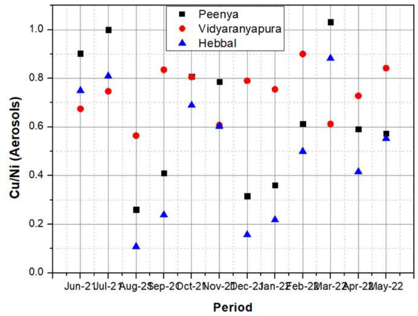


Fig 13: The Cu/Ni concentration ratio for rainwater samples collected from different sampling stations during the study period for wet and bulk precipitation and aerosols

The metal-to-metal ratios (Fe/Zn) and (Cu/Ni) in Peenya for wet precipitation (WP) highlight variations in iron and zinc concentrations across different periods, with Fe/Zn ratios ranging from approximately 0.79 to 3.06. Ratios significantly deviating from 1 suggest potential influences from specific industrial activities or natural sources, as seen in some periods with elevated Fe/Zn ratios. Similarly, the Cu/Ni ratios in Peenya varied from about 0.05 to 2.67, indicating fluctuations in anthropogenic emissions or geological influences impacting copper and nickel levels in the samples. In bulk precipitation (BP) samples, the Fe/Zn ratios ranged from approximately 0.95 to 2.21, reflecting variations in iron and zinc concentrations influenced by industrial activities or atmospheric processes. The Cu/Ni ratios in BP ranged from around 0.05 to 0.59, suggesting changes in anthropogenic emissions or combustion processes affecting copper and nickel levels. In aerosol samples from Peenya, the Fe/Zn ratios varied from approximately 1.7 to 4.35, indicating potential sources of iron-rich aerosols such as industrial emissions or natural sources like soil dust. The Cu/Ni ratios in aerosols ranged from around 0.26 to 1.03, reflecting different pollution sources impacting copper and nickel concentrations in the airborne particulate matter.

Similarly, in Vidyaranyapura, the Fe/Zn ratios in wet precipitation (WP) and bulk precipitation (BP) samples varied, with Fe/Zn ratios ranging across different periods. The Cu/Ni ratios in WP and BP samples also showed variations, indicating changes in copper and nickel concentrations influenced by sources such as vehicular emissions or industrial activities. In Hebbal, the Fe/Zn ratios in WP and BP samples displayed significant variations across different periods, suggesting fluctuations in iron and zinc concentrations influenced by local sources or atmospheric processes. The Cu/Ni ratios in Hebbal also showed variability, reflecting changes in copper and nickel levels impacted by factors like meteorological conditions or specific pollution sources. These metal-to-metal ratios provide valuable insights into the relative concentrations of different metals and their potential sources in the atmospheric samples collected from Peenya, Vidyaranyapura, and Hebbal, aiding in understanding metal pollution dynamics and potential environmental interactions.

3.7 Statistical Analysis (Scavenging Ratio): Exploring scavenging ratios between wet precipitation (WP) and aerosol samples across Peenya, Vidyaranyapura, and Hebbal provides insights into rainwater's efficiency in removing pollutants from the atmosphere. A higher scavenging ratio indicates more effective pollutant capture by rainwater, resulting in lower metal concentrations in aerosols, offering valuable information on rainfall's role in mitigating atmospheric pollution and environmental processes' variability among the studied areas.

Fig 14: Scavenging ratios (Fe, Cu, Zn, Ni, Pb, Cd, Cr and Mn) for different sampling locations

The analysis of scavenging ratios (SRs) for Iron (Fe), Copper (Cu), Zinc (Zn), Nickel (Ni), Lead (Pb), Cadmium (Cd), Chromium (Cr), and Manganese (Mn) across Peenya, Vidyaranyapura, and Hebbal reveals significant variations and potential influencing factors. Across the sampling period from June 2021 to May 2022, Fe SRs ranged from 0 to 1.43, Cu SRs from 0 to 2.29, Zn SRs from 0 to 1.88, Ni SRs from 0 to 2.24, Pb SRs from 0 to 3.04, Cd SRs from 0 to 7.14, Cr SRs from 0 to 5.38, and Mn SRs from 0 to 4.28. These variations suggest dynamic interactions between local emission sources, aerosol composition, meteorological conditions, and scavenging processes. Peenya, as an industrial hub, exhibited generally higher SRs for several metals, especially during months with limited rainfall, potentially due to elevated local emissions. Vidyaranyapura showed consistently higher SRs for Pb, Cd, Cr, and Mn, indicating a stronger influence of local sources or more favorable scavenging conditions at this residential-vehicular location. Hebbal, another industrial area, exhibited moderate variations in SRs, suggesting a combination of factors influencing scavenging dynamics. Wind patterns played a significant role, with prevailing winds potentially carrying pollutants from industrial areas to the sampling locations, impacting SRs. The analysis also highlighted unique events such as exceptionally high Cd SRs in Peenya during August and elevated Cr SRs in Vidyaranyapura in September, warranting further investigation into specific local sources or meteorological conditions. Overall, the comparison of SRs across locations underscores the complex interplay of emission sources, aerosol characteristics, rainfall patterns, and wind dynamics in shaping trace metal scavenging ratios in urban environments, emphasizing the need for comprehensive and localized pollution monitoring and management strategies.

4. Conclusion:

Rainfall Patterns and Hydrological Dynamics: Seasonal variations in Bengaluru and Mysuru from June 2021 to May 2022 highlight distinct rainfall phases, crucial for water resource management and environmental understanding. Peaks during monsoon months and dry spells in winter illustrate the region's hydrological dynamics and seasonal trends.

pH Levels and Environmental Dynamics: pH variations in rainwater across Peenya, Vidyaranyapura, and Hebbal reflect seasonal changes and environmental influences. South-West Monsoon months show stable pH, while North-East Monsoon and Pre-Monsoon periods exhibit fluctuations, indicating environmental impacts.

Trace Metal Concentrations and Pollution Dynamics: Fluctuations in Fe, Cu, Zn, Ni, Pb, Cd, Cr, and Mn concentrations reveal seasonal and anthropogenic influences. Higher metal concentrations during monsoon seasons emphasize the need for pollution monitoring and mitigation strategies.

Comparison of Aerosol and Precipitation Data: Aerosols exhibit higher Cd and Cr concentrations compared to precipitation, indicating atmospheric deposition sources. Seasonal variations influence metal concentrations, highlighting complex environmental interactions.

Statistical Analysis and Correlation Tests: Strong correlations between pH and Fe, Zn, Pb, Cd, Cr, and Ni underscore pH's influence on metal concentrations in rainwater. Factor analysis identifies major polluted areas (Peenya and Vidyaranyapura) and pollution sources, guiding targeted management strategies.

Metal-to-Metal Ratios and Scavenging Ratios: Fe/Zn and Cu/Ni ratios vary across sampling periods and locations, revealing elemental relationships and pollution dynamics. Scavenging ratios indicate local emissions' impact on metal deposition, emphasizing the role of rainfall in mitigating atmospheric pollution.

Implications for Environmental Management: Comprehensive analysis provides valuable insights for pollution control, sustainable management, and environmental stewardship. Continuous monitoring, targeted strategies, and deeper investigation into sources and meteorological factors are essential for effective pollution management and environmental protection.

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