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Spatiotemporal Variability of PM 2.5 and Black Carbon and its Dynamic Relationship with Meteorological Factors in Pakistan: A Review

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ABSTRACT

PM2.5 and BC air pollution threatens human and environmental health. Pakistan's growing urbanization makes PM2.5 and BC's spatiotemporal variability and meteorological interaction crucial for air quality management and public health interventions. This review study examines PM2.5 and BC spatiotemporal distributions in Pakistan and their complicated connections with meteorological factors. To assess PM2.5 and BC levels in Pakistan, a comprehensive literature review examined several research. Urban concentrations were higher than rural ones. We also observed seasonal and diurnal pollution changes. Industrial, vehicle, biomass, and dust storm emissions contributed to PM2.5 and BC pollution. This study examined the dynamic association between PM2.5/BC, temperature, humidity, wind speed, and atmospheric stability. These variables affect atmospheric pollutant dispersal and transformation. Our research shows complex interactions between climatic circumstances, PM2.5, and BC deposition, transit, and dilution. Stagnant atmospheric conditions, low wind speeds, and temperature inversions led pollution events to worsen. Effective air pollution remediation requires understanding PM2.5, BC, and meteorological factors' spatiotemporal patterns and dynamic connections. This technique helps policymakers and urban planners identify high-risk locations, prioritize pollution management, and execute targeted solutions. The findings might also inform pollution reporting procedures to protect vulnerable populations. This review illuminates Pakistan's PM2.5 and BC spatiotemporal variability. It stresses the importance of meteorological elements in air pollution dynamics. However, extensive monitoring programs, emission inventories, and improved modeling are needed to improve knowledge. Such efforts will enhance predictions and air pollution management, protecting human health and the environment.

Introduction

According to the World Health Organization (2016), ambient air pollution was a contributing factor in almost 3.7 million deaths globally in 2015 (Kuehn, 2014). The greatest levels of fine particular and coarse specific matters were found in regions of low and moderate income in South and East Asia (WHO, 2014). Most research on the links between air pollution and health has been limited to either wealthy nations or emerging nations like China's well-established system of surveillance (Atkinson et al., 2015). More attention must be paid to south Asian nations like Pakistan, which have had significant economic development and rising sources of air pollution including automobiles and polluting industries with high population expansion (from 107 million in 1990 to 197 million in 2017) (Mishra et al., 2023; Nations, 2017). The association between air pollution and the rising rates of hypertension and coronary artery disease in Pakistan's metropolitan regions is unclear (Furrer et al., 2022).

Earlier research assessed PM2.5 levels in two locations in Karachi, Pakistan's largest metropolis, and established a statistically significant correlation between PM2.5 mass and increased risk of cardiovascular diseases (Abdurrahman et al., 2020). Some PM2.5 elements and carbon black may be more harmful than others, hence it may be deceptive to use overall PM2.5 levels as the health effect indicator. Transition metals and CB are two components of PM2.5 that have been linked to increased CVD risk, whereas sea spray components have shown a weaker or nonexistent link (Moryani et al., 2020). There have been just a few of epidemiological studies completed too far in Asia that have documented distinct PM2.5 profiles with a greater percentage of hazardous components. Of these investigations, even fewer have looked at PM2.5's effect on cardiovascular morbidity as opposed to mortality (Ahmad et al., 2019). In underdeveloped nations, where resources are few, it is essential to pinpoint the origins of PM2.5 components with the greatest health implications in order to effectively combat pollution. Particulate Matter refers to the presence of solids and liquid droplets in the air. Particulate matter affects air quality significantly and has negative health consequences for humans. Particles may originate from both natural and human-made processes (Sawlani et al., 2019). Particulate matter emissions come from a wide variety of sources, such as factories, cars, homes using fossil fuels, farms burning agricultural leftovers, etc. PM2.5 is the abbreviation for particles less than 2.5 micrometers in size per cubic metre of air. Fine particulate matter is airborne particles less than 2.5 micrometres in diameter. Asthma, lung cancer, skin problems, and acute respiratory symptoms are just some of the illnesses that have been linked to particulate matter. The deterioration of the environment due to PM2.5 is a big concern. Particulate matter in the air is one of Asia's most pressing environmental problems. Human health is negatively affected by exposure to PM2.5 (Bennett et al., 2019).

In this review study we will focus on recent production of PM 2.5 and black carbon in Pakistan. We will mainly the focus on spatiotemporal variability and its dynamic relationship with meteorological factors in Pakistan. This review examines how weather patterns and urban landscapes impact each other, and how these impacts vary across different cities in Pakistan like Karachi, Lahore, Faisalabad and Islamabad. Through the analysis of spatiotemporal data on temperature, wind speed, precipitation, and other meteorological factors, this research aims to provide a comprehensive understanding of the patterns and dynamics of weather variability in different cities of Pakistan. The findings of this study can help urban planners and policymakers make informed decisions about how to manage and mitigate the impacts of weather-related hazards in different cities of Pakistan.

Pakistan's Current Pollution Scenario

Since rapid urbanization and a rise in vehicle loads have resulted in an unparalleled rate of air pollution, the current state of air quality in Pakistan seems gloomy. People are more susceptible to air pollution-related ailments because of insufficient infrastructure and resources, lack of political will and poor enforcing of regulations. The Institute for Health Metrics and Evaluation found that in 2017, air pollution in Pakistan was the leading environmental/occupational cause in the country's high rate of fatalities and disability. Emissions of several kinds of air pollutants, including greenhouse gases, are also predicted to rise dramatically as the economy expands and energy needs rise. It has been very challenging to accurately analyze the situation due to the dearth of healthcare data and the absence of continuous monitoring stations. Local and regional studies (outside of big cities and provincial capitals) are very rare. Air pollution is linked to a variety of health problems. For instance, in Karachi, when particulate matter pollution is severe, the number of people visiting the emergency room and being admitted to a hospital for cardiovascular illness goes up. There haven't been enough comprehensive epidemiological studies conducted on the subject of air pollution's effects on human health for an accurate tally to be made. However, research has shown that Pakistan is one of the nations with the greatest rates of early mortality with almost 105 thousand fatalities annually due to elevated levels of particular matter 2.5 (Imran et al., 2022). According to the World Health Organization, outdoor air pollution in Pakistan caused about 22,000 premature adult deaths and 163,432 DALYs (disability-adjusted life years).It is also important to learn more about and keep closer tabs on the situation in the different cities around Pakistan. There was an attempt to compile a database of monitoring efforts spread out across many cities and eras in Pakistan **(Table 1)** ((Khwaja et al., 2013).

Table 1. Sources and pollution concentration in various cities

City	Species above WHO standards	Max Pollution Concentration	Sources of pollution	Reference

Lahore Karachi, Quetta	&P.M 2.5, CO	Lahore and Quetta	Vehicular emissions	(Ghauri et al., 2007)
Lahore	$PM_{2.5}$, and CO	Traffic congested sites	Road dust is being blown about by the turbulence caused by all the passing cars	(Stone et al., 2010)
Karachi	$PM_{2.5}$	Korangi	Biomass burning	(Khwaja et al., 2013)
Lahore	$PM_{2.5}$	PU Lahore	Biomass burning and fossil fuel combustion	(Biswas et al., 2008)
Lahore	$PM_{2.5}$	Jauhar Town Lahore	Industrial and Vehicular Emissions Transboundary Pollution	(Lodhi et al., 2009)

Sources of Pollution in Pakistan

There have been reports of very high levels of many contaminants in the air over Pakistan. The prevalence of these air pollutants has been related to many industries (Shahid et al., 2015). The industries and transportation are significant contributors to yearly emissions of NO_x, accounting for around (43.2% and 39.6%, respectively). Significant contributors to yearly emissions of SO_2 and CO may be found in the residential, thermal and industrial power generating, and transportation sectors, with 62.9% and 23.0% and 75.6% and 14.6%, respectively. The absence of cross-sectoral and source apportionment research in these studies makes it impossible to appreciate the complexities of the problem in its entirety, despite the fact that they do present a basic picture. However, in the following parts, we will examine the main sources of air pollution in Pakistan.

1. Traffic

In Pakistan, vehicular emissions contribute significantly to pollution levels in the atmosphere. Over the last several decades, Pakistan has seen a massive growth in the number of cars on the road. The number of registered automobiles in Pakistan increased fourfold from 2006 to 2018 (from 5,633,353 to 23,588,268), as reported by the Pakistan Bureau of Statistics (Anjum et al., 2021a). Vehicles in Pakistan are generally old, poorly maintained, polluting, and powered by antiquated engines, and they rely heavily on diesel fuel (Javed et al., 2015).

In recent decades, a growth in the number of cars on the road has led to deteriorating conditions. Many more automobiles, rickshaws, motorbikes, and delivery vans are already on Pakistani roads thanks in large part to the country's accommodating leasing system provided by lending institutions. Motor cab and taxi registrations in Pakistan have risen by more than five times between 1990 and 2017. In contrast, the number of heavy vehicles has increased fivefold, including buses and diesel hauling engines. Researchers performed a research that demonstrated how the kind of gasoline used greatly affected the emissions produced by vehicles. Compared to compressed natural gas (CNG) vans and buses, which generated between two and twenty times higher CO emissions, buses and diesel vans emitted five times more sulfur oxide and fourteen times more HC (Yasar et al., 2013). Study revealed that increasing automobile ownership is a significant contributor to deteriorating air quality in Pakistan's largest cities. It was compared to US norms, the typical vehicle in Pakistan generatesm3.6, 8, 20, and 25 times more hydrocarbon, lead, carbon, and NOx per km according to this research, and the yearly increase rate for on-road cars was found to be larger than 8.5 percent (Hussain et al., 2018).

2. Industrial Pollution

Air pollution in Pakistan is often blamed on the country's rapid and mostly unplanned industrialization (Rasheed et al., 2015). To produce roughly 162 tons of nitrogen oxid, 285 tons of carbon monoxide, 378 tons of sulfur products and nearly 4400 tons of PM 2.5, Pakistan's industrial sector uses around 16% of the country's total oil. **Figure 1** depicts projected oil and petroleum consumption in Pakistan by different industries from 2000 to 2030 (Rana et al., 2019), indicating that industrial oil and petroleum usage is expected to grow, along with associated emissions. Researchers have shown that during the last 11 years, emissions of atmospheric industrial pollutants including HCHO and NO_x have grown, albeit at a slower rate than the expansion of pollutant concentrations recorded in other industries. One possible explanation is that Pakistan's long-term energy problems, which this research was conducted during, stifled the country's industrial

development. There are no detailed records of the quantities of chemicals imported, used, or discharged in the nation, however, in recent years, the energy crisis has been brought under control forcing enterprises to produce power. There has to be stronger monitoring in place and more extensive research conducted in the nation. Improved communication with the industrial sector, forecasting future development potential, and creating emission inventories are all facilitated by SMART monitoring systems that depend on the collaboration of the industrial sector. Various businesses produce various amounts of pollution, therefore a blanket solution is not likely to work. Instead, SMART methods are proposed. Because of the absence of PPE, employees in industries like tanneries are exposed to dangerous levels of air pollutants including CO_2, SO_2, H_2S, NH_3, and Cl_2 throughout the leather manufacturing process. Approximately 600 tanneries make up Pakistan's leather sector; they are concentrated in the cities of Sialkot, Kasur, and Karachi (Baruah et al., 2022). The Factory Act of 1934, which is the principal health and safety control law in the nation, is obsolete and is the only autonomous safety legislation and occupational health in the country. And due of poor execution, businesses might choose to disregard even these laws. The steel, cement, sugar, and fertilizer industries in Pakistan have been identified as major contributors to poor air quality because to their use of high S content furnace oil and the generation of particle pollution. Poor urban air quality has also been linked to the use of waste fuels like old tires, wood, paper, textiles, and biomass, as well as the use of old and worn out equipment like boilers and generators, especially in medium and small-scale industries like steel recycling, brick kilns, and plastic molding.
However, research on the chemistry sector of Pakistan and its potential for producing less prevalent but more hazardous carcinogenic pollutants has been severely lacking. This might be because to difficulties in tracking less prevalent contaminants in Pakistan due to technology limitations. Less frequent air contaminants including cadmium, toluene, and benzene should also be examined in depth to better understand the effects of industrial emissions in Pakistan (Baruah et al., 2022).

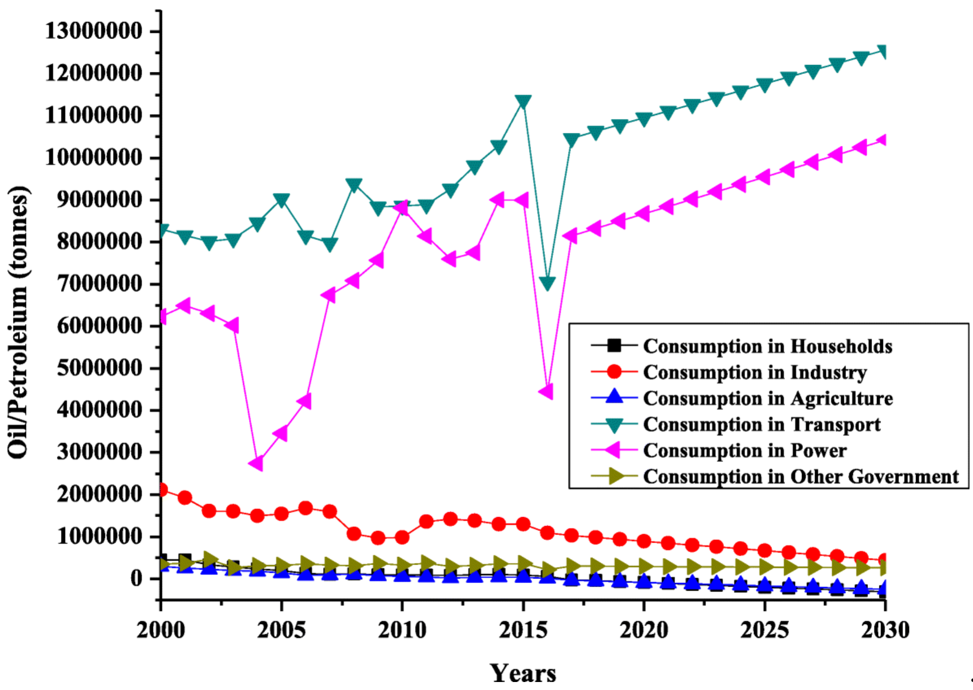

Figure 1. Oil and petroleum energy use projections for homes, businesses, farms, cities, and utilities from 2000 to 2030 (Rehman and Deyuan, 2018)

3. Constructions

Dust and particle pollution from construction sites are well-documented to have a negative impact on local air quality. Construction operations may raise PM10, TSP, and PM2.5 levels by 16%, 20%, and 42%, respectively (Yan et al., 2019), albeit these numbers can vary depending on the specifics of the project. The building industry in Pakistan has a major effect on the country's air quality. The construction sector is a major contributor to pollution because of all the processes involved, from making raw materials and bricks to operating massive pieces of gear. The brick kiln effects on people's health and pollution were investigated (Khan et al., 2019). And discovered that carbon dioxide (CO_2) was the most environmentally hazardous pollutant created by brick kilns, followed by particulate matter, carbon monoxide, sulfur oxyde, nitrogen oxide, fluoride compounds, and carcinogenic dioxins. Carcinogenic dioxins, sulfur dioxide particulate matter, nitrogen oxides, carbon monoxide, and fluoride compounds were the most hazardous contaminants to human health. Traditional brick kilns that use coal and plastic as fuels need to be replaced with ecologically acceptable alternatives (Khan et al., 2019).

4. Biologically-induced emissions

Emissions from biological sources, such as trees and plants, are known as "biogenic emissions." They have an impact on people's health and well-being, but aren't often considered a major source of pollution (Hussain et al., 2019) found a correlation between exposure to certain aeroallergens generated by natural vegetation and the development of health problems like asthma in Pakistan. Natural pollen, biogenic trace gases, and fungal spores have been extensively studied for their effects on human health, and recently there has been a burgeoning interest in interact with main air pollutants. Pollen grains, derived allergens, and their sub-particles were discovered to have a greater influence on Allergenicity after being exposed to air pollution, according to research. Atmospheric air pollution is thought to have a role in exacerbating the deleterious effects of pollen, and this might be a serious problem in a less-studied location like Pakistan (Sénéchal et al., 2015).

Formaldehyde, glyoxal, ozone, methane and other volatile organic chemicals were also released as part of the biogenic process, in addition to pollen. In the context of Pakistan, there is a dearth of literature on all of these contaminants. The existence of organic carbon is mostly attributable to biogenic emissions in Pakistan. The emission of biogenic volatile chemicals from plants contributes to the high concentrations in main cities of Pakistan (Hashmi et al., 2020)

3.5. Uncontrolled Fires

Open burning of solid and agricultural waste is commonplace in developing nations like Pakistan for a variety of economic and social reasons. When it comes to significant air pollutants, black carbon, and greenhouse gases, open burning of biomass waste is blamed as a major contributor. Because cutting down on open fires may greatly lessen the negative effects on health and the environment. Factors emission for various biomass fuels used in Pakistan were evaluated. Based on the results of this investigation bagasse and straw are responsible for more than Ninety percent of all gaseous pollutants released. This research found that burning agricultural residues such rice straw, corncobs, rice husk, and bagasse released an estimated 80 Gt of CO, 3 Gt of CO2, 8.19 Gt of NO2, 15.70 Gt of NOX, and 1.42 Gt of SO2 (Irfan et al., 2014). Using 15 years of satellite data, to calculate the total emissions from agricultural residue burning in Pakistan. This research found that between 2000 and 2015, emissions of gaseous pollutants such as CO, NOx, CH4, N2O, NH3, OC, NMVOCs, and BC, PM2.5, rose by 37-63%, mostly due to increases in the agricultural sector. Most likely as a consequence of their extensive agricultural activity, areas in Punjab and Sindh emitted much more of these gaseous pollutants, notably CO. According to this research, the months of June, followed by the months of February and November, are the worst for emissions due to agricultural residue burnings in the districts of Muzaffargarh, Jafferabad, and Noushahro Feroze (Azhar et al., 2019).

Pollution in Lahore

Lahore, the provincial capital of Punjab, is located between 31°15′-31°45′ N and 74°01′-74°39′ E and is Pakistan's second-largest metropolis. According to one report, "Particulate Matter, ozone (O_3), zinc, carbon monoxide (CO), lead, carbon dioxide, and as well as some others" dominate the city's air quality (Ghauri et al., 2007). Lahore's air quality has worsened in recent years as a result of the city's increased industrialization and urbanization. A rise in Lahore's industrial and vehicle populations, together with deforestation and agricultural fires, have all played a role in this crisis. Population growth causes a decline in natural resources (Ahmed et al., 2019).

One of the most pressing problems in the region under consideration is the alarming rise in PM2.5 concentration. The only way out of this terrifying predicament is by vigilant observation, thorough analysis, and the implementation of preventative measures. Therefore, we concluded that it was crucial to measure and analyze PM2.5 levels in the region under investigation. To resolve an environmental problem, it is necessary to take the appropriate mitigation steps (Asghar, 2018). From November 2017 to October 2018, Sana et al. analyzed the PM2.5 concentration at three sample stations located on Gulberg, Ravi road, and Jail road to better comprehend Lahore city's air quality. PM2.5 concentrations were found to change both monthly and seasonally. Geographic information system data was used to analyze air quality. At the Gulberg monitoring site, PM2.5 concentrations range from 23 to 70 g/m^3. PM2.5 concentrations were from 34 to 170 g/m3 at the Jail road station, and from 70 to 188 g/m^3 at the Ravi road station. Ravi road had the highest concentration, whereas the

Gulberg sample station had the lowest. Geographic information system maps reveal PM2.5 concentration shifts throughout the research region. Then, the data is compared to the guidelines set out by the NAAQS-USEPA, the NEQS, and the WHO. The results reveal that between March 2018 and August 2018, the PM2.5 concentration was over the NEQS and NAAQS-USEPA requirements at the Ravi road and Jail road stations, while it was also above the norms at the Gulberg station. Industrial pollutants, vehicle emissions, and the burning of agricultural waste may all contribute to the elevated levels. Air quality may be affected by meteorological conditions as well. An alarmingly high PM2.5 concentration has a direct effect on human health and other environmental variables, making it a major problem for air quality (Basheer et al., 2019).
High levels of air particle matter give Lahore the reputation of being Pakistan's most polluted city. Researchers looked at the chemical make-up of PM2.5 and its sources in Lahore to learn how we may best reduce PM2.5 pollution in the city. Daily and overnight PM2.5 samples were taken in Lahore, Pakistan, and analyzed in July of 2018. Using reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) model, researchers in Lahore used techniques like concentration weighted trajectory calculation, principal component analysis, and spatial distribution analysis of black carbon to pinpoint PM2.5's origins and generating zones. To further identify the most important sources of air pollution, the fuel consumption situation in Pakistan was also analyzed. Carbonaceous chemicals made up the majority of the detected mass of PM2.5, with ions such as NO_3, Cl, and NH^{4+} coming in second and third, respectively. Despite a relatively high amount of secondary organic carbon (47%), primary organic carbon nevertheless predominated in OC samples from Lahore. Research into the relationship between PM2.5 and weather conditions found none. According to the CWT analysis and the geographical distribution of black carbon, pollution in Lahore is mostly attributable to local emission sources, with some contributions coming from the western regions of India. Controlling emissions from industry, transportation, and power plants would have noticeable benefits on reducing PM2.5 in Lahore right away, while majority of pollution is believed to originate from primary emissions from nearby sources (Ahmad et al., 2020).
In the urban regions of Lahore, Pakistan, PM2.5 samples are collected and analyzed twice a year, once in the winter and once in the summer. There is a significant difference between the two sample times in terms of the mass concentrations of PM2.5 and its carbonaceous species. In the winter, average OC levels are 50.7 30.5 g/m^3 and in the summer, they drop to 14.6 5.6 g/m^3, while EC levels rise to 26.5 18.0 g/m^3 from 8.6 3.4 g/m^3. The reported average OC/EC ratios throughout the winter and summer are 2.1 and 1.9, respectively. During the colder months, the OC and EC are highly correlated, suggesting they originate from the same mechanism. Enhanced photochemical reactions lead to increased biogenic emissions and secondary organic aerosol generation are responsible for the poor OC-EC association seen during the summer. In the winter, SOC accounts for 16.7% of total organic carbon, whereas in the summer it accounts for 22.6%. Inhalation dose is used to calculate the potential for exposure to EC. Human health may be negatively impacted by the increased chance of inhaling EC during the winter. Principal component analysis (PCA) revealed that emissions from combustion sources, vehicle emission, and secondary organic aerosol generation were the most important contributors to the carbonaceous species of PM2.5 in Lahore. When light levels are raised, biogenic emissions and the production of secondary organic aerosols are boosted showed that both regional and local pollution sources contributed to the elevated levels of PM2.5 and its carbonaceous species in Lahore (Ahmad et al., 2022).
To determine whether the levels of different particulate matter in specific locations of Lahore are within the globally recommended range, measurements were taken. This research was a cross sectional analysis of 24-hour PM concentration. The research took place in several parts of Lahore, Pakistan, where the authors found it most practical to do so. In certain regions of Lahore, a monitoring electronic gadget measured PM2.5, PM1, and PM10 concentrations. All measured particulate matter averaged well above World Health Organization guidelines. Lahore's average PM2.5 concentration was 79.43 micrograms per cubic meter, which is much higher than the WHO's recommended threshold (25 micrograms per cubic meter) and might increase the risk of developing severe respiratory and cardiovascular disorders (ASLAM et al., 2019).
Clean air, reduced pollution, and effective policy decisions about air pollution and climate change may all benefit from an evaluation of the patterns and variability of atmospheric particles. This research looked at fifteen major cities in South Asia and examined the patterns and variations in PM2.5 concentrations according to weather conditions. It used a wide variety of statistical and time-frequency models to evaluate the impact of climate. The patterns were discovered using the

Mann-Kendall test and other cutting-edge trend research tools. Most cities in this research showed extremely unhealthy air conditions throughout the winter, with Lahore having the worst air quality (105.43 g/m^3). Lahore showed increasing

PM2.5 trends. Temperature, precipitation, humidity, and wind speed were analyzed using Spearman rank and Pearson's correlation and linear regression to identify their impact on PM2.5 levels **(Table 2)**. Despite the variations in weather, most cities showed a sensitivity to humidity in PM2.5 concentrations ahead of temperature, precipitation, and wind speed. The majority of cities have an inverse correlation between PM2.5 and weather conditions. We ran bi-wavelet coherence (WC) analysis to learn more about the temporal relationships between PM2.5's frequency components and weather conditions. It was clear from this WC analysis that all climatic parameters had impacted PM2.5 concentrations over time, since there was a strong association between phase and antiphase correlations (Fattah et al., 2023).

Table 2. Statistical Analysis

Parameters	Min	Max	Skewness	Variance	Mean ± STD
Windspeed	0.86	8.89	0.722	1.62	3.40 ± 1.27
Rainfall	0	66.5	4.8	47	2.06 ± 6.89
Humidity	10.9	94.56	-0.181	263.25	52.29 ± 16.23
Temp	1.83	21.4	-0.29	10.20	12.68 ± 3.19

Pollution in Karachi

Over ninety-five percent of whole human population resides in areas with unhealthy air, making air pollution a major environmental concern on a global scale (Pangaribuan et al., 2019). The globe Health Organization (WHO) estimates that around 4.2 million and 3.8 million premature deaths occurred due to air pollution in the globe in 2018 and 2019, respectively, with 91% of the fatalities occurring in poor countries (Kumar et al., 2019). By 2050, the majority of the world's population is expected to be residing in urban areas, according to a United Nations assessment published in 2014. According to a 2014 study by Simpson et al., the majority of the world's ambient air pollution comes from the expansion of urban populations, vehicle emissions, and industrial activity.

Increases in industrial expansion, population, vehicle traffic, road dust, urbanization, emerging economic growth, motor vehicles with poor emission control and poor regulatory policies are all contributing to the deteriorating air quality in developing Southeast Asian countries like Pakistan (Lurie et al., 2019a). Rising populations and incomes in emerging nations have led to a dramatic rise in vehicle traffic, which in turn has increased emissions of harmful air pollutants (Ma et al., 2019). Inadequate laws, political challenges, and budgetary constraints mean that most developing nations lack sufficient air quality control systems (Malashock et al., 2018). One reason air pollution is still a severe environmental concern and human health danger is because in low-income nations, economic growth is of higher importance than air pollution mitigation or control.

With a yearly growth rate of 6%, Karachi has become the biggest metropolis in Pakistan (Lurie et al., 2019a). The city accounts for 30 percent of Pakistan's industrial sector output (Anjum et al., 2021b). There are about 4.14 million automobiles on Karachi's roadways. Old, overloaded buses serve almost 42% of Karachi's passengers, making it the worst public transportation system in the world, according to a 2019 research that assessed 100 large cities. Karachi is the only megacity without a comprehensive public transportation network. Municipal trash incineration and open burning are also major contributors to Karachi's poor air quality (Moryani et al., 2020).

South Asia's most polluted city is Karachi, Pakistan. To assess air quality, two mixed industrial and residential areas, Korangi and Tibet Center, were tested for PM2.5 over 24 hours. PM2.5, black carbon, water-soluble ions and trace elements were examined in samples from August 2008 to August 2009 to evaluate pollution's regional and temporal patterns and causes. The positive matrix factorization and elemental enrichment factor distinguished anthropogenic from natural causes. Korangi had 101 45.6 g m3 of 24-hour PM2.5, whereas Tibet Center had 76.5 38.4 g/m^3. Each site's 24-hour sample exceeded the WHO's 25 g/m^3 criteria **(Figure 2)**. Winter PM2.5 levels increased, suggesting more combustion and less air dispersion. EFs indicate substantial anthropogenic trace element inputs. Due to adjacent industry, Korangi experienced substantially more air pollution than Tibet Center. PMF research identified five sources and their contributions in Korangi and Tibet Center: 1) burning oil (25% and 21%), 2) resuspension of soil and urban dust (28% and 25%), 3) motor vehicle emissions (23% and 5%), 4) sea spray (13% and 26%), and 5) industry (11% and 23%). The findings showed that Karachi needs tight PM2.5 emission limitations to reduce air pollution's health concerns (Lurie et al., 2019b).

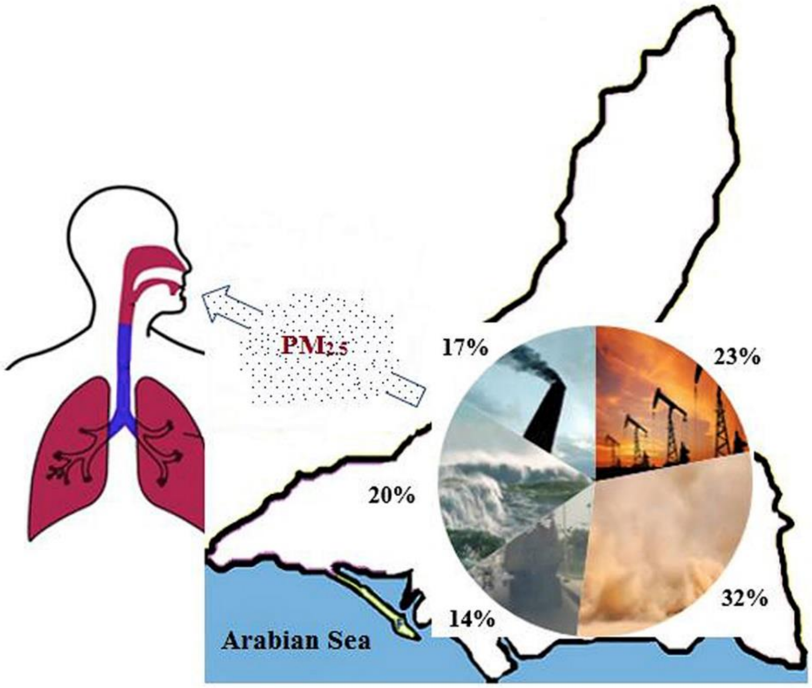

Figure 2. Effect PM 2.5 in Karachi

In Karachi, Pakistan, researchers measured a commuter's exposure to black carbon (BC) and their inhalation dosage while riding in a vehicle, bus, auto-rickshaw, or motorcycle. During the colder months, microAeth® AE51 BC monitors were used to track the actual concentrations of exposure during peak and off-peak business hours. During peak hours, exposure levels were twice as high as they were during off-peak hours. All four modes of transportation showed a similar pattern with respect to the steepness of the inhaled dose. Motorbikes were determined to be the most vulnerable, followed by auto-rickshaws, then vehicles, and finally buses. When considering inhaled doses, however, the order was flipped, with auto rickshaws having the greatest inhalation dosage, followed by buses, motorcycles, and cars. Driving on roads with less traffic and fewer junctions led to less exposures, as shown by a spatiotemporal study. Therefore, the major influences for BC exposure while driving were found to be traffic density, road geometry, travel time, and urbanicity (Lu et al., 2019).

Pollution in Faisalabad

The escalation of air pollution in numerous developing countries can be attributed to the concurrent rise of industrialization and overpopulation (Javed et al., 2016). Several studies conducted in high-income Asian countries have revealed that the concentration of numerous air pollutants frequently exceeds ambient air quality standards and guidelines established by the World Health Organization. The utilization of non-renewable sources of energy such as biomass and diesel in numerous developing nations has been linked to a rise in regional air pollution levels. Particulate matter that is suspended in the air is a prevalent component of the atmosphere and serves as a primary gauge of air quality within a designated region. There is a wide range of variation in the chemical make-up, concentration, and size of particulate matter, all of which are described by generally accepted standards based on size criteria ranging from PM2.5 to PM10 to Total Suspended Particles. It has also been determined that PM4 is the respirable size fraction (Shahid et al., 2016). Rapid industrialization, agriculture, refineries, waste incineration, biomass burning, motor vehicles, utilities, brick kiln, industrial emissions power plants, factories, large population, and heavy traffic are just some of the anthropogenic sources of particulate matter that contribute to poor air quality in urban areas. Other factors include secondary production processes and environmental causes, such as dust storms and sea spray. Transport of mineral dust from dry areas is recognized as a major source of air pollution in several Asian countries. Air quality management and epidemiological research cannot proceed without first assessing the quantity of particulate matter in the atmosphere and the toxicity of its components (Dinoi et al., 2017). Toxic particulate matter in the environment has been linked to an increase in cardiovascular and respiratory disease mortality and morbidity in several epidemiological studies, particularly in urban regions. The present study has demonstrated that the association between particulate matter and adverse health outcomes is more pronounced for PM2.5 as compared to PM10 or total suspended particles. This is attributed to the ability of PM2.5 to penetrate deeply into the alveolar regions of the human respiratory system. The relationship between the movement and dispersion of particulate matter in the atmosphere and meteorological factors, including relative humidity, wind direction, atmospheric pressure, speed, air temperature and rainfall, has been well-established (Leghari et al., 2013). Numerous monitoring programs have been implemented worldwide to investigate atmospheric PM, revealing inconsistencies and imbalances in the trace element components and particulate matter.

The atmospheric particulate matter is largely composed of carbonaceous aerosol, which comprises of elemental carbon and organic carbon. On average, the coarse particulate matter is subsidized by 20-35% and fine particulate matter is subsidized by 20-45% by these components. As a major component of both fine and coarse particulate matter, carbonaceous aerosols play a crucial role in the interactions of light particles in the atmosphere. As such, they are linked to adverse climatic and environmental effects, as well as a decline in air quality and public health (Choomanee et al., 2020). Carbon in its elemental form is frequently utilized as a replacement for black carbon and is emitted into the atmosphere predominantly via combustion mechanisms. Light absorbed by the atmosphere has a major effect on the planet's overall radiative balance, is primarily attributed to elemental carbon. The identification of the six primary origins of elemental carbon has been established through the utilization of organic tracers. These sources include biomass burning, cigarette smoke, coal combustion, cooking, vegetative detritus, and vehicle exhaust. The prevalence of carbonaceous aerosols in PM2.5, obtained from the combustion of agricultural waste and wood fuel, has been observed to exert a impact on the reduction of visibility and air quality. Additionally, it has been found to induce radiative forcing at a regional level (Bisht et al., 2016).

The air pollution control in Pakistan is hindered by inadequate information available to policy and decision-makers. Despite sporadic reports highlighting airborne particulate matter as a significant health and environmental issue in urban areas of Pakistan, the matter has not gained widespread attention. The concentration of particulate matter typically exceeds the documented acceptable limits set forth by the World Health Organization, National Environmental Quality Standards, and the United States Environmental Protection Agency by a significant margin. As per the report by the World Bank, the yearly impact of particulate matter on health in Pakistan amounts to 1% of the Gross Domestic Product, resulting in 700 fatalities among children and 22,000 premature deaths among adults. The degradation of air quality in the country is attributed to the lack of competencies in air quality management. Numerous international entities and governmental institutions have provided evidence indicating that air pollution poses a significant threat to the well-being of inhabitants, ecological systems, and overall quality of life (Niaz et al., 2015). Likewise, the present study underscores Faisalabad, renowned as the textile hub of Pakistan, as a city of pronounced pollution. The atmosphere of urban areas is deteriorating progressively due to the escalation of industrialization, the construction of commercial zones, and the rapid pace of urbanization (MAK SHAHID and AWAN, 2012).

The environmental impact of Faisalabad, the prospective megacity, is enormous because of its massive population and many industrial and anthropogenic sources of coarse particles and fine airborne particulate matter. The current study examined PM10 and PM2.5 concentrations and carbonaceous aerosols like organic carbon, elemental carbon, and total carbon in samples from five sectors: residential, health, commercial, industrial, and vehicular. This huge metropolis with businesses and agriculture presents its initial statistics. The study found that ambient PM2.5 and PM10 levels in Faisalabad consistently exceeded US-EPA 24-h standards and National Environment Quality Standards, affecting air quality and health. In summer and winter, PM2.5 averaged 124.71 ± 64.38 µg/m3 and 119.16 ± 64.91 µg/m3 and for total carbon. For PM10, TC ranged from 34.52 to 289.21 µg/m3 with an average of 44.04 to 300.02 µg/m3, 191.04 ± 87.98 (winter season), and an average of 181.50 ± 87.38 (summer season). Weather did not affect particle concentration. Faisalabad's air quality is low to seriously pollute, according to AQI and PI findings. The following sample locations have moderate AQI:, Saleemi Chowk, Pepsi Factory, Ittehad Welfare Dispensar, Nazria Pakistan Square, Kashmir Road, and Allied Hospital had higher AQI values. This research may help Faisalabad policymakers implement rigorous air pollution reduction plans (Aslam et al., 2020).

Air pollution is a major problem that may have devastating effects on human and nonhuman health on a worldwide scale. The purpose of this study was to determine the primary sources of air pollution in Faisalabad, Pakistan, a typical South Asian industrial metropolis. This study focused on carbon monoxide, fine particulate matter-2.5, coarse particulate matter-10, and total suspended particulate. Twenty locations representing the residential, healthcare, commercial/industrial, and transportation sectors of the city were surveyed over the course of a month. Total suspended particles, PM10, PM2.5, and

CO averaged 1037.62 383.6 g/m3, 434.62 65 g/m3, 35.88 1.7 g/m3, and 6.4 1.95 g/m3, respectively. The highest Air Quality Index values were recorded in business districts, followed by locations immediately around hospitals and manufacturing hubs. The acquired findings were compared to the permissible limits established by the Pakistan National Environmental Quality Standards. The results show that Faisalabad city's air quality is below the USEPA and NEQs criteria for TSP, PM10, PM2.5, and CO. lti-pollutant strategy to address the many causes of air pollution **(Figure 3)** (Aslam et al., 2021).

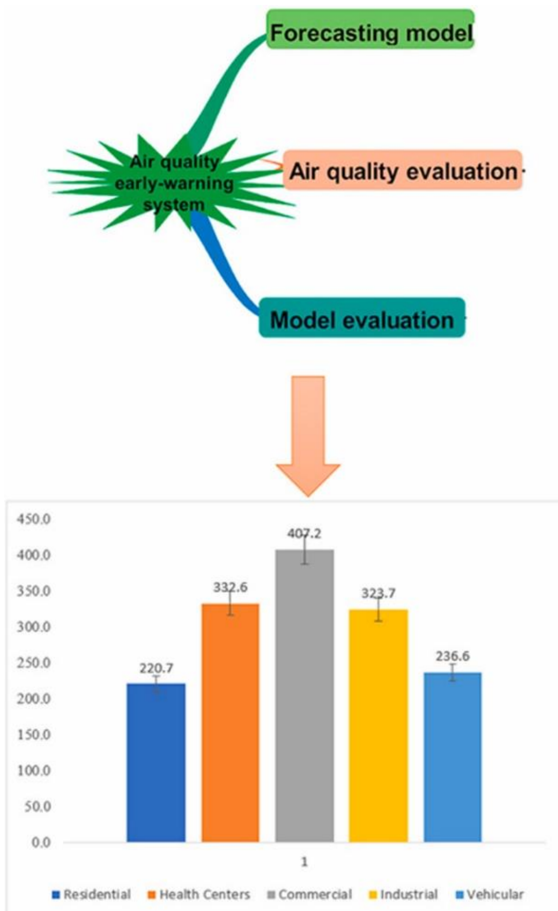

Figure 3. Air- quality in Fasialabad

Pollution in Islamabad

Islamabad, Pakistan's capital, is renowned worldwide for its cleanliness and abundance of green space. But the city's health and environment are worsening as a result of increasing urbanization and significant traffic flux. Particulate matter pollution is a major barrier to environmental and human health. The purpose of this research was to investigate the health and ecological effects of Islamabad's poor air quality. Two parallel medium volume air samplers with a flow rate of 100L/min and a Whatman 47 mm quartz filter were used to gather samples of the particulate matter in the air. Specifically in the winter, when 23 of 30 measured days were hazardous, the results demonstrated that PM2.5 is more destructive to ecosystems and outdoor activities. The air quality index for PM2.5 stayed between moderate and excellent during the other seasons, while for PM10 it remained between moderate and good throughout all four seasons. AirQ $^{+}$ software (WHO) estimated eight health endpoints using the obtained mean PM concentration. Long-term exposure to PM2.5 has been linked to 2,139 excess deaths from all causes, 26 from heart disease, and 24 from lung cancer, while annual admissions to hospitals for respiratory and cardiovascular disorders due to short-term exposure averaged 137 and 38, respectively. Long-term exposure to PM10 is associated with 488 deaths from chronic bronchitis in adults and 239 deaths from postneonatal baby all-cause mortality, respectively. As a result, 26 children in Islamabad develop asthma per year due to prolonged exposure to PM10 (Mehmood et al., 2019). The 379 filter sets were gathered from the Islamabad neighborhood of Nilore using a Gent sampler. This research set out to quantify natural and human-caused changes in the relative abundance of coarse particulate matter. Principal component analysis and cluster analysis were carried out using MATLAB software for the purpose of source identification. In accordance with Pakistan's 24-hour air quality regulations, coarse particle masses throughout the research period were 37.3 28.0, 11.9, 15.1 g/m^3, respectively. In applying PCA to PM2.5 data, we see signatures of suspended soil, vehicle exhaust, road dust, tyre wear, wood combustion, biomass burning, refuse incineration, nickel smelter, fertilizers, and fungicides. In contrast, for PM2.5-10 data, we see signatures of coal combustion, refuse incineration, fertilizers, and fungicides. Cluster analysis of PM2.5 and PM2.5-10 datasets identifies automobile-related sources, suspended soil particles, coal combustion and wood as the primary contributors to air pollution (Waheed et al., 2012).

A total of 379 filter sets were collected from the Nilore locality in Islamabad utilizing a Gent sampler. The purpose of this study was to measure the alterations in the proportion of trace elements present in coarse and fine particulate matter, caused by both natural and anthropogenic factors. The process of source identification was conducted through the utilization of MATLAB software for Principal Component Analysis and Cluster Analysis. The study adhered to Pakistan's 24-hour air quality regulations, and the mean masses of fine and coarse particles during the research period were recorded as 15.1 ± 11.9 g/m3 and 37.3 ± 28.0 g/m^3, respectively. The application of Principal Component Analysis (PCA) to PM2.5 data reveals the presence of distinct signatures associated with various sources, including wood combustion, vehicle exhaust, road dust, tyre wear, refuse incineration, biomass burning, nickel smelter, fertilizers, suspended soil, and fungicides. In contrast, the PM2.5-10 data exhibits discernible characteristics associated with refuse incineration fertilizers, coal combustion, and fungicides. The PM2.5 and PM2.5-10 datasets were subjected to cluster analysis, revealing that the major sources of air pollution are suspended soil particles, wood and coal combustion and automobile-related sources (Siddique et al., 2012).

Other Cities

The World Health Organization (WHO) reports that urban outdoor air pollution is accountable for 1.3 million fatalities each year. The reduction of air pollution has the capacity to lower the worldwide prevalence of illnesses such as pneumonia, heart disease, and lung cancer. Many urban areas, including Multan, Pakistan, face considerable health challenges due to air pollution. The primary cause of this pollution is the exposure to particulate matter (PM) and ozone (O_3). The lack of national inventories that provide estimations of air pollution emissions in Pakistan is a significant concern, alongside the absence of regular air quality monitoring. As per the Pakistan Environmental Protection Agency (Pak-EPA), a noteworthy fraction of motor vehicle emissions can be ascribed to a restricted subset of diesel and two-stroke automobiles that discharge smoke. Nevertheless, the exact extent of this contribution remains indeterminate. The occurrence of particulate matter (PM) in the atmosphere is hypothesized to be predominantly ascribed to the heightened concentrations of sulfur content detected in diesel fuel for automobiles (0.5-1%) and furnace oil (1-3.5%). The use of contaminated "waste" fuels, such as old tires, paper, wood, and textile waste, in combination with diesel electric generators, in various settings including commercial and residential areas, large facilities, and small-to-medium scale industries such as brick kilns, steel rerolling, steel recycling, and plastic molding, has been identified as a significant contributor to environmental pollution. Multan city generates an estimated 48,000 metric tons of solid waste per day. A significant proportion of this waste is deposited in regions characterized by low altitude or subjected to incineration under suboptimal thermal conditions. This activity leads to the discharge of particulate matter (PM) and other harmful carcinogenic pollutants, thus making a significant contribution to the air pollution levels in the urban area. The continuous measurement of three meteorological parameters, namely PM 2.5 (particulate matter with a diameter less than 2.5 m), PM 10 (particulate matter with a diameter less than 10 m), and O_3, is conducted by the air quality monitoring system. The data measurements obtained will advance our understanding in the field of atmospheric sciences and air quality monitoring. Consequently, this will enhance our ability to manage regional resources towards achieving sustainable and enduring expansion. A preliminary plan for monitoring air quality has been established in collaboration with the PMD. The aim of this plan is to collect relevant data pertaining to the local environment. The objective of this proposal is to offer suggestions for executing an action plan that will

improve the air quality in Multan City. The suggested plan of action involves enhancing environmental regulations, executing infrastructure-related measures such as road enhancements to alleviate dust emissions, and conducting educational initiatives targeted at advocating for air pollution control in schools and the broader community (Vuillermoz et al., 2014).

This research reports on the prevalence of common health problems related to particulate matter (PM) pollution in the air across the city of Sialkot in Pakistan. Using a light-scattering laser photometer, particle size distributions were tracked at nine separate sample locations. Concentrations of PM1.0, PM2.5, and PM4.0 varied between 282 and 528 micrograms per cubic meter (g/m^3), 360 and 677 g/m^3, and 382 and 724 g/m^3, respectively, whereas concentrations of PM10 varied between 440 and 843 g/m^3. The PM levels around the city were then extrapolated using this information. Particle pollution levels were determined to be the highest at China Chowk. The city of Sialkot's ambient air was shown to have a particulate matter load that was over the National Ambient Air Quality Standards (NEQS). With a p-value less than 0.05, Analysis of Variance (ANOVA) found statistically significant differences in PM concentrations across all sample locations.

25.4%, 37.3%, 20.9%, and 16.4% of the population were affected by influenza, cough, eye, or skin disorders, respectively (Mumtaz et al., 2017).

Conclusion and Future perspective

The present review paper offers a thorough examination of the spatiotemporal fluctuations of PM2.5 and black carbon (BC) in Pakistan, along with their dynamic correlation with meteorological parameters. The results emphasize the noteworthy spatial heterogeneity and temporal fluctuations of said pollutants throughout the nation. The study has identified urban areas as hotspots exhibiting elevated concentrations of PM2.5 and BC in comparison to their rural counterparts. The analysis has also unveiled the intricate interrelationship between meteorological variables and air contamination. Temperature, humidity, wind velocity, and atmospheric steadiness have an impact on the scattering and aggregation of pollutants. Drawing upon an analysis of the spatiotemporal fluctuations of PM2.5 and black carbon (BC), as well as their dynamic interplay with meteorological factors in Pakistan, a number of suggestions can be proffered for forthcoming research and interventions. The objective of these guidelines is to augment our comprehension of the dynamics of air pollution and to aid in the implementation of efficient air quality management strategies.

- Long-term monitoring campaigns should be conducted in different regions of Pakistan to capture the seasonal and interannual variations in PM2.5 and BC levels. The aforementioned activity is expected to yield significant data that can be utilized for trend analysis, identification of pollution hotspots, and assessment of the efficacy of pollution control measures.
- The improvement of emission inventories can be achieved by the integration of data from various sectors, including but not limited to industry, transportation, and residential sources. The improvement of precision in source apportionment investigations and the development of focused interventions aimed at mitigating particular sources of pollution can be facilitated through this approach.
- Advanced modeling techniques are employed to simulate and predict air pollution episodes by coupling advanced air quality models with meteorological models. The comprehension of intricate interplays between meteorological conditions and air pollution can be enhanced, thereby facilitating the creation of efficient early warning systems and focused interventions.
- Conducting source apportionment studies is crucial in identifying the primary sources of PM2.5 and BC pollution in particular regions. The aforementioned approach can aid policymakers in the execution of focused control measures and regulations aimed at reducing pollution originating from particular sources.
- The integration of remote sensing data is a recommended approach to enhance the spatial coverage of air pollution data. This method involves the utilization of remote sensing data, including satellite observations, to complement ground-based monitoring. By doing so, the combination of these two sources of data can provide a more comprehensive understanding of air pollution patterns and trends. The integration of various techniques can aid in enhancing the comprehension of the spatial dispersion and conveyance of contaminants, particularly in areas that are remote or not easily accessible.

Refrence

Abdurrahman, M.I., Chaki, S., Saini, G., 2020. Stubble burning: Effects on health & environment, regulations and management practices. Environmental Advances 2, 100011.

Ahmad, M., Alam, K., Tariq, S., Anwar, S., Nasir, J., Mansha, M., 2019. Estimating fine particulate concentration using a combined approach of linear regression and artificial neural network. Atmospheric Environment 219, 117050.

Ahmad, M., Chen, J., Yu, Q., Lee, H., Khan, M.T., Ali, S.W., Nawab, A., Panyametheekul, S., 2022. Characteristics, sources, and exposure risk of the carbonaceous species of PM2. 5 in Lahore, Pakistan.

Ahmad, M., Cheng, S., Yu, Q., Qin, W., Zhang, Y., Chen, J., 2020. Chemical and source characterization of PM2.5 in summertime in severely polluted Lahore, Pakistan. Atmospheric Research 234, 104715.

Ahmed, A., Nasir, A., Basheer, S., Arslan, C., Anwar, S., 2019. Ground water quality assessment by using geographical information system and water quality index: A case study of chokera, Faisalabad, Pakistan. Water Conserv. Manag 3, 7-19.

Anjum, M.S., Ali, S.M., Imad-ud-din, M., Subhani, M.A., Anwar, M.N., Nizami, A.-S., Ashraf, U., Khokhar, M.F., 2021a. An Emerged Challenge of Air Pollution and Ever-Increasing Particulate Matter in Pakistan; A Critical Review. Journal of Hazardous Materials 402, 123943.

Anjum, M.S., Ali, S.M., Subhani, M.A., Anwar, M.N., Nizami, A.-S., Ashraf, U., Khokhar, M.F., 2021b. An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review. Journal of Hazardous Materials 402, 123943.

Asghar, M.Z., 2018. Comparative assessment of physico-chemical parameters of waste water effluents from different industries in Lahore, Pakistan. Proceedings of the International Academy of Ecology and Environmental Sciences 8, 99.

Aslam, A., Ibrahim, M., Mahmood, A., Mubashir, M., Sipra, H.F.K., Shahid, I., Ramzan, S., Latif, M.T., Tahir, M.Y., Show, P.L., 2021. Mitigation of particulate matters and integrated approach for carbon monoxide remediation in an urban environment. Journal of Environmental Chemical Engineering 9, 105546.

Aslam, A., Ibrahim, M., Shahid, I., Mahmood, A., Irshad, M.K., Yamin, M., Ghazala, Tariq, M., Shamshiri, R.R., 2020. Pollution Characteristics of Particulate Matter (PM2.5 and PM10) and Constituent Carbonaceous Aerosols in a South Asian Future Megacity. Applied Sciences 10, 8864.

ASLAM, S., T KHAN, F., ASLAM, S., 2019. The Injurious Particulate matter Concentrations in the Atmosphere in Lahore. PJMHS.

Atkinson, R.W., Mills, I.C., Walton, H.A., Anderson, H.R., 2015. Fine particle components and health—a systematic review and meta-analysis of epidemiological time series studies of daily mortality and hospital admissions. Journal of exposure science & environmental epidemiology 25, 208-214.

Azhar, R., Zeeshan, M., Fatima, K., 2019. Crop residue open field burning in Pakistan; multi-year high spatial resolution emission inventory for 2000–2014. Atmospheric Environment 208, 20-33.

Baruah, U.D., Robeson, S.M., Saikia, A., Mili, N., Sung, K., Chand, P., 2022. Spatio-temporal characterization of tropospheric ozone and its precursor pollutants NO2 and HCHO over South Asia. Science of The Total Environment 809, 151135.

Basheer, S., Rashid, H., Nasir, A., Nawaz, R.A., 2019. Spatial and temporal variability analysis of PM2. 5 concentration in Lahore City. Environmental Contaminants Reviews (ECR) 2, 06-10.

Bennett, J.E., Tamura-Wicks, H., Parks, R.M., Burnett, R.T., Pope III, C.A., Bechle, M.J., Marshall, J.D., Danaei, G., Ezzati, M., 2019. Particulate matter air pollution and national and county life expectancy loss in the USA: A spatiotemporal analysis. PLoS medicine 16, e1002856.

Bisht, D., Tiwari, S., Dumka, U., Srivastava, A., Safai, P., Ghude, S., Chate, D., Rao, P., Ali, K., Prabhakaran, T., 2016. Tethered balloon-born and ground-based measurements of black carbon and particulate profiles within the lower troposphere during the foggy period in Delhi, India. Science of the Total Environment 573, 894-905.

Biswas, K.F., Ghauri, B.M., Husain, L., 2008. Gaseous and aerosol pollutants during fog and clear episodes in South Asian urban atmosphere. Atmospheric Environment 42, 7775-7785.

Choomanee, P., Bualert, S., Thongyen, T., Salao, S., Szymanski, W.W., Rungratanaubon, T., 2020. Vertical variation of carbonaceous aerosols with in the PM2. 5 fraction in Bangkok, Thailand. Aerosol and Air Quality Research 20, 43-52.

Dinoi, A., Cesari, D., Marinoni, A., Bonasoni, P., Riccio, A., Chianese, E., Tirimberio, G., Naccarato, A., Sprovieri, F., Andreoli, V., 2017. Inter-comparison of carbon content in PM2. 5 and PM10 collected at five measurement sites in Southern Italy. Atmosphere 8, 243.

Fattah, M.A., Morshed, S.R., Kafy, A.A., Rahaman, Z.A., Rahman, M.T., 2023. Wavelet coherence analysis of PM2.5 variability in response to meteorological changes in South Asian cities. Atmospheric Pollution Research 14, 101737.

Furrer, M., Mostofi, H., Spinler, S., 2022. A study on the impact of extreme weather events on the ceramic manufacturing in Egypt. Resources, Environment and Sustainability 7, 100049.

Ghauri, B., Lodhi, A., Mansha, M., 2007. Development of baseline (air quality) data in Pakistan. Environmental Monitoring and Assessment 127, 237-252.

Hashmi, M.Z., Ashraf, K., Adnan, S., Wang, S., Pongpiachan, S., Su, X., Ahmed, Z., 2020. Spatio-temporal assessment and climatology of atmospheric organic carbon over Pakistan. Arabian Journal of Geosciences 13, 1-13.

Hussain, A., Ahmed, F., Dharmage, S.C., Aslam, M.S., Abbas, Z., 2019. Aero and Food Allergens Sensitization Patterns in a Clinic-Based Sample in Pakistan: A One Year Retrospective Study. Pakistan Journal of Zoology 51.

Hussain, M., Akhtar, F., Khan, S.S., 2018. Impact and Ratio of Lead in Ambient Air from Vehicular Emission in Quetta Valley, Pakistan, IOP Conference Series: Materials Science and Engineering. IOP Publishing, p. 012044.

Imran, N., Rahman, A., Chaudhry, N., Asif, A., 2022. Effectiveness of a school-based mental health intervention for school teachers in urban Pakistan: a randomized controlled trial. Child and Adolescent Psychiatry and Mental Health 16, 1-12.

Irfan, M., Riaz, M., Arif, M.S., Shahzad, S.M., Saleem, F., van den Berg, L., Abbas, F., 2014. Estimation and characterization of gaseous pollutant emissions from agricultural crop residue combustion in industrial and household sectors of Pakistan. Atmospheric environment 84, 189-197.

Javed, W., Wexler, A.S., Murtaza, G., Ahmad, H.R., Basra, S.M., 2015. Spatial, temporal and size distribution of particulate matter and its chemical constituents in Faisalabad, Pakistan. Atmósfera 28, 99-116.

Javed, W., Wexler, A.S., Murtaza, G., Iqbal, M.M., Zhao, Y., Naz, T., 2016. Chemical characterization and source apportionment of atmospheric particles across multiple sampling locations in Faisalabad, Pakistan. CLEAN–Soil, Air, Water 44, 753-765.

Khan, M.W., Ali, Y., De Felice, F., Salman, A., Petrillo, A., 2019. Impact of brick kilns industry on environment and human health in Pakistan. Science of the Total Environment 678, 383-389.

Khwaja, H.A., Fatmi, Z., Malashock, D., Aminov, Z., Kazi, A., Siddique, A., Qureshi, J., Carpenter, D.O., 2013. Effect of air pollution on daily morbidity in Karachi, Pakistan. Journal of Local and Global Health Science 2012, 3.

Kuehn, B.M., 2014. WHO: More than 7 million air pollution deaths each year. Jama 311, 1486-1486.

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., 2019. The nexus between air pollution, green infrastructure and human health. Environment international 133, 105181.

Leghari, S.K., Zaidi, M.A., Ahmed, M., Sarangzai, A.M., 2013. Assessment of suspended particulate matters level and role of vegetation in ambient air of North-East Balochistan, Pakistan. FUUAST Journal of Biology 3, 37-43.

Lodhi, A., Ghauri, B., Khan, M.R., Rahman, S., Shafique, S., 2009. Particulate matter (PM2. 5) concentration and source apportionment in Lahore. Journal of the Brazilian Chemical Society 20, 1811-1820.

Lu, Y., Lin, S., Fatmi, Z., Malashock, D., Hussain, M.M., Siddique, A., Carpenter, D.O., Lin, Z., Khwaja, H.A., 2019. Assessing the association between fine particulate matter (PM2. 5) constituents and cardiovascular diseases in a mega-city of Pakistan. Environmental Pollution 252, 1412-1422.

Lurie, K., Nayebare, S.R., Fatmi, Z., Carpenter, D.O., Siddique, A., Malashock, D., Khan, K., Zeb, J., Hussain, M.M., Khatib, F., 2019a. PM2. 5 in a megacity of Asia (Karachi): Source apportionment and health effects. Atmospheric Environment 202, 223-233.

Lurie, K., Nayebare, S.R., Fatmi, Z., Carpenter, D.O., Siddique, A., Malashock, D., Khan, K., Zeb, J., Hussain, M.M., Khatib, F., Khwaja, H.A., 2019b. PM2.5 in a megacity of Asia (Karachi): Source apportionment and health effects. Atmospheric Environment 202, 223-233.

Ma, T., Duan, F., He, K., Qin, Y., Tong, D., Geng, G., Liu, X., Li, H., Yang, S., Ye, S., 2019. Air pollution characteristics and their relationship with emissions and meteorology in the Yangtze River Delta region during 2014–2016. Journal of Environmental Sciences 83, 8-20.

MAK SHAHID, K.H., AWAN, M., 2012. Characterization of Solid Aerosols related to Faisalabad Environment and their probable sources.

Malashock, D., Khwaja, H.A., Fatmi, Z., Siddique, A., Lu, Y., Lin, S., Carpenter, D., 2018. Short-term association between black carbon exposure and cardiovascular diseases in Pakistan's largest megacity. Atmosphere 9, 420.

Mehmood, T., Tianle, Z., Ahmad, I., Li, X., 2019. Integration of AirQ+ and particulate matter mass concentration to calculate health and ecological constraints in Islamabad, Pakistan, 2019 16th international bhurban conference on applied sciences and technology (ibcast). IEEE, pp. 248-254.

Mishra, R.K., Kumar, D.J.P., Narula, A., Chistie, S.M., Naik, S.U., 2023. Production and beneficial impact of biochar for environmental application: A review on types of feedstocks, chemical compositions, operating parameters, techno-economic study, and life cycle assessment. Fuel 343, 127968.

Moryani, H.T., Kong, S., Du, J., Bao, J., 2020. Health risk assessment of heavy metals accumulated on PM2. 5 fractioned road dust from two cities of Pakistan. International Journal of Environmental Research and Public Health 17, 7124.

Mumtaz, M.W., Danish, M., Raza, M.A., Mukhtar, H., Arshad, M., Afzal, S., Zubair, M., Raza, S.A., 2017. PARTICULATE MATTER ASSESSMENT AT SELECTED POINTS IN AMBIENT AIR OF DISTRICT SIALKOT, PAKISTAN. FEB-FRESENIUS ENVIRONMENTAL BULLETIN, 5693.

Nations, U., 2017. World population prospects: the 2017 revision, key findings and advance tables. Department of Economics and Social Affairs PD, editor. New York: United Nations 46.

Niaz, Y., Zhou, J., Iqbal, M., Nasir, A., Dong, B., 2015. Ambient Air Quality Evaluation: A Comparative Study in China and Pakistan. Polish Journal of Environmental Studies 24.

Pangaribuan, M., Chuang, K.-J., Chuang, H.-C., 2019. Association between exposures to air pollution and biomarkers of cardiovascular disease in Northern Taiwan. Atmospheric Pollution Research 10, 1250-1259.

Rana, A., Parvez, S., Ul-Haq, Z., Batool, S., Chaudhary, M., Mahmood, K., Tariq, S., 2019. Anthropogenic, biogenic and pyrogenic emission sources and atmospheric formaldehyde (HCHO) and nitrogen dioxide (NO2) columns over different landuse/landcovers of South Asia. Ecol. Env. Res 17, 10989-11015.

Rasheed, A., Aneja, V.P., Aiyyer, A., Rafique, U., 2015. Measurement and analysis of fine particulate matter (PM2. 5) in urban areas of Pakistan. Aerosol and Air Quality Research 15, 426-439.

Rehman, A., Deyuan, Z., 2018. Pakistan's energy scenario: a forecast of commercial energy consumption and supply from different sources through 2030. Energy, sustainability and society 8, 1-5.

Sawlani, R., Agnihotri, R., Sharma, C., Patra, P.K., Dimri, A., Ram, K., Verma, R.L., 2019. The severe Delhi SMOG of 2016: A case of delayed crop residue burning, coincident firecracker emissions, and atypical meteorology. Atmospheric Pollution Research 10, 868-879.

Sénéchal, H., Visez, N., Charpin, D., Shahali, Y., Peltre, G., Biolley, J.-P., Lhuissier, F., Couderc, R., Yamada, O., Malrat-Domenge, A., 2015. A review of the effects of major atmospheric pollutants on pollen grains, pollen content, and allergenicity. The Scientific World Journal 2015.

Shahid, I., Kistler, M., Mukhtar, A., Ghauri, B.M., Ramirez-Santa Cruz, C., Bauer, H., Puxbaum, H., 2016. Chemical characterization and mass closure of PM10 and PM2. 5 at an urban site in Karachi–Pakistan. Atmospheric environment 128, 114-123.

Shahid, M.Z., Liao, H., Li, J., Shahid, I., Lodhi, A., Mansha, M., 2015. Seasonal variations of aerosols in Pakistan: Contributions of domestic anthropogenic emissions and transboundary transport. Aerosol Air Qual. Res 15, 1580-1600.

Siddique, N., Waheed, S., Daud, M., Markwitz, A., Hopke, P., 2012. Air quality study of Islamabad: preliminary results. Journal of Radioanalytical and Nuclear Chemistry 293, 351-358.

Stone, E., Schauer, J., Quraishi, T.A., Mahmood, A., 2010. Chemical characterization and source apportionment of fine and coarse particulate matter in Lahore, Pakistan. Atmospheric Environment 44, 1062-1070.

Vuillermoz, E., Cristofanelli, P., Putero, D., Verza, G., Alborghetti, M., Melis, M.T., Rasul, G., Listo, L., Bonasoni, P., 2014. Air quality measurements at Multan, Pakistan. Sustainable Social, Economic and Environmental Revitalization in Multan City: A Multidisciplinary Italian–Pakistani Project, 137-147.

Waheed, S., Jaafar, M.Z., Siddique, N., Markwitz, A., Brereton, R.G., 2012. PIXE analysis of PM2. 5 and PM2. 5–10 for air quality assessment of Islamabad, Pakistan: Application of chemometrics for source identification. Journal of Environmental Science and Health, Part A 47, 2016-2027.

WHO, G., 2014. Burden of disease from Ambient Air Pollution for 2012. Description of Method, Version 1.

Yan, H., Ding, G., Li, H., Wang, Y., Zhang, L., Shen, Q., Feng, K., 2019. Field evaluation of the dust impacts from construction sites on surrounding areas: a city case study in China. Sustainability 11, 1906.

Yasar, A., Haider, R., Tabinda, A.B., Kausar, F., Khan, M., 2013. A comparison of engine emissions from heavy, medium, and light vehicles for CNG, diesel, and gasoline fuels. Pol. J. Environ. Stud 22, 1277-1281.