Remote Sensing of Urban Structure and Vegetation Effects on Atmospheric Pollutants

Hafiz Muhammad Abubakar[1], Hasnain Ahmad[1], Furqan Arshad[2], Zain Ali[3], Usman Nazir[4], Sara Khalid[4],
[1] School of Computer and IT (SCIT), Beaconhouse National University, Lahore, Pakistan
{f2021-641,f2021-597}@bnu.edu.pk
[2] University of California, Davis, United States
furarshad@ucdavis.edu
[3] University of San Diego, San Diego, United States
zali@sandiego.edu
[4] Planetary Health Informatics Lab, NDORMS
University of Oxford, United Kingdom
{usman.nazir, sara.khalid}@ndorms.ox.ac.uk

***Abstract*—Urbanization and industrialization have reshaped cities globally, yet their environmental costs, particularly on air quality, remain underexplored in the context of urban planning. This study delves into the contrasting urban typologies of Lahore and Islamabad, two major cities in Pakistan, to assess the interplay between green spaces, urban design, and air pollution. Leveraging Sentinel-5P satellite data, we analyze concentrations of CO, SO_2, and NO_2 from 2018 to 2024. The findings reveal stark differences: Lahore, characterized by unregulated urban sprawl and fragmented greenery, exhibits consistently higher pollutant levels. In contrast, Islamabad, with its planned urban layout and abundant green belts, demonstrates a clear mitigation of pollutant levels. Our results highlight the inverse correlation between green space density and pollutant concentrations, underscoring the critical role of vegetation in moderating urban emissions. This study offers actionable insights for sustainable urbanization, advocating for green infrastructure integration and strategic urban planning. These findings not only inform policymakers but also set the stage for future research on data-driven, city-specific air quality management strategies.**

***Index Terms*—Urban Planning, Air Quality, Green Infrastructure, Remote-Sensing, Urbanization**

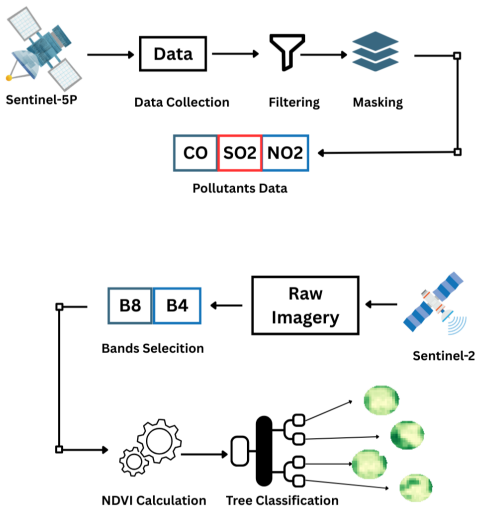


Fig. 1: Workflow for Pollutant Estimation and Land Cover Classification

I. Introduction

Greenhouse gases are the main cause behind climate change, as they contribute to the increasing global warming in the region, resulting in a lot of rain, particularly in the monsoon season, which leads to severe floods. According to the World Health Organization (WHO), more than 33 million people (15% of the total Pakistani population) were affected by floods in 2022. Within this group, approximately 6.4 million people were in such dire straits that they required humanitarian support [1]. Although contributing less than 1% to the global greenhouse gas emissions, Pakistan is on the list of countries that are most vulnerable to global warming and extreme weather events, making it the fifth most vulnerable country to climate change [2], [3].

According to the Climate Change Performance Index—an independent monitoring tool, Pakistan ranks 31st in the CCPI for this year, with mixed ratings: high in greenhouse gas emissions and energy use, low in climate policy and very low in Renewable Energy [4]. Categorized as the lungs of the Earth, trees, and other green spaces that make up forests play a crucial role in the sustainability of the planet. According to the United Nations (UN), forests cover 31% of the world's land surface and absorb approximately 15.6 billion tonnes of carbon dioxide (CO_2) annually [5].

Urbanization or urban sprawl (unplanned expansion) play a crucial role in increasing the adverse effects of these pollutant gases. Urbanization in Pakistan presents a dual narrative: planned cities such as Islamabad offer insights into sustainable urban development, while unplanned expansions such as informal settlements in Lahore highlight the challenges of rapid and unmanaged growth. Planned cities, with their structured layouts and allocated green spaces, can potentially mitigate greenhouse gas (GHG) emissions. This study will analyze and compare the relationship of rapid urbanization

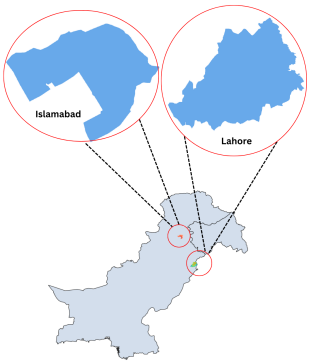


Fig. 2: Spatial extent of the study regions.

and green spaces with greenhouse gas hotspots in the cities of Lahore and Islamabad. This study also serves as an anchor for comparing and contrasting the trends of greenhouse gas and their potential effects on the population emissions between Lahore, the unplanned city and Islamabad, the planned city, respectively.

This study asks whether urban planning typology and green space density drive differences in city-scale atmospheric pollutant concentrations, hypothesizing that planned cities with integrated vegetation exhibit lower CO, NO_2, and SO_2 levels than unplanned ones. We address this using Sentinel-5P NRTI Level-3 and Sentinel-2 SR data over Lahore and Islamabad from 2018 to 2024, computing annual mean pollutant composites alongside NDVI-based green space maps. We present findings that examine whether vegetation density and urban structure correlate with measured CO, NO_2, and SO_2 concentrations over the study period.

II. Literature Review

Urbanization has been a global phenomenon that drastically altered the landscape of cities worldwide. Not only did it change the way how humans have had lived throughout past years but it also impacted our climate. Although urbanization may have a minimal global warming effect, but its contribution on urban warming i.e. locally increased temperature is substantial [6]. Majority of global urban population growth is occurring in low- and middle-income countries [7], [8].

Lahore has witnessed rapid urban sprawl, with its built-up areas expanding significantly, from 17,930 hectares in 1998 to 65,180 hectares in 2021—a staggering 263.5% increase over two decades [9]. Urban Sprawl refers to the unplanned, low-density expansion of urban areas into surrounding rural land. This phenomenon is characterized by scattered development, increased reliance on automobiles, and inadequate infrastructure. For cities like Lahore, urban sprawling had detrimental effects on environmental health largely due to the growth of transportation networks and industrial activities in suburban areas.

Green spaces have long been recognized as an important countermeasure to GHG emissions, yet the quantitative role of these spaces in reducing emissions in different types of urban areas (planned vs. unplanned) is poorly understood. Extremely limited amount of studies directly compare planned cities (like Islamabad) with unplanned cities (like Lahore) in the South Asian setting, despite several examining urbanization's impact on GHG emissions. Compared to the sprawl and chaotic, informal settlements that define unplanned cities, planned cities typically include planned infrastructure, designated green spaces, and controlled urban layouts that may affect GHG emissions differently. In this case, a comparison study might offer insightful information about how urban design can either lessen or worsen the environmental effects of urbanization.

It is commonly known that air pollution is a significant cause of premature mortality [10]. Because of their detrimental effects on the cardiorespiratory system, South Asian nations are disproportionately affected. In addition to harming the environment and public health, these pollutants cost nations a lot of money. This study uses Sentinel-5P satellite data to identify gaseous emissions throughout Lahore and Islamabad in order to address the effects of these pollutants. A more thorough method of assessing respiratory health has been made possible by recent developments in remote sensing and health data analytics, especially with the incorporation of satellite-derived air quality measures. Numerous studies have demonstrated the detrimental impact of pollutants including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) on public health and respiratory conditions [11].

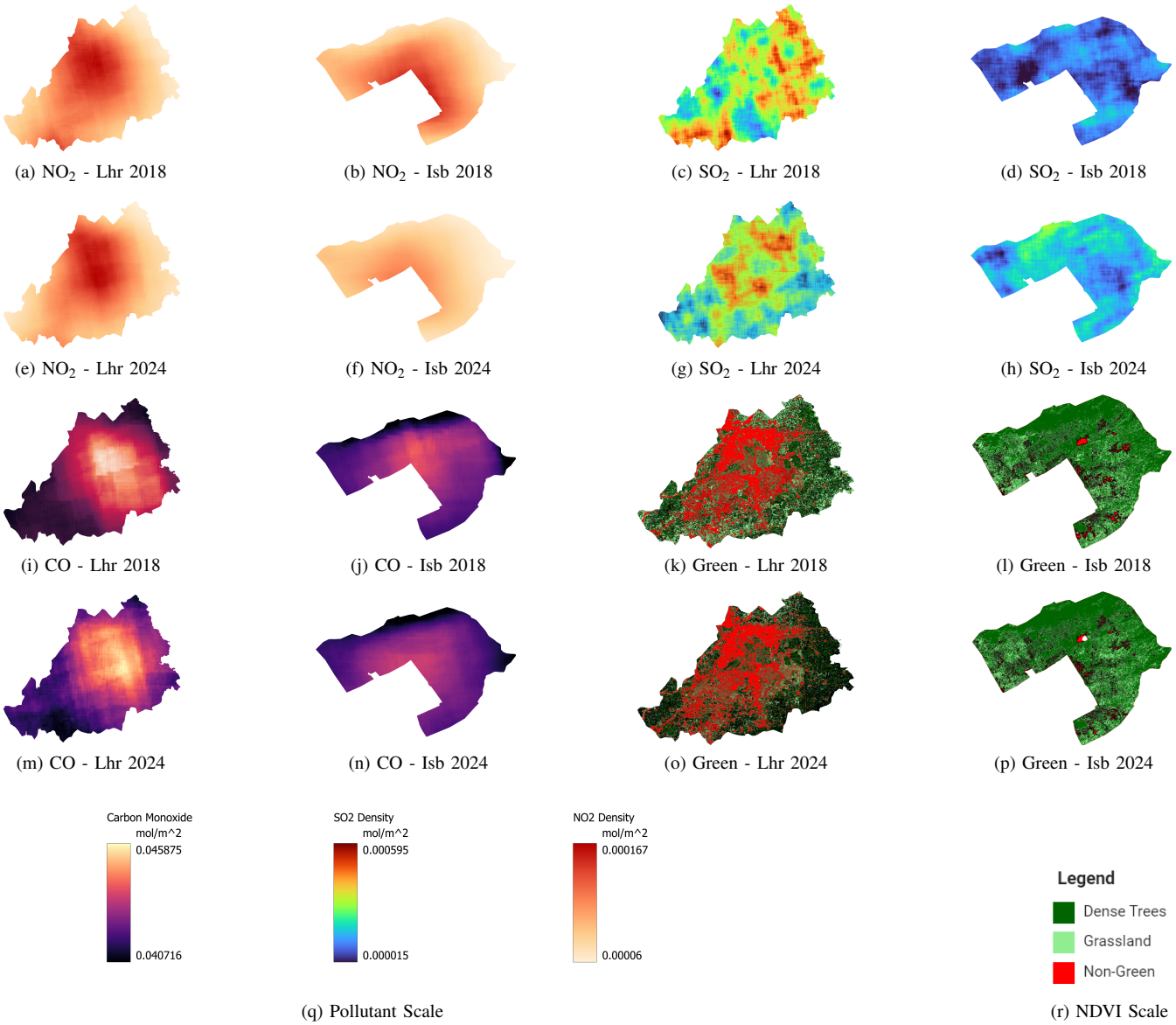
III. Methodology

A. Study Region

This study focuses on Lahore ($\sim$1,772 km^2) and Islamabad ($\sim$906 km^2), two contrasting cities in Pakistan that highlight the impact of urban planning on environmental outcomes and climate change, as shown in Figure 2. Lahore's industrial sprawl and poor air quality demonstrate the challenges of unregulated growth, while Islamabad's planned layout offers a model of how green spaces and zoning can mitigate environmental degradation. Comparing the temporal trends of air quality and green spaces in these cities allows this study to explore how urban design and policy influence climate resilience, public health, and ecological preservation, offering valuable insights for sustainable urbanization in rapidly developing regions.

B. Assessing Pollutant Concentrations

CO, NO_2, and SO_2 column number densities were retrieved from Sentinel-5P NRTI Level-3 collections (`COPERNICUS/S5P/NRTI/L3_CO`, `L3_NO2`, `L3_SO2`) on Google Earth Engine, at a native spatial resolution of 3.5×5.5 km^2 per pixel, filtered by date and clipped to each city boundary. The collections yielded 6,817 (CO), 29,181 (NO_2), and 10,533 (SO_2) images for 2018, and 64,736 (CO), 64,453 (NO_2), and 45,277 (SO_2) images for 2024. Annual mean composites were computed across all valid observations



(a) NO_2 - Lhr 2018 (b) NO_2 - Isb 2018 (c) SO_2 - Lhr 2018 (d) SO_2 - Isb 2018

(e) NO_2 - Lhr 2024 (f) NO_2 - Isb 2024 (g) SO_2 - Lhr 2024 (h) SO_2 - Isb 2024

(i) CO - Lhr 2018 (j) CO - Isb 2018 (k) Green - Lhr 2018 (l) Green - Isb 2018

(m) CO - Lhr 2024 (n) CO - Isb 2024 (o) Green - Lhr 2024 (p) Green - Isb 2024

(q) Pollutant Scale (r) NDVI Scale

Fig. 3: Temporal comparison of pollutant concentrations and green space distribution between Lahore and Islamabad (2018 vs. 2024). (a)–(d) NO_2 and SO_2 for 2018; (e)–(h) for 2024; (i)–(l) CO and green spaces for 2018; (m)–(p) CO and green spaces for 2024; (q)–(r) color scales for pollutants and NDVI classification.

within the study period. The full process is outlined in Algorithm 1.

C. Green Spaces Detection

Green space detection was conducted using Sentinel-2 SR Harmonized data `COPERNICUS/S2_SR_HARMONIZED`) at 10 m spatial resolution, filtered to less than 10% cloud cover. This yielded 116 and 213 cloud-free scenes over Lahore, and 30 and 70 over Islamabad, for 2018 and 2024 respectively. The notable resolution difference between Sentinel-5P (3.5×5.5 km^2) and Sentinel-2 (10 m) reflects their complementary roles: Sentinel-5P for city-scale atmospheric column concentrations and Sentinel-2 for fine-scale land surface vegetation classification. The full process is outlined in Algorithm 2.

The Normalized Difference Vegetation Index (NDVI) was calculated using the formula:

$$\text{NDVI} = \frac{B8 - B4}{B8 + B4} \tag{1}$$

where $B8$ represents the Near-Infrared (NIR) band and $B4$ represents the Red band. The mean NDVI image for the year was used to represent average vegetation density across the study area. Threshold values were applied to classify green spaces into categories based on their NDVI values:

- NDVI ≥ 0.40: Dense trees (high vegetation density)

Algorithm 1: Assessing CO, NO_2, SO_2 using Sentinel-5P

Input: Sentinel-5P satellite imagery data, temporal range, geographic region of interest
Output: Visualizations of CO, NO_2, SO_2 concentrations using GIS
Step 1: Data Acquisition: Acquire Sentinel-5P satellite imagery for the specified geographic region and temporal range;
Step 2: Temporal Filtering: Filter the acquired imagery to include only data within the desired time frame;
Step 3: Cloud Masking: Apply cloud masking techniques to remove clouds and cloud shadows from the imagery;
Step 4: Mean Value Calculation: Calculate the mean concentration values of CO, NO_2, and SO_2 from the filtered and masked images;
Step 5: Layering: Overlay the mean concentration data onto a GIS;
Step 6: Visualization: Generate visualizations (heatmaps) of CO, NO_2, and SO_2 concentrations;

Algorithm 2: Green Space Detection using NDVI

Input: Sentinel-2 surface reflectance data, Islamabad administrative boundary, year 2018
Output: Green space classification map (dense trees, grassland, non-green areas)
Step 1: Data Acquisition: Load Sentinel-2 SR harmonized data for Islamabad from the Earth Engine repository;
Step 2: Cloud Filtering: Filter images with less than 10% cloud cover;
Step 3: NDVI Calculation: Compute NDVI using $(B8 - B4)/(B8 + B4)$;
Step 4: Mean NDVI: Generate mean NDVI composite for the year 2018;
Step 5: Classification: Apply NDVI thresholds to classify pixels into:
- Dense Trees (NDVI ≥ 0.40)
- Grassland ($0.25 \leq$ NDVI ≤ 0.38)
- Non-Green Areas (NDVI < 0.19)

Step 6: Output: Export green space classification map for visualization;

- $0.25 \leq$ NDVI ≤ 0.38: Grassland (moderate vegetation density)
- NDVI < 0.19: Non-green areas (built-up or non-vegetated regions)

IV. Qualitative Results and Discussion

A. Temporal Analysis: Pollutant Concentrations and Green Space Distribution

The comparative analysis between Lahore and Islamabad reveals significant differences in pollutant concentrations and green space distribution over the 6-year study period. Figure 3 demonstrates the temporal evolution of NO_2 and SO_2 concentrations, while Figure 3i-3p shows the relationship between CO levels and green space coverage. The concentration scales and classification systems are provided in Figure 3q and 3r.

The 2018-2024 comparison clearly illustrates how Lahore's unplanned urban sprawl has led to increased pollutant concentrations, while Islamabad's structured development with integrated green spaces has maintained relatively lower pollution levels. The inverse relationship between green coverage and gaseous pollutants is particularly evident when comparing the two cities' development patterns.

B. Analysis and Discussion

The temporal analysis of SO_2, NO_2, and CO over Lahore and Islamabad from 2018 to 2024 reveals a general upward trend in pollutant concentrations, with NO_2 exhibiting the highest volatility over Lahore as shown in Figure 3e. CO concentrations in Islamabad declined between 2018 and 2024 (Figures 3n, 3m), attributable to greater green space coverage and limited industrial activity, whereas Lahore shows comparatively less reduction due to rapid urbanization and higher industrial emissions. The coarser resolution of Sentinel-5P (3.5×5.5 km^2) captures city-scale pollutant gradients but smooths sub-district variation, while Sentinel-2 at 10 m resolves fine-scale vegetation structure; together, the two datasets are complementary, with Sentinel-5P quantifying atmospheric concentrations at urban scale and Sentinel-2 delineating the green space patterns that spatially correlate with those concentrations.

V. Conclusion and Future Work

This comparative analysis of Lahore and Islamabad highlights the decisive role of urban planning and green infrastructure in mitigating air pollution. Lahore's unregulated urban expansion and industrial activities within residential areas result in substantially higher concentrations of CO, NO_2, and SO_2, whereas Islamabad's planned layout and integrated green spaces effectively suppress pollutant levels and sustain better air quality. The observed inverse relationship between vegetation density and pollutant concentration confirms green infrastructure as a functional component of urban resilience rather than a purely aesthetic feature, emphasizing the need for data-driven urban planning and industrial regulation. Future work should extend this analysis across additional urban and rural regions using multi-year and seasonal datasets, conduct pixel-level correlation analysis between NDVI and pollutant concentrations to statistically establish the relationship between green space density and pollutant suppression, integrate satellite and ground-based observations for improved validation, and explore machine learning approaches to enhance scalability and analytical efficiency.

REFERENCES

[1] "Situation reports on the flooding in pakistan," *World Health Organization*, 2022. [Online]. Available: https://www.who.int/publications/situation-reports-on-flooding-pakistan. [Accessed: Dec. 28, 2024].

[2] "Global climate risk index 2021," *Germanwatch*, 2021. [Online]. Available: https://www.germanwatch.org/sites/default/files/Global%20Climate%20Risk%20Index%202021_2.pdf. [Accessed: Dec. 28, 2024].

[3] "Pakistan recognized as highly vulnerable to climate change," *Press Information Department, Government of Pakistan*, 2024. [Online]. Available: https://pid.gov.pk/site/press_detail/25011. [Accessed: Dec. 28, 2024].

[4] "Pakistan- climate change performance index," *Climate Change Performance Index (CCPI)*, 2024. [Online]. Available: https://ccpi.org/country/pak/. [Accessed: Dec. 28, 2024].

[5] "Mapping the world's forests: A green globe in the fight against climate change," *World Economic Forum*, 2023. [Online]. Available: https://www.weforum.org/stories/2023/01/mapping-worlds-forests-green-globe-climate-change/. [Accessed: Dec. 28, 2024].

[6] D. Zhou et al., "Urbanization contributes little to global warming but substantially intensifies local and regional land surface warming," *Earth's Future*, vol. 10, no. 5, pp. e2021EF002401, 2022.

[7] "World cities report 2022," *UN-Habitat*, 2022. [Online]. Available: https://unhabitat.org/wcr/.

[8] D. Satterthwaite, "Climate change and urbanization: Effects and implications for urban governance," 2008. www.un.org.development.desa.pd/files.

[9] M. Basheer and M. Waseem, "Spatiotemporal analysis of urban growth and land surface temperature: A case study of lahore, pakistan," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 48, pp. 25–29, 2022.

[10] K. Newell et al., "Cardiorespiratory health effects of particulate ambient air pollution exposure in low-income and middle-income countries: a systematic review and meta analysis," *The Lancet Planetary Health*, vol. 1, no. 9, pp. e368–e380, 2017.

[11] C.Y. Hu et al., "Association between ambient air pollution and parkinson's disease: Systematic review and meta-analysis," *Environmental research*, vol. 168, pp. 448–459, 2019.