Spatial Assessment of Atmospheric Contamination and Urban Heat Phenomenon in Urban Centers of Sindh, Pakistan

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Rapid urbanization and industrialization in Sindh, Pakistan, particularly in urban centers like Karachi, have led to significant challenges related to air pollution and climate change. This study uses Geographic Information Systems (GIS) to analyze air quality indices (AQI) in Sindh, focusing on particulate matter such as PM2.5. It offers a novel approach by visually mapping the spatial patterns and potential correlations between air pollution and temperature, a topic not extensively covered before. Through interpolation methods and temporal graphing of AQI values, the study identifies areas with high air pollution and examines their spatial distribution throughout the year. The comparison of PM2.5 concentrations with land surface temperature (LST) maps reveals patterns where higher pollution levels often align with urban centers, intensifying the urban heat island effect due to excess heat generated by human activities. Beyond impacting human health, air pollution affects ecosystems, soil, water, and biodiversity. The study highlights how areas with significant air pollution tend to have higher surface temperatures, indicating a direct link between pollution and temperature increases. However, the relationship is complex, as the effects of air pollution on climate are influenced by factors like geographic location, meteorological conditions, and pollutant composition. This research provides valuable insights into the spatial dynamics of atmospheric contamination and its implications for urban heat formation in Sindh, enhancing the understanding of how human activities, air quality, and climate change interact.

Keywords: Air Pollution, Urban Heat Island, Climate Change, Spatial Analysis, Urbanization.

Introduction:

Urbanization, a defining feature of the 21st century, has significantly altered the natural environment, with over half of the global population now living in urban areas. This rapid expansion has led to substantial challenges, particularly concerning air pollution and urban heat islands (UHIs). High levels of atmospheric pollutants, including particulate matter (PM) and nitrogen oxides (NOx), result from human activities and industrial processes, posing risks to health and climate stability. Simultaneously, urban heat islands intensify temperature differences between urban and rural areas, affecting health, energy consumption, and local climate patterns [1]. Addressing these challenges requires in-depth research to understand spatial dynamics and driving forces, utilizing advanced methodologies such as geographic information systems (GIS) and remote sensing.

Recent studies have underscored the severity of air pollution and its effects on urban environments. [2] conducted a study monitoring air quality in Karachi's major industrial zones from 2020 to 2022. The research found that pollutant concentrations were moderate post-monsoon compared to pre-monsoon due to cyclical effects. Levels of particulate matter (TSPM, PM2.5, PM10), SO2, NO2, and CO exceeded environmental standards. Notably, North Karachi had a lower risk due to its smaller industrial base. The elevated pollutant levels pose health risks and negatively impact plant growth and soil quality, highlighting the need for local environmental standards to address these issues [3].

The rapid urbanization and industrial development in Pakistan, particularly in major urban centers like Karachi, have intensified challenges related to air pollution and climate change. This research employs GIS techniques to assess air quality indices (AQI) in Pakistan, focusing on particulate matter such as PM2.5. By analyzing AQI values and identifying areas with high air pollution, the study aims to illuminate the spatial distribution of atmospheric contamination and its implications for urban heat island formation [4].

Moreover, this study explores the relationship between urban growth, atmospheric contamination, and the urban heat island effect in Sindh province, Pakistan. Urbanization in Sindh, especially in densely populated cities like Karachi, contributes significantly to air pollution [5][6]. The rapid expansion of urban areas increases emissions from vehicles, industrial operations, and energy consumption, all of which release pollutants into the atmosphere. Additionally, urbanization leads to deforestation and land degradation, reducing natural barriers that mitigate air pollution. These factors exacerbate air quality issues in Sindh's urban centers.

Objectives:

- To assess the spatial distribution of air pollution in urban centers of Sindh, Pakistan: Identify areas with high levels of particulate matter (PM2.5) and analyze temporal variations in air quality indices (AQI).
- To examine the relationship between air pollution and the urban heat island effect: Compare PM2.5 concentrations with land surface temperature (LST) maps to illustrate spatial patterns and potential correlations between air pollution and temperature.
- To explore the impacts of urbanization on air quality and land surface temperature (LST): Use GIS and remote sensing techniques to analyze the effects of urban expansion on environmental parameters in Sindh.
- To provide insights for urban planning and environmental management: Develop strategies for mitigating the adverse impacts of urbanization, focusing on pollution control and climate adaptation measures.

By achieving these objectives, the study aims to enhance understanding of atmospheric contamination and its implications for urban heat phenomena in Sindh.

World Map of Global Climate Risk Index:

Study Area: Sindh is situated between 23° 42’ North to 28° 29’ North latitude and 66° 41’ East to 71° 10’ East longitude. It is bordered by the Arabian Sea to the south, the Indian states of Gujarat and Rajasthan to the east, Punjab province to the north, and Balochistan province to the west. The Indus River runs through the province from north to south, serving as a crucial water source and influencing regional agricultural activities. Urban areas in Sindh include Karachi, Hyderabad, Sukkur, Larkana, and Mirpurkhas. Karachi, the provincial capital, is the largest city in Sindh and Pakistan's primary economic hub, located between 24° 45’ North to 25° 37’ North latitude and 66° 42’ East to 67° 34’ East longitude, about eighty miles west of the Indus River. Its surrounding areas include Dadu District to the north and northeast, Thatta District to the east, the Arabian Sea to the south and southwest, and Lasbela District (Balochistan) to the northwest [7]. Figure 1 shows the World Map of Global Climate Risk Index 2000-2019.

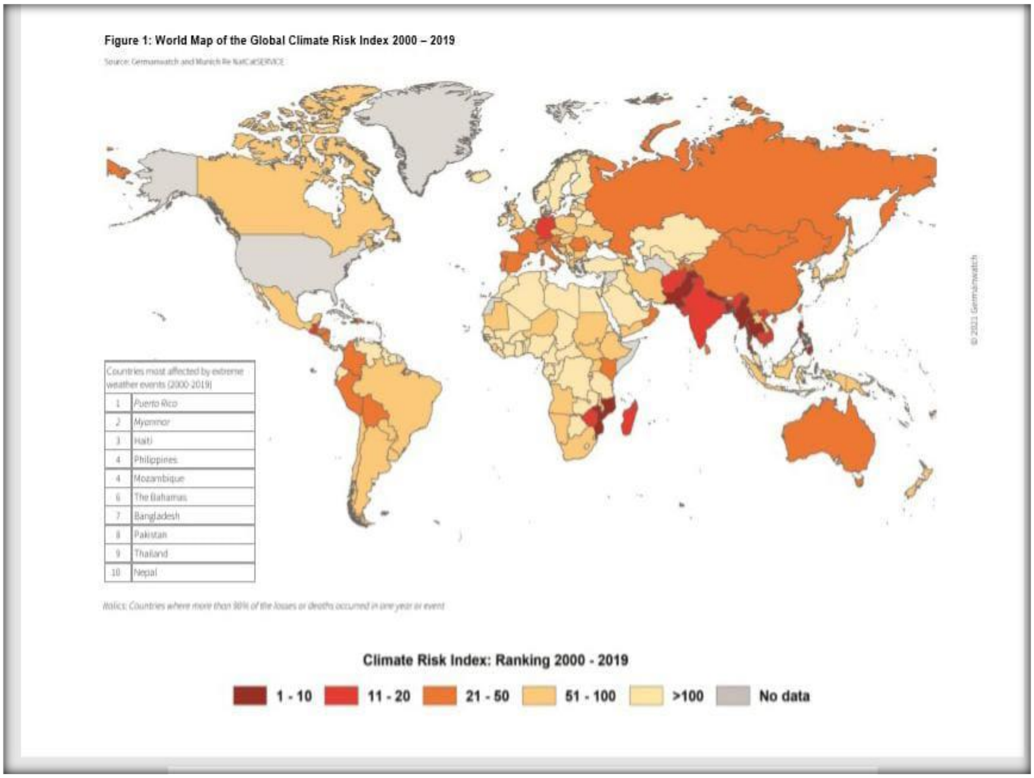


Figure 1: World Map of Global Climate Risk Index 2000-2019.

Sindh's urban areas are marked by rapid growth and diverse populations, as illustrated in Figure 2. Cities such as Hyderabad, located on the east bank of the Indus River, are vital commercial and cultural hubs. Likewise, Sukkur, situated further north along the Indus, is renowned for its historical significance and strategic location [8]. Sindh's urban landscape combines historical heritage with modern development, confronting challenges related to infrastructure development, environmental conservation, and socio-economic disparities [9].

Study Area of Sindh:

Methodology:

Figure 3 shows the flow diagram of the methodology. This study utilized secondary data sources, including research papers, articles, and air quality data from IQAir, alongside MODIS satellite imagery from the United States Geological Survey (USGS). The data were analyzed using ArcGIS software to perform spatial analysis and mapping, focusing on PM2.5 concentrations and Land Surface Temperature (LST) to assess the impacts of urbanization on air quality and the urban heat island effect in Sindh [10]. The study leveraged secondary data to estimate the effects of urbanization on air quality and LST in Sindh, using sources from research papers, articles, and USGS, with additional air quality data from IQAir. A quantitative research design was employed to analyze spatial and environmental data, suitable for measuring urbanization effects [11].

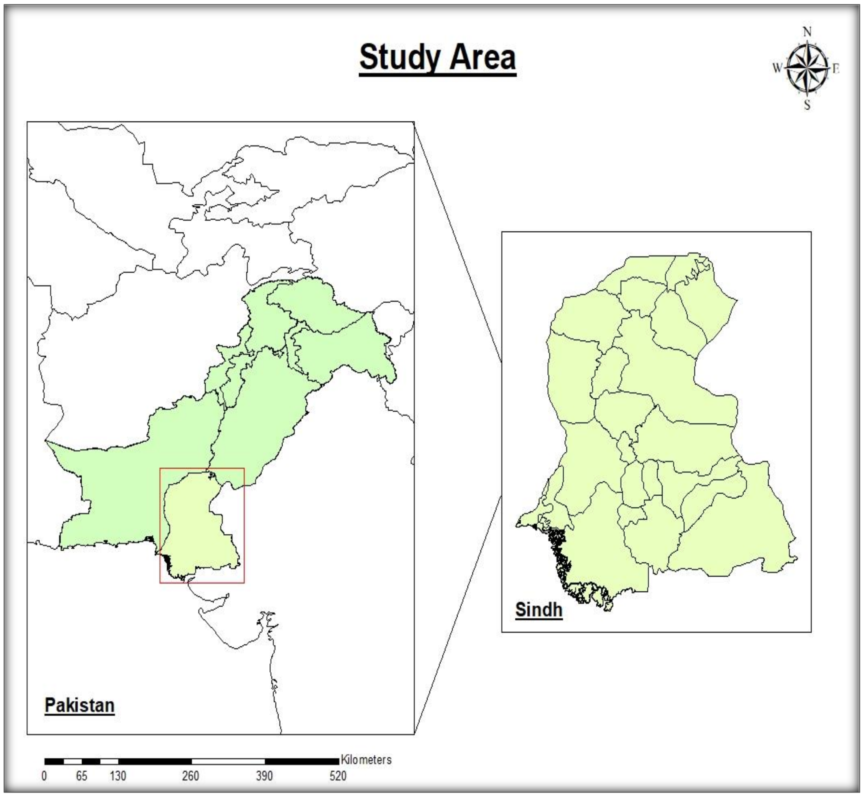


Figure 2: Study site.

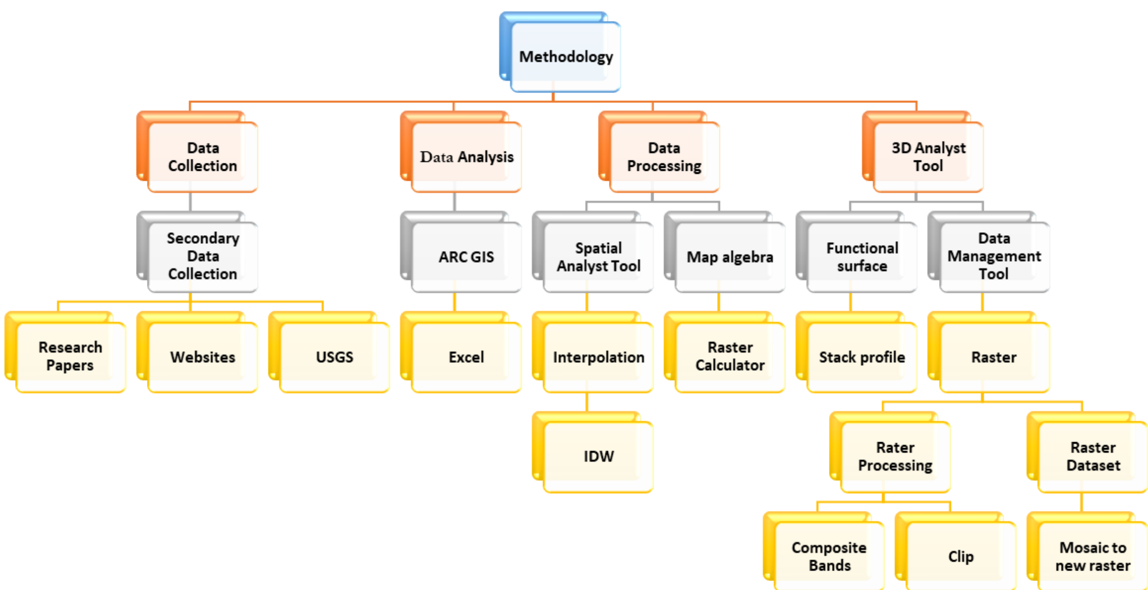


Figure 3: Flow diagram of methodology.

Data analysis was conducted using ArcGIS for spatial analysis and mapping. ArcGIS is a geographic information system software used for working with maps and geographic data. Air quality data, specifically PM2.5 concentrations, were interpolated to highlight areas with higher pollution levels. PM2.5, or particulate matter with a diameter of less than 2.5 micrometers, is a common air pollutant. Satellite imagery was mosaicked and clipped to align with the Sindh shapefile, and LST values were converted to Celsius using the Raster Calculator in ArcGIS to create an urban heat island map illustrating urbanization effects. LST stands for Land Surface

Temperature, which measures the surface temperature of the land. Excel was used for data organization and preliminary statistical analysis [12].

Comprehensive datasets covering Sindh were utilized to ensure extensive spatial coverage. Ethical considerations focused on the proper use and citation of secondary data sources since the research did not involve human participants. The study faces limitations, including reliance on the accuracy and resolution of secondary data, potential gaps in temporal coverage, and the precision of interpolated air quality maps based on data point distribution [13]. Despite these limitations, the structured methodology provides a systematic approach to understanding urbanization's impacts on environmental parameters in Sindh, offering valuable insights for urban planning and environmental management.

Results and Discussion:

This research employed MODIS Land Surface Temperature (LST) data, analyzed using ArcGIS, to examine temperature fluctuations in the Sindh region during 2023. Data from both LST Terra and LST Aqua were evaluated and converted to degrees Celsius. **Figure 4** presents the LST Terra data, revealing a maximum temperature of 44.69°C and a minimum temperature of 12.83°C. This dataset provides an overview of temperature distribution throughout Sindh, demonstrating notable spatial variation.

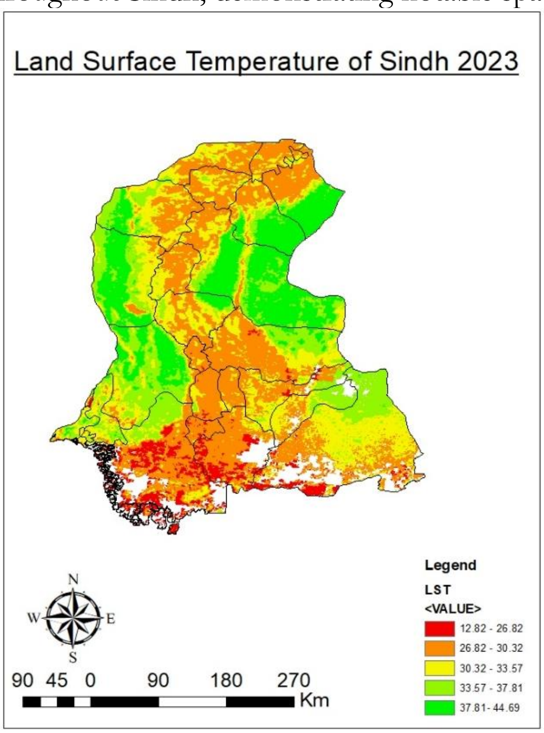


Figure 4: Land Surface Temperature (Terra) of Sindh

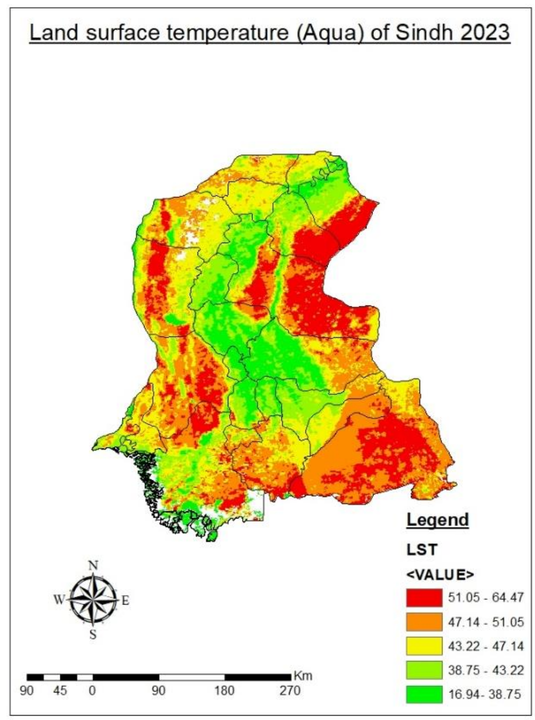
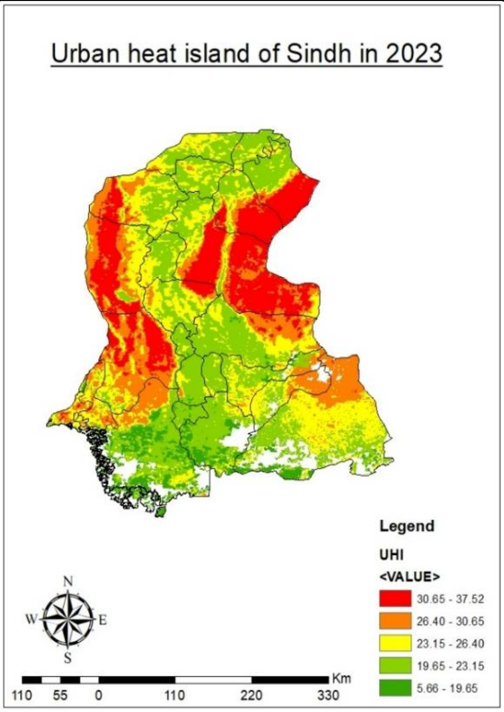


Figure 5: Land Surface Temperature (Aqua) of Sindh

In Figure 5, the LST Aqua data shows a maximum temperature of 64.48°C and a minimum temperature of 16.94°C. The higher maximum temperature in the Aqua dataset is likely due to the afternoon data collection time, which generally records higher temperatures compared to the morning data collection time of the Terra dataset.

Figure 6 highlights the Urban Heat Island (UHI) effect within Sindh, with temperatures ranging from a high of 37.52°C to a low of 5.66°C. This map demonstrates the notable temperature increase in urban areas compared to rural regions. A consistent observation across all datasets is the higher temperatures in urban areas, attributed to the UHI effect. Urbanization contributes to this effect through extensive concrete surfaces, reduced vegetation, and increased emissions. The elevated temperatures in Sindh's urban areas align with global patterns of the UHI effect.



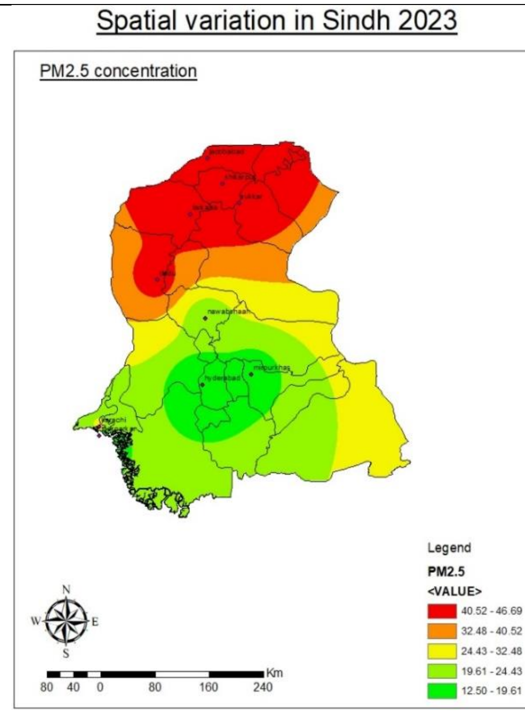


Figure 6: Urban Heat Island of Sindh 2023 **Figure 7:** PM2.5 Conccentration

Additionally, spatial interpolation analysis was performed to evaluate air quality in urban areas of Sindh. Data from IQAir were used to create maps of PM2.5 concentrations and the Air Quality Index (AQI). A point shapefile was generated specifically for urban areas to visualize variations in air quality. **Figure 7** displays PM2.5 concentration levels in urban Sindh, highlighting areas with higher pollution levels. This information is crucial for understanding the spatial distribution of air pollutants.

Figure 8 illustrates the Air Quality Index (AQI) for urban Sindh, highlighting regions with poor air quality. The map reveals that urban centers suffer from worse air quality, likely due to higher traffic, industrial activities, and other urban pollutants. Figure 9 presents the population density map of Sindh, showing that urban areas, particularly Karachi, have significantly higher population densities compared to rural regions. This high population density contributes to the observed temperature and air quality issues.

Figure 10 utilizes MODIS data to classify land use and land cover in Sindh. The classification includes rangeland, barren land, water bodies, built-up areas, irrigated agriculture, mangroves, and orchards. The map clearly indicates that built-up areas are most prevalent in Karachi, underscoring the extensive urban development in the city.

These findings highlight the importance of using remote sensing and spatial analysis to monitor environmental conditions. The distinct temperature profiles and air quality metrics observed in urban areas underscore the need for targeted climate adaptation, pollution control measures, and urban planning strategies. The high population density and significant urban development in Karachi exacerbate these environmental challenges, necessitating focused intervention.

The integration of LST Terra and Aqua data, along with UHI, air quality, population density, and land use analyses, provides a comprehensive view of environmental dynamics in Sindh. This approach emphasizes the critical role of spatial analysis in environmental monitoring and urban management, enabling the development of more effective strategies to mitigate adverse environmental impacts in urban areas. The study's findings align with and extend existing research on urban heat islands (UHIs) and air pollution. The observed higher temperatures in urban centers of Sindh, particularly Karachi, support the well-documented UHI effect, where urbanization leads to increased heat retention due to extensive concrete surfaces, reduced vegetation, and higher emissions. This phenomenon has been extensively studied in various global contexts, including cities in North America, Europe, and Asia, showing a consistent pattern of elevated temperatures in urban environments compared to rural areas.

Spatial variation in Sindh 2023

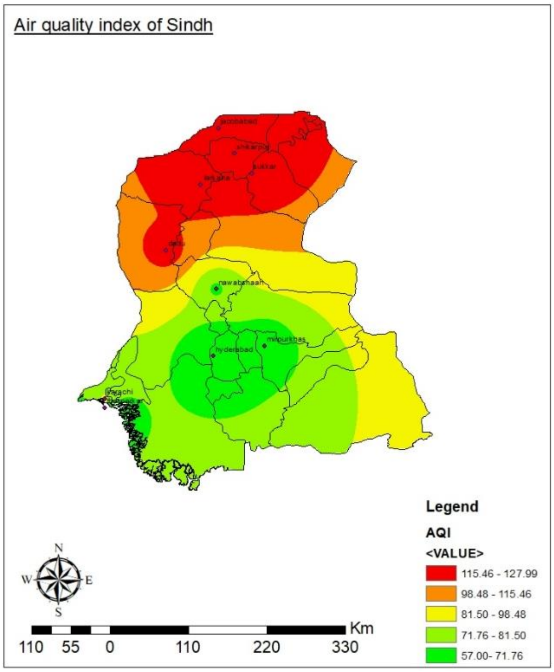


Figure 8: Air Quality Index

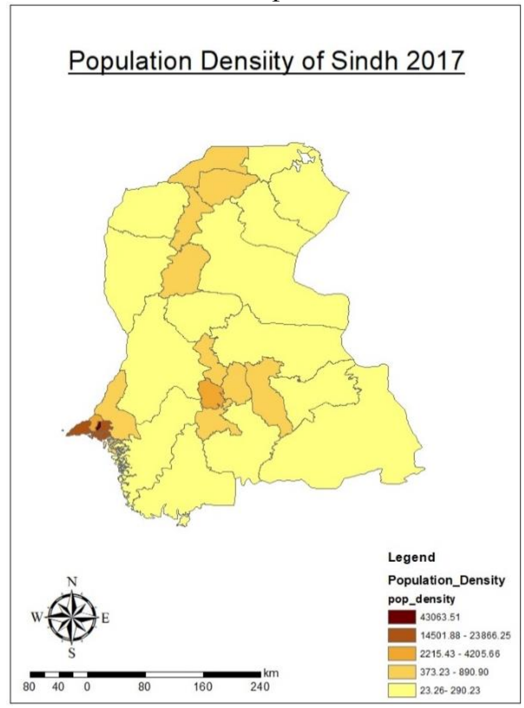


Figure 9: Population Density of Sindh 2017

For example, a study by [14] on urban heat islands in North American cities identified similar temperature discrepancies between urban and rural areas, attributing these differences to the concentration of buildings, roads, and other infrastructure that absorb and retain heat. Our results, with a high temperature of 44.69°C in the LST Terra dataset and 64.48°C in the LST Aqua dataset, align with these findings, demonstrating the significant impact of urbanization on local climate.

The spatial analysis of PM2.5 concentrations and AQI in urban Sindh identifies areas with higher pollution levels, consistent with findings from other densely populated and industrialized regions. [15] reported that urban centers with high population densities and industrial activities often experience poorer air quality due to increased emissions from vehicles, factories, and other sources. The high AQI values observed in Karachi and other urban centers in Sindh reflect similar trends, underscoring the urgent need for effective pollution control measures.

Additionally, the use of remote sensing and GIS techniques in this study aligns with methodologies used in previous research for monitoring environmental parameters. For instance, [16] utilized MODIS data to examine land surface temperature and its relationship to urbanization in Chinese cities, noting significant temperature increases in areas with rapid urban growth. Our analysis of LST and land use/land cover in Sindh using MODIS data follows this approach, yielding robust and comparable results.

In terms of land use and land cover, the classification showing extensive urban development in Karachi is supported by studies on urban expansion in developing countries. [9] highlighted that rapid urbanization in regions like South Asia often leads to substantial changes in land use, with natural landscapes converted to built-up areas. This transformation contributes to both the Urban Heat Island (UHI) effect and deteriorating air quality, as observed in our study.

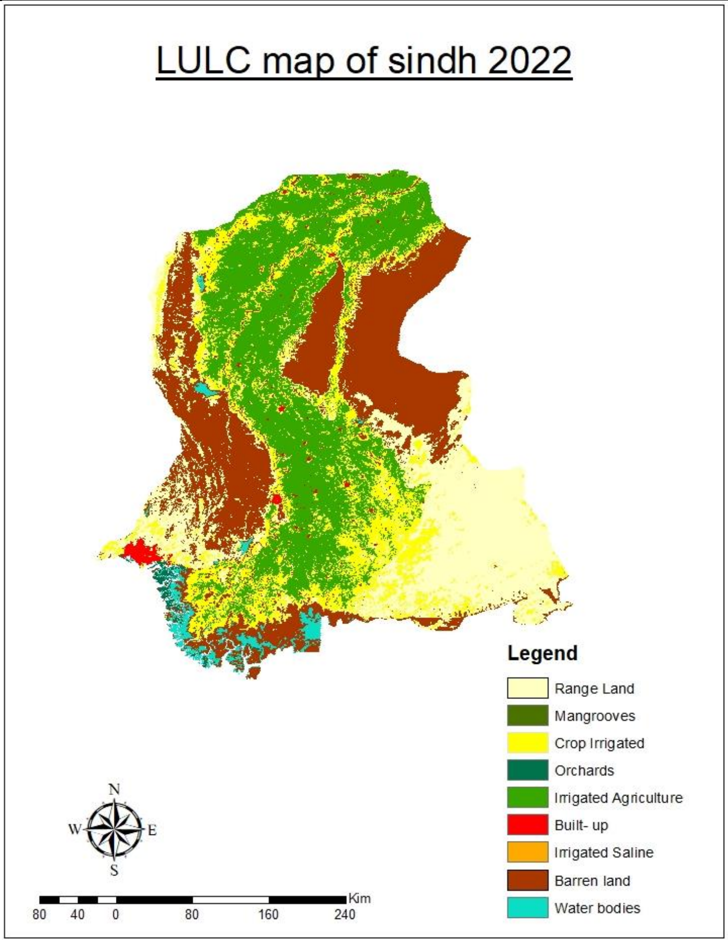


Figure 10: LULC MAP of Sindh 2022

These findings highlight the importance of implementing targeted climate adaptation and pollution control measures in urban areas. Strategies such as increasing green spaces, improving public transportation, and enforcing stricter emission regulations can help mitigate the adverse effects of urbanization on temperature and air quality. Future research should continue to monitor these trends and evaluate the effectiveness of various interventions in reducing environmental stress in urban centers.

Overall, this study enhances the existing body of knowledge by providing a comprehensive spatial assessment of atmospheric contamination and urban heat phenomena in Sindh. It validates our results with related research and underscores the critical role of urban planning and environmental management in addressing these challenges. Areas with elevated air pollution levels often coincide with urban centers, exacerbating the UHI effect due to human activities that generate excess heat. Surface temperature maps reveal heightened temperatures in areas with significant air pollution, indicating a direct relationship between pollution levels and increased temperatures. By juxtaposing PM2.5 concentrations with LST maps, this research visually illustrates spatial patterns and potential correlations between air pollution and temperature.

Conclusion:

The comprehensive analysis of MODIS Land Surface Temperature (LST) data, air quality measurements, population density, and land use classifications reveals significant environmental dynamics in Sindh, particularly in urban areas like Karachi. The study highlights the pronounced Urban Heat Island (UHI) effect, with urban areas consistently exhibiting higher temperatures due to extensive concrete surfaces, reduced vegetation, and higher emissions. Spatial interpolation analysis of air quality data indicates that urban centers experience elevated PM2.5 levels and poorer air quality, likely driven by dense populations and industrial activities. The population density map further confirms that urban areas, especially Karachi, have significantly higher population densities, which contribute to the observed environmental challenges. The land use and land cover classification map provides critical insights into the distribution of various land types across Sindh, highlighting the extensive built-up areas in Karachi. This urban expansion correlates with the issues of higher temperatures and poor air quality. These findings underscore the need for targeted climate adaptation strategies, pollution control measures, and sustainable urban planning. Future research should focus on longitudinal studies to monitor these trends over time and assess the long-term impacts of urbanization on regional climate and air quality. The integration of remote sensing data and spatial analysis tools proves invaluable for environmental monitoring and management, offering a solid foundation for developing effective mitigation strategies to address the adverse impacts of urbanization in Sindh.

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