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Enhancing Urban Sustainability through Air Pollution Analysis and Accessibility Estimation: A Case Study of Tehran Metropolis

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Abstract

The increase in motor vehicles has greatly increased air pollution in the Tehran metropolis and turned it into a challenge. By analyzing transportation pollutants, low-carbon cities and sustainable development strategies for urban districts can be achieved. This study deals with the spatio-temporal analysis of pollutants and transportation accessibility in the urban districts of Tehran. The concentrations of CO and NO2 pollutants were extracted from the Sentinel-5P satellite using coding in the GEE environment. OSM data were used to calculate the accessibility of the 22 urban districts. Moran's global autocorrelation indicated a clustered spatial distribution pattern of pollutants. The high autocorrelation value equal to 0.94 for CO and NO2 pollutants indicated their cumulative state in the atmosphere. By performing LISA, most clusters of these pollutants were identified in the central districts and southern suburbs. The average accessibility indicator of the 22 districts was 24.82 km/km2. About half of Tehran's urban districts had a high density of road transport networks. These districts are located in CO and NO2 clusters owing to the high traffic volume of motor vehicles. The results of this study emphasize the factors that aggravate Tehran's air pollution, including the clustered pattern of pollutants in the atmosphere and dense transportation network in urban districts. By integrating air pollution analysis and accessibility estimations into urban planning frameworks, cities can strive to achieve long-term sustainability goals.

Keywords: sustainable development, Sentinel-5P, pollutant clustering, accessibility

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ارتقاء پایداری شهری با تحلیل آلودگی هوا و برآورد دسترسی: مطالعه موردی کلانشهر تهران

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چکیده

ازدیاد وسایط نقلیه موتوری آلودگی هوای کلانشهر تهران را به شدت افزایش و به یک چالش تبدیل نموده است. با تحلیل آلاینده‌های حمل‌ونقلی می‌توان به شهرهای کم‌کربن و استراتژی‌های توسعه پایدار مناطق شهری دست یافت. این مطالعه به تحلیل مکانی-زمانی آلاینده‌ها و قابلیت دسترسی حمل‌ونقل در مناطق شهری تهران می پردازد. با کدنویسی در محیط GEE غلظت آلاینده‌های CO و NO2 از ماهواره Sentinel-5P استخراج شد. برای محاسبه دسترسی ۲۲ منطقه شهری، از داده‌های OSM استفاده شد. خودهمبستگی کلی موران الگوی توزیع فضایی خوشه‌ای را برای آلاینده‌ها نشان داد. مقدار خودهمبستگی بالا برابر ۰/۹۴، برای آلاینده‌های CO و NO2 نشان از حالت تجمعی آنها در جو داشت. با انجام آنالیز LISA، بیشترین خوشه‌های این آلاینده‌ها در مناطق مرکزی و حومه‌های جنوبی شناسایی شدند. میانگین شاخص دسترسی مناطق ۲۲ گانه برابر km/km2 ۲۴/۸۲ به دست آمد. حدود نیمی از مناطق شهری تهران با تراکم بالای شبکه حمل و نقل جاده‌ای شناسایی شدند. این مناطق به دلیل حجم بالای تردد وسایل نقلیه موتوری در خوشه‌های CO، NO2 قرار داشتند. نتایج این پژوهش بر عوامل تشدید آلودگی هوای تهران از جمله الگوی خوشه ای آلاینده‌ها در جو و شبکه حمل و نقل متراکم در مناطق شهری تأکید می‌کنند. با ادغام تحلیل آلودگی هوا و برآورد دسترسی در چارچوب برنامه‌ریزی شهری، شهرها می‌توانند در جهت دستیابی به اهداف بلندمدت پایداری تلاش کنند.

کلیدواژه‌ها: توسعه پایدار، Sentinel-5P، خوشه‌بندی آلاینده‌ها، دسترسی حمل‌ونقل

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1. Introduction

Air pollution is an important challenge in the sustainable development of urban districts. Air pollution is one of the main causes of death in third world countries (WHO, 2022). Pollutant analysis plays an important role in warning people and controlling air pollution in the future (Xiang, 2023). CO and NO_2 are two common urban pollutants that can be reduced by reducing the use of motor vehicles (Tondelli et al., 2022). Low-carbon city development is an important method for achieving sustainable development strategies (Peng & Deng, 2021). Urban areas are important for achieving sustainable development because they account for 70 percent of greenhouse gas emissions (Part, 2022). According to a report by Tehran’s Air Quality Control Company, this city has only three days of clean air in 2022, and mobile sources with a share of 83% in the production of polluting gases are the most important source of air pollution in the capital (AirQualityControlCompany, 2022). Transportation accounts for approximately 20 percent of greenhouse gas emissions, and road transportation accounts for three-quarters of this share (Rodrigue, 2020). A dense transportation network indicates higher traffic volume and a greater number of roads. This can lead to the emission of CO and NO_2 pollutants (Chen, 2023; Park & Ko, 2021; Qin et al., 2022; Sohrab et al., 2022). Various solutions have been proposed for reducing environmental pollution (Ghahremanlou & Kubiak, 2023; Straatemeier & Bertolini, 2020). The Sentinel-5P satellite with a Tropomi sensor was launched by the European Space Agency in 2017 to monitor air pollution. The superiority of this satellite over ground stations includes spatial-temporal investigation of pollutants, a comprehensive understanding of air pollution, and the ability to report pollutants in inaccessible places. These features make it a valuable tool in pollutant analysis (EuropeanSpaceAgency, 2017; Rocheleau, 2021). The concentrations of pollutants can be extracted from this satellite by coding in the Google Earth Engine (GEE) environment (Gorelick et al., 2017). The use of spatial statistical analysis to investigate pollutants has achieved good results in polluted countries worldwide, and has received less attention in Iran (Gharibi & Shayesteh, 2021; Qi, Wang, Wang, & Wei, 2022; Ye, Ma, Ha, Yang, & Weng, 2018). Daily trips in Tehran increased from 14.6 to 19.3 million between 2004-2019 (TrafficOrganization, 2020), which could potentially be due to the growth of transportation infrastructure.

Urbanization through construction, the development of road transport networks, and the destruction of vegetation leads to air pollution (Ghahremanlou et al., 2022). Most of the studies have been conducted in big cities, while for sustainable development, they should be focused on urban areas (McGrath, 2018). Carbon monoxide and nitrogen dioxide are mainly generated by vehicle combustion processes. High levels of CO and NO_2 are commonly found in urban areas with heavy traffic congestion (Restrepo, 2021; Yin et al., 2022; Zefreh & Torok, 2021). Monitoring emissions of carbon monoxide and nitrogen dioxide pollutants in urban areas is essential due to public health impacts, economic benefits, and achieving urban sustainability (Emereibeole et al., 2023; Hamilton, 2017; Jonidi Jafari et al., 2021; Reche et al., 2022).

Based on a review of previous studies, the Sentinel-5P satellite is less popular because of its coding and computational complexity. In this study, using Python coding, the concentrations of CO and NO_2 pollutants in Tehran were extracted from the Sentinel-5P satellite for 2022. Clustering patterns were analyzed using spatial statistical techniques. The transportation accessibility indicator was then calculated for the 22 urban districts. The superiority of this research is to achieve sustainable development by analyzing the relationship between transportation accessibility and pollutants in urban districts.

2. Material and Methods

In this study, the Sentinel-5P satellite was used to monitor CO and NO_2 pollutants in air. ArcGIS 10.8 software and Google Earth Engine (GEE) platform were used during the analysis process.

2.1. Study Area

As shown in Figure 1, the Iranian capital Tehran is a metropolis with 22 districts that lie within the geographic coordinates of 34 –36.5 °north and 50 –53 °east. Tehran is the most populous city in Iran and the most densely populated urban epicenter in the country.

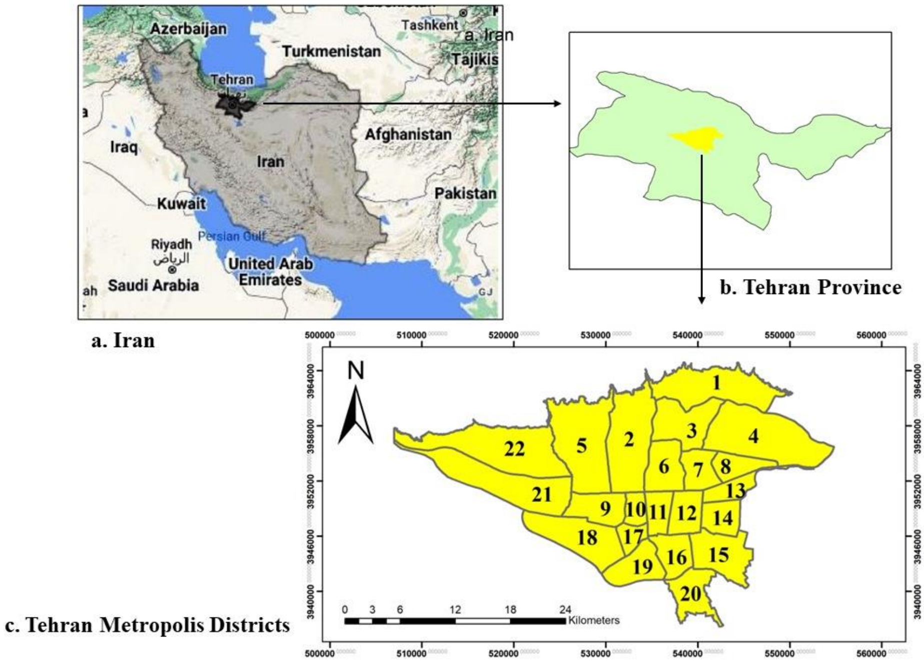

Figure 1. The study area's geographic position

2.2. Data Collection Methods

To extract pollutants from the Sentinel-5p satellite, Python coding was performed in the Google Earth Engine (GEE) environment. The characteristics of CO and NO_2 pollutants are listed in Table 1. To calculate accessibility, the data of Tehran's street network collected from www.download.geofabrik.de. The administrative boundary layer of the urban districts was prepared from Tehran Municipality.

Table 1. Specifications of Sentinel-5p satellite products for the investigated pollutants in 2022 (Source: www.earthengine.google.com, www.scihub.copernicus.eu)

Name	Units	Image Collection	Number of images (daily)
CO_column_number_density	mol/m^2	COPERNICUS/S5P/NRTI/L3_CO	728
NO_2_column_number_density	mol/m^2	COPERNICUS/S5P/NRTI/L3_NO2	759

2.3. Indicators' Research

Depending on available information and goals, different formulas and relationships can be used in any study. In this study, we utilized certain relationships to approximate the outcomes.

2.3.1. Global Spatial Autocorrelation Indicator

Global spatial autocorrelation depicts the distribution pattern of random, dispersed, or clustered observations. The global Moran's I indicator was employed to achieve this objective (Moran, 1948):

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\frac{1}{n}\sum_{i=1}^{n} (x_i - \bar{x})^2 * \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}} \quad (1)$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n is the number of spatial units, which in this study is n=22. xi and xj are observations (pollutants) of spatial units i and j, respectively; wij is an element of the spatial weight matrix W that describes the spatial arrangement of all spatial units in a sample. Moran's I values vary from -1 to 1, and if 0 < I < 1, there is a positive correlation between the observations, and if -1 < I < 0, it indicates a negative correlation between the observations. While I values equal to 0 or close to it indicate the distribution of observations randomly (no correlation).

The Z statistic, in its standardized form, is frequently employed to ascertain the significance of the Global Moran's I:

$$Z(I) = \frac{I - E(I)}{\sqrt{\mathrm{Var}(I)}} = \frac{I - \left[-\frac{1}{n-1}\right]}{\sqrt{E(I^2) - [E(I)]^2}} \quad (2)$$

In the context of Moran's I, E(I) and Var(I) represent expected value and variance, respectively.

2.3.2. Local Spatial Autocorrelation Indicator

This was used to identify and determine the intensity of clustering with high (HH) or low (LL) values and spatial outlier points (HL and LH). The expression for the local Moran's I for a given observation 'i' can be expressed as in Equation 3 (Anselin, 1995).

$$I_i = \frac{(x_i - \bar{x}) * \sum_{j=1}^{n} w_{ij}(x_j - \bar{x})}{\frac{1}{n}\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (3)$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and n and wij are the same as the above explanation.

2.3.3. Transport Network Density Indicator

The transportation system-based accessibility indicator reflects the density of communication infrastructure within a region. This measure can be computed and represented in unit of (km/km^2) as per Equation 4 (Cordera et al., 2017).

$$D = \frac{Network\ Kilometers}{Surface\ of\ the\ study\ area(km^2)} \quad (4)$$

3. Results and discussion

This study investigated the distribution pattern and intensity of CO and NO_2 concentrations and their relationship with transportation in 22 districts of Tehran.

3.1. Temporal Trend of Pollutants Concentrations

To monitor CO, NO_2 air pollutants in Tehran City, Python programming was used in the GEE environment for 2022. A sample script for the CO pollutant extraction is shown in Figure 2. To understand the general trend of upward or downward changes in each pollutant, the trend line is shown in Figure 3. The daily concentration patterns of the two pollutants, CO and NO_2, in the first and last quarter of the year were higher than the average values, which is probably due to the reopening of schools and the increase in car traffic. The range of CO changes in mol/m^2 values was 0.077-0.017 and for NO_2, the range of changes was much smaller (a and b in Figure 3). Previous studies confirm the results (Ghannadi et al., 2022; Gharibi & Shayesteh, 2021).

```
2022_01 *
Imports (1 entry)
var table: Table users/aghahremanlou/Tehran

Map.centerObject(table);
Map.addLayer(table);


//carbon monoxide2022

var co = ee.ImageCollection('COPERNICUS/S5P/NRTI/L3_CO')
.filterBounds(table)
.filterDate('2022-01-01','2023-01-01')
.select('CO_column_number_density');

var co_clip = co.map(function(img){
  return img.clip(table).rename('Carbon Monoxide')
  .copyProperties(img,['system:time_start','system:time_end']);
});

print(co_clip);

print(ui.Chart.image.series(
 co_clip, table, ee.Reducer.mean(), 1000, 'system:time_start')
  .setOptions({

    title: 'Co changes in Tehran',
    hAxis: {title: 'time'},
    vAxis: {title: 'value'},
    trendlines: {0 : {color: 'red'}},
    pointSize: 2.0,
    lineWidth: 1.0,
    series: {
      0 : {color: 'green'}
    }}));


///// spatial pattern for CO2022//////

var mean = co_clip.mean();

var proj = ee.Projection('EPSG:4326');

var reproj = mean.reproject(proj,null,1000);

Map.addLayer(mean);


Export.image.toDrive({
  image: reproj,
  description: 's5_mean_coreproject',
  scale: 1000.0,
  region: table,
  maxPixels: 1e9
});
```

Figure 2. Sample script executed in the GEE environment to monitor CO changes

Figure 3. Trend of time changes of pollutants on different days in 2022

3.2. Spatial Variation Trend of Pollutants

The spatial distribution pattern of pollutants was identified using the Global Moran's I spatial autocorrelation measure. The outcomes, derived from applying Equations 1 and 2, are presented in Table 2 and Figure 4.

Table 2. Statistical data on the spatial distribution of pollutants

Item	Moran's I	Z-score
CO	0.94	49.12
NO_2	0.94	49.00

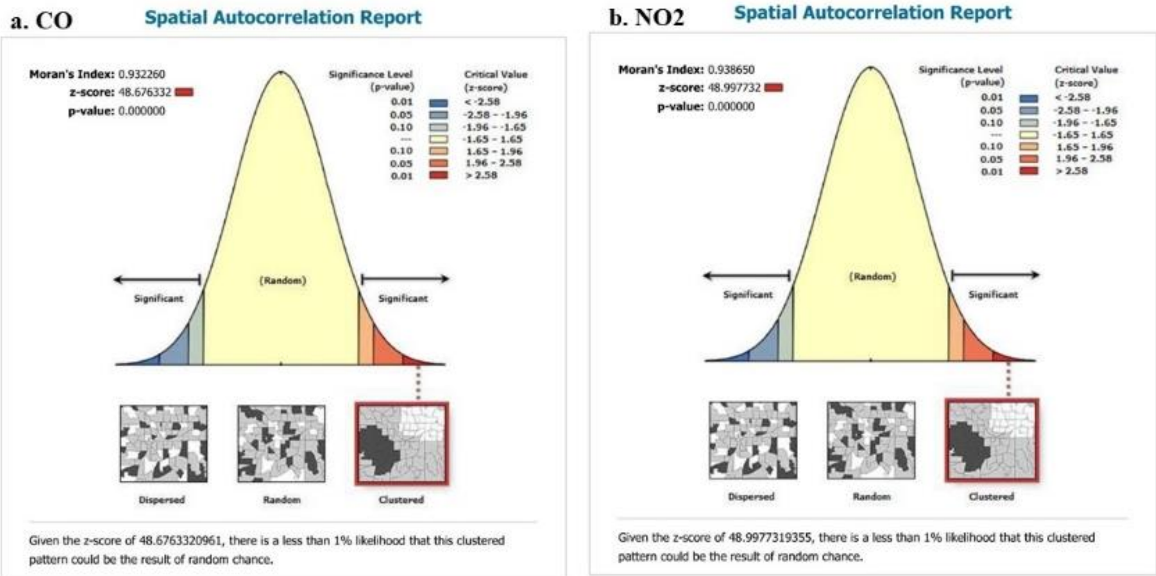

Figure 4. Spatial distribution pattern of pollutants

According to the available results, the spatial distribution patterns of the pollutants were clustered. The values of the Global Moran’s I indicator for CO and NO_2 were close to 1, indicating a high autocorrelation between pollutants in the atmosphere. The Z-values for the pollutants represent a 99% confidence level. To map the clusters and determine the centers of pollutants in the 22 districts of Tehran. Values were calculated using Equation 3 in ArcMap 10.8 software, and the results are shown in Figure 5 and Table 3.

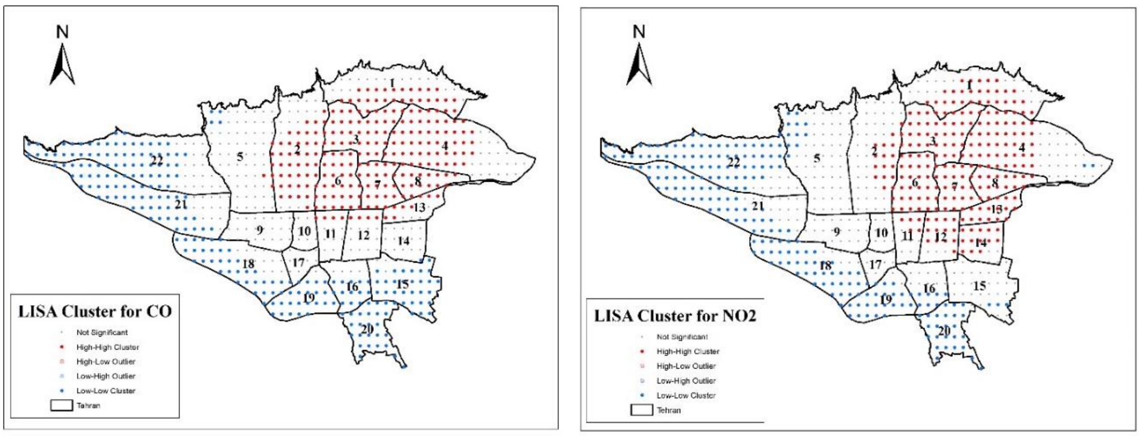

Figure 5. Map of Tehran City pollutants epicenters

Table 3. List of the number and intensity of pollutants clusters in Tehran

Item	HH	LL	LH	HL	NS
CO	238	234	0	0	289
NO_2	234	223	0	0	304

* HH = number of high-high clusters; LL = number of low-low clusters; NS = not significant.

According to Table 3, the local Moran's I indicator values of pollutants indicate a high cluster state in high values (HH) and a low cluster state in low values (LL) in Tehran’s city districts. The spatial output from processing 728 satellite images from 2022 to determine the CO foci of Tehran City showed that 17 districts had a positive correlation (HH and LL clusters). HH clusters in the 10 districts included east, northeast, and north districts, and LL clusters were in the southern, southwestern, and western marginal districts. The spatial output of NO_2 in Tehran showed that the spatial distribution of this pollutant was almost similar to that of CO at the regional level. with the difference being that 19 districts had a positive correlation (HH and LL clusters). In addition, the surfaces of districts 3, 6, 7, 8, and 13 were completely surrounded by HH clusters, while district 20 was completely surrounded by LL clusters of NO_2 pollutants.

3.3. Transportation's Network Accessibility

To understand the relationship between transportation and the concentration of pollutants, using Equation 4, the values of the street transportation network density indicator were calculated, and the average accessibility indicator of the 22 districts was obtained be 24.82 km/km^2. Accessibility results are shown in Figure 6. The highest accessibility indicator based on the transportation network infrastructure is related to District 10 (36.51 km/ km^2), which is in the center of the city and has the highest connectivity in the street network. Eleven districts in Tehran have values higher than the average transport accessibility indicator. This indicates that half of Tehran's urban districts have high connectivity in the transportation network, which is mainly located in the city center and in CO and NO_2 clusters because of the high volume of motor vehicle traffic. Previous studies have confirmed the effect of network density on the concentrations of these two pollutants (Lei et al., 2023; Wang et al., 2021).

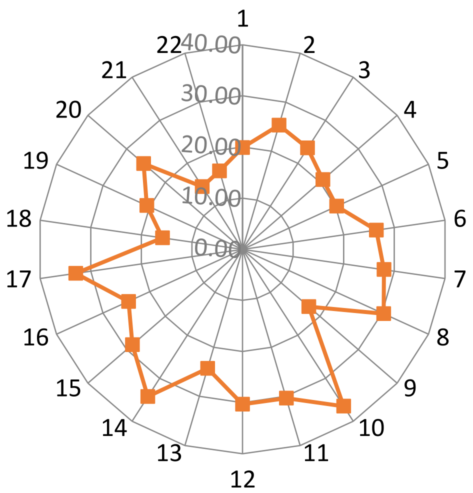

Figure 6. Accessibility of transportation network density of Tehran's urban districts in 2022

4. Conclusion

Nowadays, air pollution poses a significant challenge to the Tehran. Spatial statistical analysis of pollutants can help identify the centers of pollution so that urban planners can take effective measures accordingly. In this study, the concentration of pollutants and transportation accessibility for 22 districts of the Tehran metropolitan area were investigated spatiotemporally.

Sentinel-5p satellite images were used to monitor the air pollutants. The average concentrations of the CO and NO_2 pollutants from the satellite were obtained using Python in the GEE environment. The temporal investigation of pollutants shows that the daily behavioral patterns of CO and NO_2 concentrations in the first and last quarters of the year are higher than the average, which is probably due to the reopening of schools. The distribution of pollutant concentrations using spatial autocorrelation showed that CO and NO_2 had the high autocorrelation, with Global Moran's indicator values equal to 0.94. In addition, the distribution patterns of the pollutants were clustered. Therefore, Tehran's air pollution intensification can be considered the result of high spatial autocorrelation values and clustering patterns of pollutants. The local spatial analysis of LISA showed that the clustering was high in high values (HH) and low in low values (LL) in the central districts and southern suburbs. The average accessibility indicator of the 22 districts was 24.82 km/km^2. The accessibility in half of the districts was higher than the urban average. This resulted in a surge in traffic volume, prolonged idling of vehicle engines, recurrent acceleration and deceleration, and extended commuting durations in these districts. All of these elements contribute to the exacerbation of air pollution.

Estimating accessibility based on road transport infrastructure in urban districts is crucial for sustainable urban planning and design. By understanding the density and connectivity of the road network, urban planners can optimize transportation systems, promote alternative modes of transportation (e.g., public transportation, cycling, and walking), and reduce reliance on personal vehicles. This can lead to reduced traffic congestion, greenhouse gas emissions, improved air quality, and increased overall urban sustainability. Analysis of CO and NO_2 pollutants, together with accessibility estimation, provides valuable data for policy and decision making. The results of this study emphasize comprehensive strategies and policies that prioritize sustainable transportation infrastructure and remote sensing air pollution monitoring. By addressing these issues, we can witness cleaner and healthier air for Tehran in the future.

The results of this study are based on data from the metropolitan area of Tehran. However, many cities worldwide are facing challenges related to urban air pollution and accessibility. The valuable techniques used in this study can also be extended to other cities.

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