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Spatio-temporal Dynamics of Urban Air Pollution: A GIS-Based Assessment in Afyonkarahisar, Turkey

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Kentsel Hava Kirliliğinin Zaman-Mekansal Dinamikleri: Afyonkarahisar, Türkiye'de CBS Tabanlı Değerlendirme

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Abstract

Investigating the causes of air pollution, a growing global problem, and implementing effective solutions are of great importance. This study aims to examine spatial dependencies using spatial clustering methods and to create pollution distribution maps based on key air pollutant parameters. An air pollution database was developed in a GIS environment using measurement location data and concentration values of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) collected from the city center of Afyonkarahisar, Turkey. Using this database, air pollution distribution maps were first generated with the Inverse Distance Weighted (IDW) interpolation method to identify spatial patterns across the study area. Spatial clusters were subsequently determined through autocorrelation analyses, including Global Moran's I, Anselin Local Moran's I, and Getis-Ord Gi statistics. According to the Global Moran's I results, spatially significant clustering at the 99% confidence level with Moran's I values of 0.31 for SO_2 and 0.28 for NO_2 during winter. The Anselin Local Moran's I and Getis-Ord Gi analyses revealed high-significance clusters concentrated in the southwestern portion of the study area. Additionally, it was found that SO_2 levels increased in zones characterized by high residential density, unplanned construction, and extensive coal use, whereas NO_2 concentrations were elevated in areas with intense vehicle traffic. In terms of temporal variation, winter exhibited the highest concentrations of SO_2, while summer showed the highest concentrations of NO_2. These findings underscore the importance of spatial analysis for understanding pollution dynamics and for informing effective air quality management strategies.

Keywords: *Urban Air Pollution, GIS, Spatial Autocorrelation Tests, Spatial Patterns*

Öz

Hızla büyüyen küresel bir sorun hâline gelen hava kirliliğinin nedenlerinin araştırılması ve etkili çözümlerin uygulanması büyük önem taşımaktadır. Bu çalışma, mekânsal kümeleme yöntemlerini kullanarak hava kirliliğine ilişkin mekânsal bağımlılıkları incelemeyi ve temel hava kirletici parametrelere dayalı hava kirliliği dağılım haritalarını oluşturmayı amaçlamaktadır. Bu kapsamda, Afyonkarahisar şehir merkezinden elde edilen lokasyon verileri ile kükürt dioksit (SO_2) ve azot dioksit (NO_2) konsantrasyon değerleri kullanılarak CBS ortamında bir hava kirliliği veri tabanı oluşturulmuştur. Bu veri tabanı yardımıyla, çalışma alanındaki mekânsal kirlilik paternlerini belirlemek amacıyla önce Ters Ağırlıklı Mesafe metoduyla dağılım haritaları üretilmiştir. Ardından, Global Moran's I, Anselin Local Moran's I ve Getis-Ord Gi istatistiklerini içeren mekânsal otokorelasyon testleri uygulanarak kirlilik kümelenmeleri belirlenmiştir. Global Moran's I analizi, kış döneminde SO_2 için 0,31 ve NO_2 için 0,28 Moran's I değerleriyle, %99 güven düzeyinde istatistiksel olarak anlamlı mekânsal kümelenmenin varlığını ortaya koymuştur. Anselin Local Moran's I ve Getis-Ord Gi analizleri ise çalışma alanının güneybatı kesiminde yüksek anlamlılığa sahip kümelerin yoğunlaştığını ortaya koymuştur. Ayrıca, SO_2 seviyelerinin yüksek konut yoğunluğunun, plansız yapılaşmanın ve kömür kullanımının yaygın olduğu bölgelerde arttığı; NO_2 seviyelerinin ise araç trafiğinin yoğun olduğu alanlarda yükseldiği belirlenmiştir. Zamansal açıdan değerlendirildiğinde, en yüksek SO_2 konsantrasyonlarının kış mevsiminde, en yüksek NO_2 konsantrasyonlarının ise yaz mevsiminde görüldüğü sonucuna ulaşılmıştır. Bu bulgular, hava kirliliği dinamiklerinin anlaşılmasında mekânsal analizlerin önemini ve etkili hava kalitesi yönetimi için sağladığı katkıları vurgulamaktadır.

Anahtar Kelimeler: *Kentsel Hava Kirliliği, CBS, Mekansal Otokorelasyon Testleri, Mekansal Paternler*

1. Introduction

Today, urbanization rates are increasing as rural populations migrate to cities for economic, social, and other reasons. Various studies have indicated that this situation increases air pollution, especially in densely populated areas (Sümer 2014). Air pollution is defined as a common problem affecting the whole world, from local to global levels, due to its negative impact on all living things, which can even lead to death.

Both scientists and international authorities are conducting various studies and carrying out activities to raise environmental awareness in order to eliminate the negative effects of air pollution and, in particular, to improve air quality. Scientific studies on this subject focus

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particularly on identifying air pollutants, researching their effects on pollution, and determining regional pollution levels (Kyrkilis et al. 2007).

The growing urban population increases the demand for housing, and as a result, the use of fossil fuels for heating and transportation grows by the day. In addition to increasing fossil fuel consumption, unplanned and distorted urbanization, industrialization, meteorological and topographical conditions, and increased traffic density negatively affect air quality (Tağıl 2007, Demiraslan et al. 2018).

Industrialization, especially in developing countries, plays a major role in this increase in pollution. In developing Turkey, air pollution has reached serious levels in recent years. The European Union (EU) and the World Health Organization (WHO) have set certain limit values for pollution. However, the results obtained from some measurements in Turkey are unfortunately above these limit values (Garipağaoğlu 2015, Alkan 2018). According to air pollution data, Turkey is one of the countries with the highest number of premature deaths due to air pollution within Europe. This situation is consistent with a report published by the Turkish Thoracic Society in 2016, which states that 32,000 people die each year in Turkey due to air pollution and that the air in 80 of 81 provinces is polluted according to WHO pollution parameters (Turkish Thoracic Society 2016, Alkan 2018). According to a WHO report with similar findings, eight of the ten most polluted cities in Europe are located in Turkey. Within Turkey, Afyonkarahisar ranks seventh in terms of air pollution (Yazıcı et al. 2018).

The fact that air pollution has such a significant negative impact on living organisms further highlights the importance of identifying and measuring the sources of pollution and the associated pollutant parameters. Air quality monitoring stations are used to determine pollution levels and take necessary measures. These stations are positioned in suitable locations and conditions within the area where pollution levels are to be detected, and measurements are carried out. In many countries, measurements necessary for periodic (daily, weekly, monthly, etc.) air pollution detection are taken at these stations, and the results obtained are presented on relevant platforms. Although there are various parameters that affect pollution, the most important ones are Particulate Matter (PM2.5- PM10), sulfur oxides (SO_x), carbon oxides (CO, CO_2), ozone (O_3), and nitrogen oxides (NO_x). The pollutant parameters obtained from the measurements and their numerical values are assessed using limit values established by national and international institutions or organizations, alongside various analytical methods. Consequently, measures to mitigate air pollution are identified (Dokuz et al. 2020, Ayturan 2019).

In Turkey, air quality measurement stations were established in 81 provinces by the former Ministry of Environment and Forestry to improve air quality and measure pollution, with the number of stations varying by province. While only PM10 and SO_2 pollutants were measured when the stations were first established, today, with the work carried out by the Ministry of Environment, Urbanization and Climate Change (MEUCC), NO, NO_2, NO_X, CO, O_3, and PM2.5 pollutants have also been measured (Int. Ref. 1). However, not all of these parameters can be measured in all provinces. Therefore, the results of the studies indicate that not all parameters can be measured, the data obtained from the stations is incomplete and insufficient, and some stations are not even in a position to identify the source of pollution due to their location. It is stated that in order to obtain more reliable results, the number of air quality measurement stations and the measurement intervals (periods) should be increased (Daylan and İncecik 2002, Gül 2005, Bazoğlu 2017, Kök 2018).

There are a limited number of studies that use multiple spatial parameters within the same study to examine the spatial dependence of air pollution parameters (Taş 2006, Özcan 2016, Koç 2018, Alkan 2018, Kök 2018). Özcan (2016) used the measurement results of SO_2 and NO_2 pollutant concentrations measured at different points in the Çiğli district of İzmir, investigated the effects of different land use types, heating types, building characteristics, transportation types, and meteorological factors on air quality (Özcan 2016). Krochmal and Kalina (1997) measured monthly SO_2 and NO_2 concentrations using passive sampling at 147 points in 30 major cities in Poland and 31 points in rural areas from May 1993 to April 1994. The measurement points were divided into five classes representing city centers, residential areas, industrial areas, traffic areas, and rural areas (Krochmal and Kalina 1997). Other studies in the literature have addressed the effects of environmental factors (heating, transportation, industry, green-open-space usage, solid and medical waste) on air pollution as separate topics in different cities (Özen 2006, Öztürk 2006, Kavak Yürük 2010, Kocaman 2010, Erdoğan 2012, Özer 2013, Tuna et al. 2013, Polat 2016, Koç et al. 2016, Kara and Tezel 2017, Santiago et al. 2017, Colvero et al. 2018, Altıkat 2020, Wang et al. 2021, Wang et al. 2022, Karimi et al. 2022). In Afyonkarahisar province, where air pollution has reached serious levels, studies evaluating pollution parameters were examined; generally, the change in SO_2 and PM

measurement results from a single station during the winter months over the years, and studies have been conducted using heating types (coal, natural gas, geothermal), topographic structure, and meteorological factors as pollutant sources (Başkır 1993, Gül 2005, Keçebaş et al. 2010, Yazıcı 2018). Keçebaş et al. (2010) emphasized in their study that the effects of other factors should also be investigated. In studies investigating the causes of air pollution, it was observed that the number of stations was insufficient and that studies using all factors causing pollution were limited (Keçebaş 2010).

The objective of the present study is to ascertain the spatial pattern of air pollution using air pollution parameter measurements taken simultaneously at 26 different locations within the city boundaries of Afyonkarahisar. In contrast to preceding research, this study has devised spatial distribution maps of air pollution for all four seasons in the city of Afyonkarahisar, encompassing the entire city with the largest number of simultaneous samples and multiple parameters. In this study, GIS-based spatial autocorrelation tests (Global Moran's I, Anselin Local Moran's I, and Getis Ord Gi) were utilized to investigate the clusters, and pollution distribution maps were created using the Inverse Distance Weighted Interpolation (IDW) method. This study is pioneering in its comprehensive examination of the correlation between air pollution in Afyonkarahisar Province and environmental variables, including building area, green area, open area, organized industrial zones, road lengths and types, and fuel type utilized for heating (natural gas, geothermal energy, coal, etc.). It also seeks to elucidate the spatial dependence of pollutant parameters. It is anticipated that this study will make a significant contribution to the existing body of knowledge by evaluating a multitude of environmental factors that contribute to air pollution.

2. Materials and Methods

2.1 Study area and material

The selected study area is the city of Afyonkarahisar. The city's strategic position as an inter-provincial junction has contributed to its rapid industrialization, positioning it among Turkey's most rapidly expanding industrial cities. Consequently, the most significant causes of air pollution specific to Afyonkarahisar can be attributed to traffic and industrial emissions. Furthermore, a significant contributing factor to the deterioration of air quality is the utilization of heating sources such as coal and natural gas. The impact of heating on the city's air pollution is exacerbated by the city's geographical location and topography, resulting in a cold climate, low air circulation due to the elevations around the city center, and unplanned construction. The impact of increased traffic, particularly during the summer months, is attributable to the rise in both intra-city and inter-city transportation (THEP 2020).

The present study utilized data obtained within the scope of the MEUCC project, which was provided by the Afyonkarahisar MEUCC Provincial Directorate. As part of the 'Air Quality Preliminary Assessment Study' project conducted by MEUCC, the concentration values of air pollutant parameters were measured at specific intervals throughout the four seasons using passive sampling methods at points in Afyonkarahisar city center where different station types (rural, heating, industrial, traffic) were located (Table 1). The measurements obtained during the winter, spring, summer, and autumn months were collated as monthly average data.

Table 1. Temporal distribution of air pollution measurements

Season	Period	Start Date	End Date
Winter	1st	December 30, 2014	January 13, 2015
	2nd	January 13, 2015	January 27, 2015
Spring	1st	March 17, 2015	March 31, 2015
	2nd	March 31, 2015	April 15, 2015
Summer	1st	July 21, 2015	August 4, 2015
	2nd	August 4, 2015	August 18, 2015
Autumn	1st	September 2, 2015	September 16, 2015
	2nd	September 16, 2015	October 1, 2015

In the study, SO_2 and NO_2 measurement results (pollutant concentrations) from the concentrations of air pollutant parameters measured by the passive sampling method were used as the pollutant type. Other pollutant parameters (PM2.5, PM10, HF, HCL, CO etc.) were not used due to lack of sufficient samples at all locations within the study area.

Passive sampling method relies on the free flow of analytic molecules from the sampled environment to a collection medium as a result of a difference in chemical potentials (Krupa and Legge 2000). It allows for the measurement of cumulative air pollutant exposures as total or average pollutant concentrations over a sampling period. The sample is collected in a suitable container and then analyzed either directly on-site or in the laboratory. Devices used for passive sampling typically rely on diffusion through a well-defined diffusion barrier or permeability through a membrane. In most cases, passive sampling greatly simplifies sampling and sample preparation, eliminates power requirements, and significantly reduces analysis costs. It is particularly suitable for determining time-weighted average concentrations. The advantages of passive sampling include the simple and low-cost installation of the devices

used, the absence of complex equipment, no power requirements, the ability to operate unattended, and the production of accurate results. The most important disadvantage is the possible effect of environmental conditions (such as temperature, air movement, and humidity) on analytic uptake (Krupa and Legge 2000, Górecki and Namieśnik 2002, Salem et al. 2009).

The spatial distribution of 26 measurement stations where air pollutant parameters were measured within the study area is given in Figure 1.

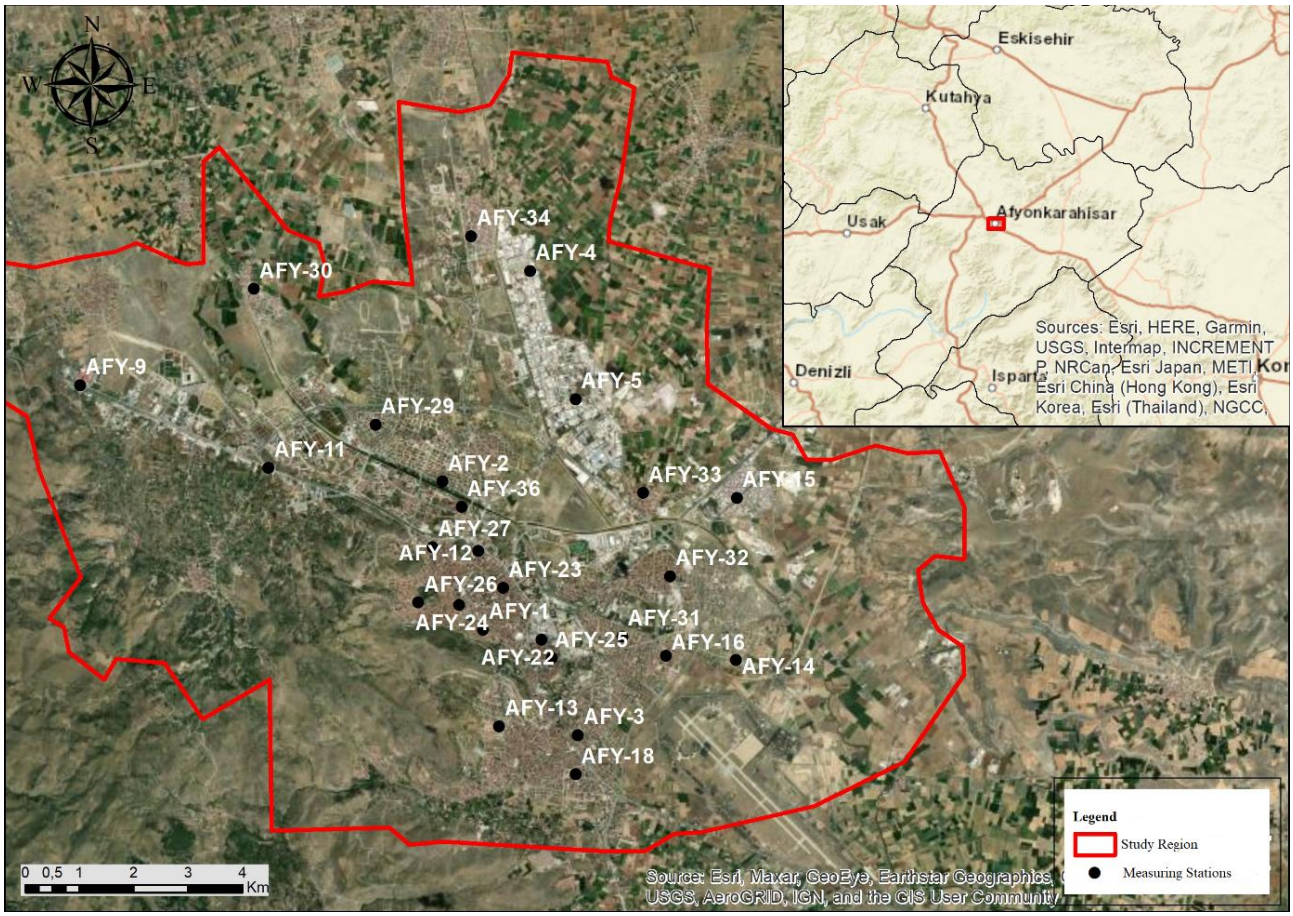


Figure 1. Study area and air pollution measurement locations

2.2 Method

In the study, the coordinate values of the obtained measurement points and the concentration values of the pollutant parameters SO_2 and NO_2 were first transferred to the GIS environment. In the second stage, pollution distribution maps were created using the Inverse Distance Weighted Interpolation (IDW) method. In the final stage, global clustering analyses were used to investigate the presence of general clustering. At the times when clustering was detected, the regions where local clusters occurred and their significance levels were examined.

2.2.1 Interpolation

The interpolation method is defined as the estimation of values for unknown locations using sample points. The IDW method is one of the most commonly used interpolation methods. The reason for this is that, as a simple deterministic method, features such as influence area barriers can be defined within the method. Furthermore, its use is widespread in studies related to air pollution. In addition, the IDW method was preferred over Kriging because the limited number and uneven spatial distribution of sampling points made variogram modeling unreliable, while IDW preserves local variation and provides robust results with simpler assumptions.

In this method, the cell value is calculated by considering various points moving away from the relevant cell and depending on the increase in distance. As the sample value moves away from the relevant cell, its effect on the cell value to be calculated decreases. In the IDW method, characteristics such as the general distribution, trend, anisotropy, and clustering of the data are examined (Taylan and Damçayırı 2016). The cell value is calculated using equation 2.1 (Taylan and Damçayırı 2016, Jumaah et al. 2019).

$$\hat{z}\,(x_0)\,\frac{\sum_{i=1}^{n} z(x_i) d_{i0}^{-r}}{\sum_{i=1}^{n} d_{i0}^{-r}} \qquad (1)$$

According to the equation, x_o is the estimated location, x_i is the observed location, di_o is the distance, and r is the upper limit determining the assigned interval. As the upper limit increases, it is understood that the similarity between the predictions and the nearest observations is very high (Taylan and Damçayırı 2016).

2.2.2 Spatial Cluster Analyses

In this study, Global Moran's I analysis from global clustering methods and Anselin Local Moran's I and Getis Ord Gi* analysis from local clustering methods were used for spatial statistical analyses.

Global Moran's I assesses whether the spatial and attribute values of the data sets are clustered, scattered, or random. The method calculates the Moran's I Index value, z-score, and p-value to evaluate the significance of this index. The Moran's I Index value is calculated using equation 2.2 (Int. Ref. 2, Yalçın and Kaya 2019).

$$I = \frac{N \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \left(x_{i-\bar{x}}\right)\left(x_{j-\bar{x}}\right)}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}\right) \sum_{i=1}^{n} \left(x_{i-\bar{x}}\right)^2} \quad (2)$$

According to the equation, n represents the number of regions, x_i and x_j represent the observed locations, w_{ij} represents the spatial proximity between region i and region j, and $\overline{x}$ represents the average value of x. In addition to Moran's I index, the calculated P-value represents the probability, and the Z-value represents the standard deviation. When the Z-score or p-value indicates statistical significance, a positive Moran's I index value indicates a tendency toward clustering, while a negative Moran's I index value indicates a tendency toward dispersion. The relationship between the P probability value and the Z value is given in Table 2.

Table 2 Relationship between P value and Z value.

Z-Value	Probability Value P	Confidence Level
<-1.65 or > +1.65	<0.10	90%
<-1.96 or > +1.96	<0.05	95%
<-2.58 or > +2.58	<0.01	99%

When examining whether clustering and dispersion exist in Anselin's Local Moran's I and Global Moran's I analyses, Local Moran's I analysis identifies regions where clusters occur and regions without significant clustering (Zhang et al. 2008). The identified clusters are high-high clustering, high-low clustering, low-high clustering, and low-low clustering. In the analyses, the Moran's I value, a z-score, a p-value, and a code representing the cluster type for each statistically significant feature are calculated. The z- and p-values represent the statistical significance of the calculated index values. The Local Moran's I Index value is calculated using equations 2.3 and 2.4 (Getis 2010, Yalçın and Kaya 2019).

$$I_i = \frac{x_{i-\bar{x}}}{S_i^2} \sum_{j=1, i\neq j}^{n} w_{ij} \left(x_{i-\bar{x}}\right) \quad (3)$$

$$S_i^2 = \frac{\sum_{j=1, i\neq j}^{n} (x_{i-\bar{x}})2}{n-1} \quad (4)$$

According to the equation, n represents the number of points, x_i and x_j represent the point values, w_{ij} represents the spatial proximity between region i and region j, and $\overline{x}$ represents the average value of the sample points.

Getis Ord Gi* defines spatial clusters containing statistically significant high values (hot spots) and low values (cold spots). It calculates the Gi* statistic, z-scores, and p-values for each feature in the dataset. Z and p values provide information about where high or low-value features are spatially clustered. For statistically significant positive z-scores, the larger the z-score, the more intense the clustering of high values (hot spot). For statistically significant negative z-scores, the smaller the z-score, the more intense the clustering of low values (cold spot). Seven different codes representing the cluster type are calculated. These codes are; Cold Spots at the 90% confidence interval, Cold Spots at the 95% confidence interval, Cold Spots at the 99% confidence interval, Hot Spots at the 90% confidence interval, Hot Spots at the 95% confidence interval, Hot Spots at the 99% confidence interval, and statistically insignificant points. The Gi* statistic value is calculated using the following equations (Dereli, 2016).

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \quad (5)$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \quad (6)$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{x})^2} \quad (7)$$

According to the equation, w_{ij} represents the weight matrix between elements i and j, x_j represents the value of feature j, and n represents the total number of features.

3. Results

3.1 Spatial Distribution of Air Pollution

Using the pollutant values measured during the winter and summer periods and the annual average values of the SO_2 and NO_2 pollution parameters, the pollution distribution maps for both parameters were created using the IDW method.

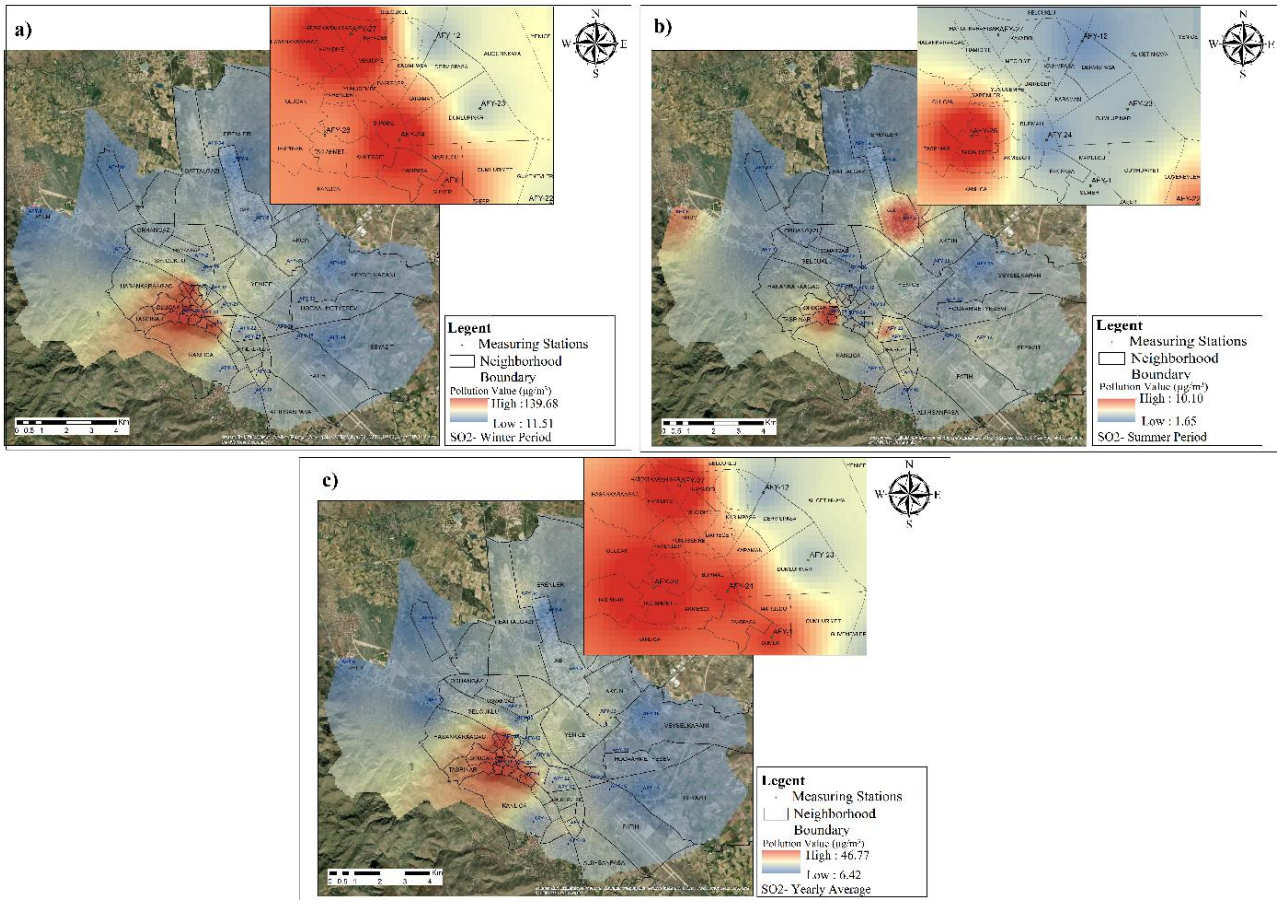


Figure 2. Air pollution distribution map for SO2 parameter in winter (a), summer (b) and annual average (c) .

3.1.1 Spatial Distribution of SO_2

The maps prepared using the values obtained from SO_2 measurements during the winter period (December 30 - January 27), summer period (July 21 - August 18), and annual average are presented in Figure 2.

When examining the spatial distribution during the winter period, it was observed that the pollution level was high in the castle and surrounding neighborhoods located in the southwest of the study area, and lower in other areas. The pollution levels were highest in the AFY-26, AFY-27, AFY-1, and AFY-24, which are located in the areas with the highest pollution levels are 139.68, 124.88, 111.97, and 110.7 µg/m^3 respectively, while in other areas, they range from 11.51 to 58.42 µg/m^3. The neighborhoods with the highest pollution levels are Hattatkarahisar, Kayadibi, Mecidiye, Hamidiye, Yunus Emre, Dairecep, Yarenler, Burmalı, Hasankaraağaç, Olucak, Taşpınar, Kanlıca, Tacı Ahmet, Akmescit, Fakıpaşa, Marulcu, and Sümer. In these neighborhoods, which are the first settlements of Afyonkarahisar, the high number of residences and unplanned construction, the lack of green areas, and the high percentage of coal use (~80%) as fuel are considered to be the causes of air pollution. In the neighborhoods of Olucak, Taşpınar, Tacı Ahmet, and Yarenler, where the coal usage rate is 100%, pollution is at the highest level among all neighborhoods. Looking at the neighborhoods of Akcin, Erenler, and Battalgazi, where the relatively high pollution rate represented by the yellow areas on the map is higher than in the surrounding neighborhoods, the percentage of coal use for domestic heating is also around 99%, demonstrating the significant impact of fossil fuel use on air pollution. Furthermore, the proximity of these neighborhoods to the organized industrial zone and the fact that they are located next to the intercity highway are considered another reason. In areas such as Selçuklu Neighborhood, where building density is low and the use of geothermal energy or natural gas is high, pollutant concentrations are low.

3.1.2 Spatial Distribution of NO_2

Maps prepared with NO_2 measurements in the study area for the winter period (December 30 - January 27), summer period (July 21 - August 18), and annual average values are given in Figure 3.

According to the results obtained from NO_2 measurements taken during the winter period, the highest pollution levels were recorded in the regions where the AFY-9, AFY-12, AFY-1, AFY-26, AFY-25, and AFY-24, with pollution levels of 52.02, 51.62, 43.12, 42.20, 41.79, and 41.65 µg/m³ respectively (Figure 3(a)).

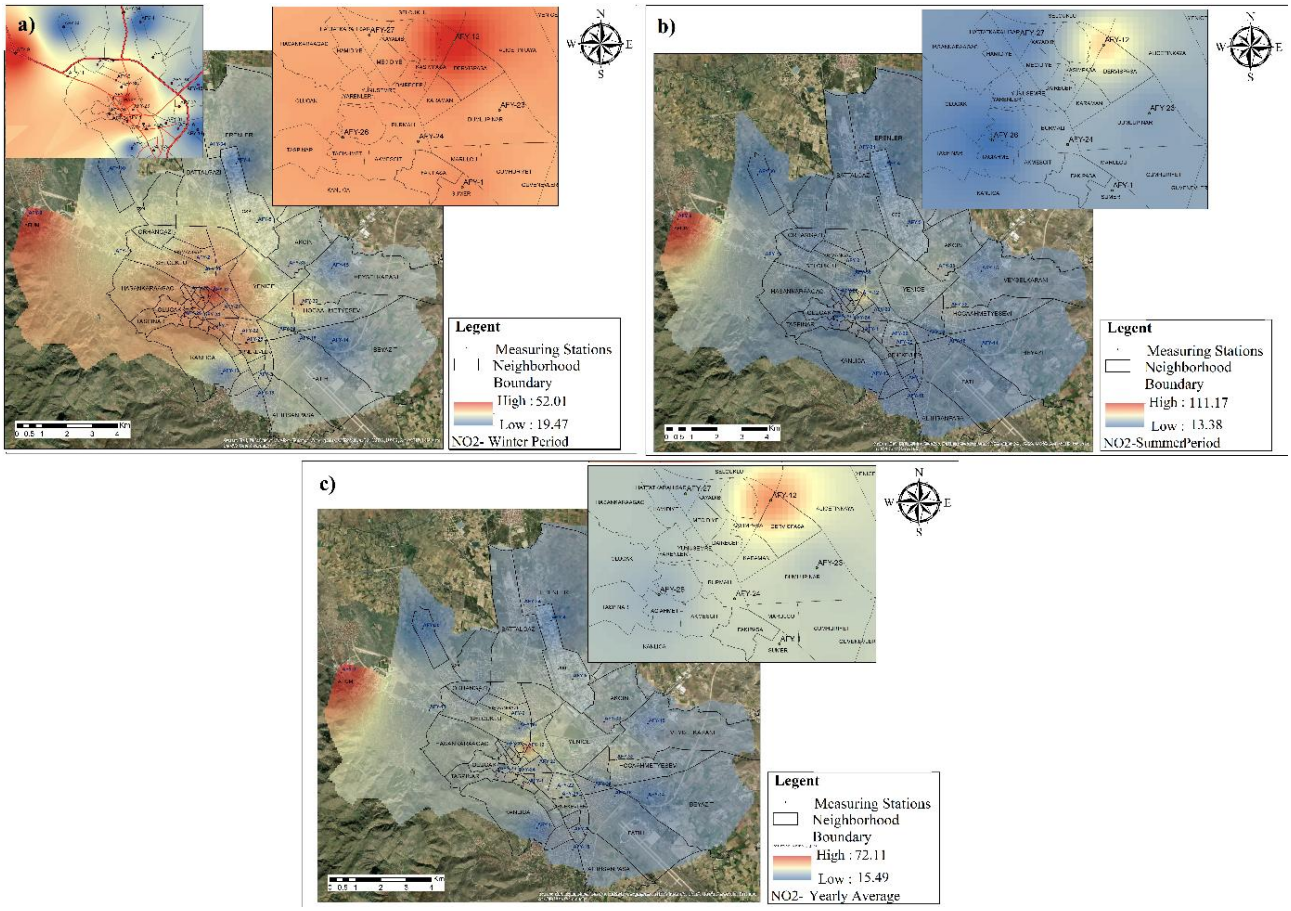


Figure 3. Air pollution distribution map for NO2 parameter in winter (a), summer (b) and annual average (c).

Pollution levels are also high at other points located in areas with high building density and close to the main road/ring road route (AFY-27, AFY-23, AFY-2, AFY-32). At the AFY-22 point, located in the area where the Small Industry and Park Afyon shopping center is located, the pollution level is 40.33 µg/m3 and is high like the others. It is estimated that the pollution level at the AFY-22 point is increased by the increase in vehicle traffic during the day and the location of industrial facilities in the area. Pollution levels decrease in areas with low building and vehicle density, such as the Beyazıt neighborhood.

According to NO_2 measurements taken during the summer, air pollution concentrations are highest during this period (Figure 3(b)). The pollution values at the AFY-9 and AFY-12 measurement points, where pollution is highest are 111.17 and 65.67 µg/m^3 respectively, while in other areas they range from 41.84 to 13.38 µg/m^3. The location of the AFY-9 point on the ring road and at an intersection, and the location of the AFY-12 point near the most heavily used main roads in the city center increase the pollution level. When examining other points with high pollution levels (AFY-33, AFY-32, AFY-24), it is assessed that the high traffic density and the presence of industrial facilities in the area where the points are located are among the causes of pollution.

When the annual average air pollution values of the NO_2 parameter are examined, it is seen that the region where air pollution is concentrated is similar to the summer period (Figure 3(c)). The point with the highest pollution level in all periods is the AFY-9 point. The AFY-9 point is located in an area where the Afium and Özdilek shopping centers are located, which are frequented by passenger buses and preferred as rest facilities for daily use, and is also an intercity road route and intersection point. It is estimated that the high population and vehicle density at shopping centers in all seasons, especially in summer, and the high vehicle density on the ring road and at the intersection increase the pollution level at this point. Considering all measurement periods, the second point with high pollution levels, AFY-12, is located in the city center and near main roads with high vehicle density. Pollution values are 72.11 µg/m^3 at point AFY-9 and 53.51 µg/m^3 at point AFY-12. In other areas, the pollution level varies between 38.85 and 15.49 µg/m^3. Pollution levels are lower in neighborhoods such as Beyazıt and Fatih, where there is less traffic and fewer industrial facilities and more open spaces.

3.2 Spatial Cluster Analyses

Data on SO_2 and NO_2 pollution parameters (measurement values for summer and winter periods) were examined to

determine whether global clusters existed. In periods where significant clusters were identified using the global Moran's I analysis, the Anselin Local Moran's I and Getis Ord Gi analyses were used to examine which areas had clusters and their significance.

3.2.1 Global Clusters

According to the Global Moran's I analysis results, significant clusters were observed only in the winter period for both parameters. The analysis results for the SO_2 and NO_2 pollution parameters using winter period data are presented in Table 3, and the analysis results using summer period data are presented in Table 4.

Table 3. Global Moran's I Cluster Analysis Results of SO_2 and NO_2 Pollutant Parameters – Winter Period

Polluting	Moran's I Value	Expected I Value	Z Value	P value
SO_2	0.307286	0.040000	4.708501	0.000002
NO_2	0.284749	0.040000	4.290312	0.000018

Table 4. Global Moran's I Cluster Analysis Results of SO_2 and NO_2 Pollutant Parameters – Summer Period

Polluting	Moran's I Value	Expected I Value	Z Value	P value
SO_2	-0.07366	0.04000	-0.46121	0.644642
NO_2	-0.02747	0.04000	0.192892	0.847044

When examining Table 3, the positive Moran's I values (close to +1) indicate clustering. Furthermore, both analyses ($z > 2.58$ and $p < 0.01$) revealed spatially significant clusters at the 99% confidence level.

Table 4 shows that the negative values of Moran's I (-1) indicate dispersion. Furthermore, both analyses ($z > -1.65$ and $p > 0.10$) reveal that there is no significant spatial clustering.

3.2.2 Local Clusters

3.2.2.1 Anselin Local Moran's I

The locations of clusters and cluster groups (High-High, High-Low, Low-Low, Low-High) were examined using the Anselin Local Moran's I analysis performed on winter season measurement data for the SO_2 and NO_2 parameters where global clustering was detected.

When examining Figure 4, it can be seen that clusters formed as High-High, High-Low, Low-Low, Low-High, and that there was no significant clustering at some points. High-High clusters formed at a 95% significance level in the neighborhoods of Hattatkarahisar, Tacıahmet, Burmalı, Sümer, and Örnekevler. A common feature of these neighborhoods, which have unplanned development and a high number of dwellings, is the high rate of coal use as fuel during the winter months. This situation is considered to be a cause of air pollution.

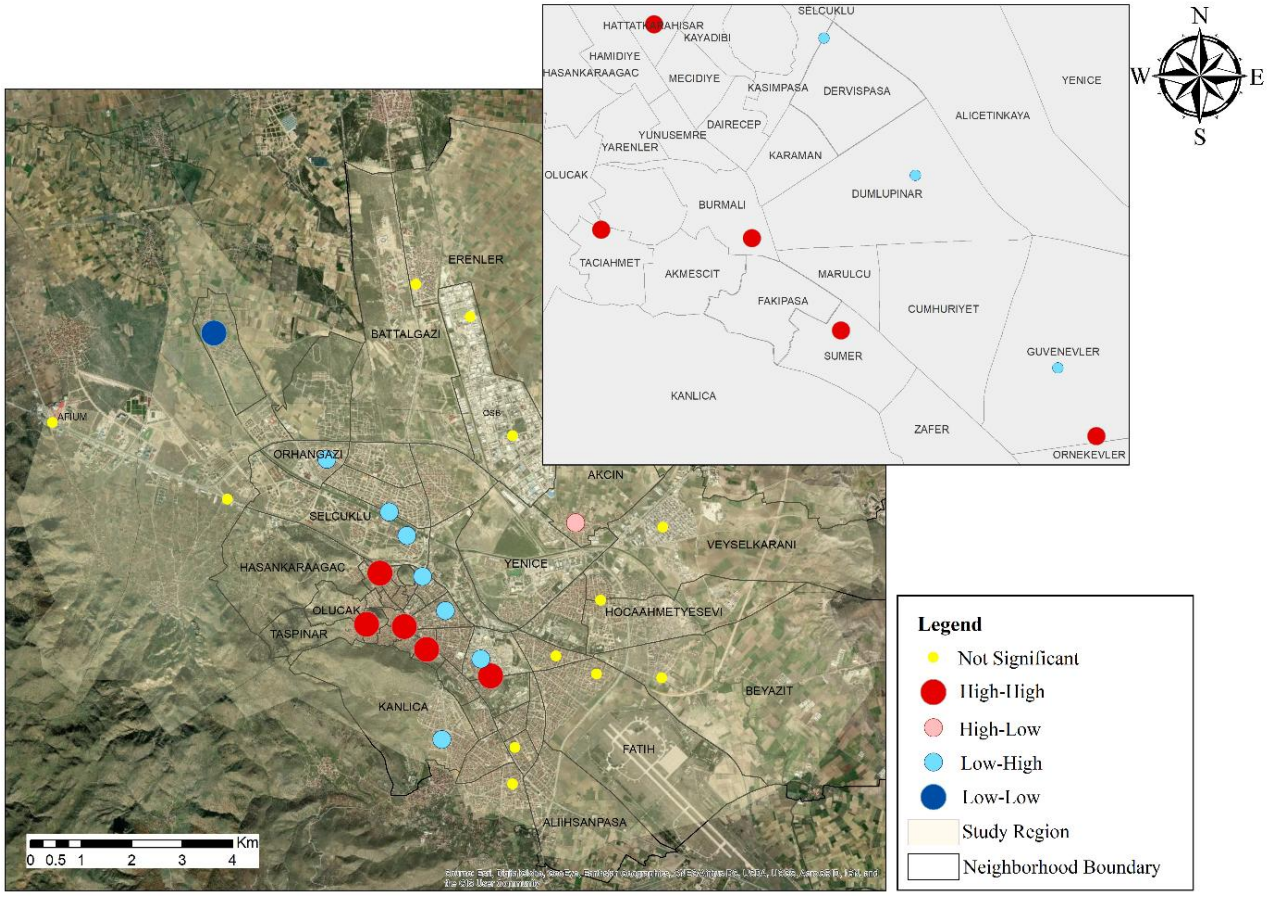


Figure 4. SO_2 parameter winter period Local Moran's I Cluster Map.

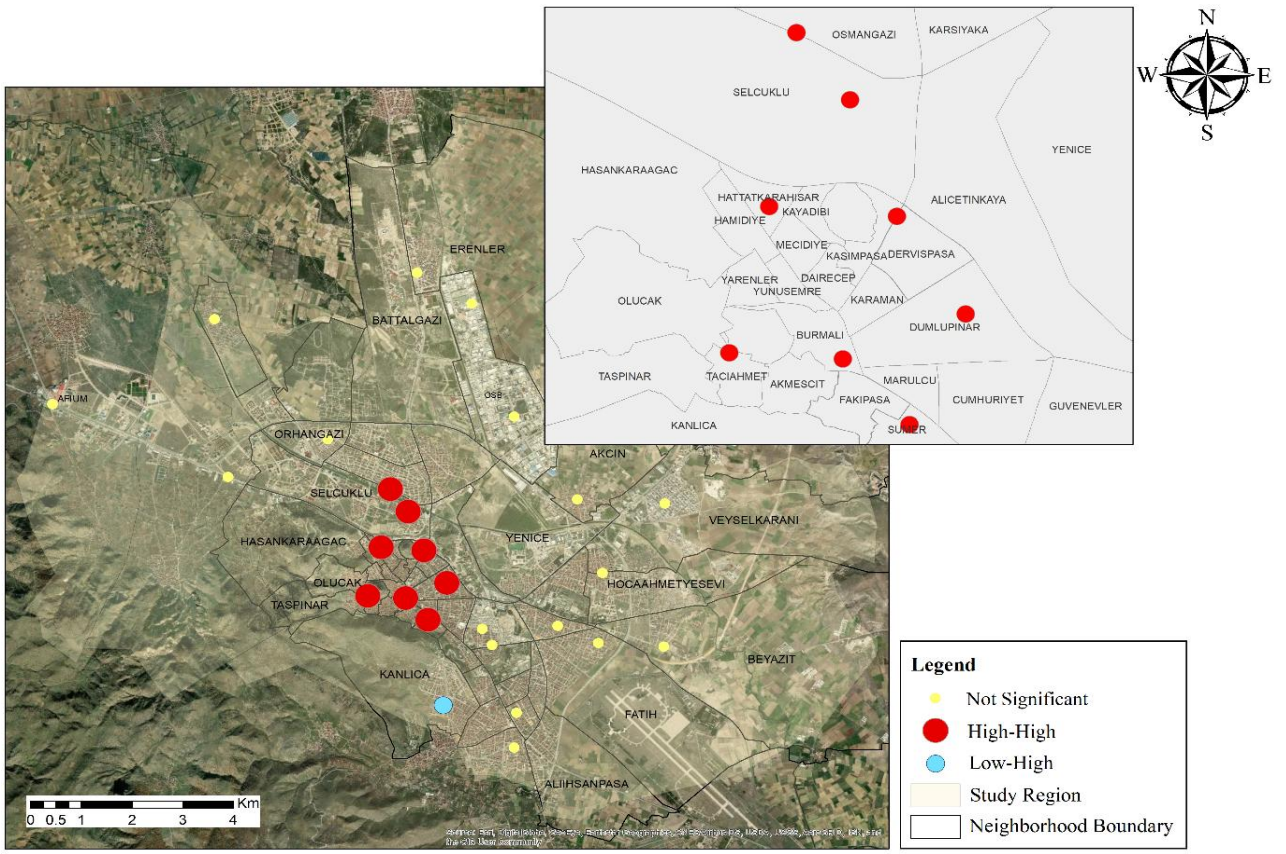


Figure 5. NO_2 parameter winter period Local Moran's I Cluster Map.

When examining Figure 5, it can be seen that clusters of High-High and Low-High have formed, and that there is no significant clustering at some points. High-High clusters formed at a 99% significance level in the Osmangazi and Selçuklu neighborhoods and at a 95% significance level in the Hatatkarahisar, Derviş Paşa, Dumlupınar, Burmalı, Tacı Ahmet, and Sümer neighborhoods. Hatatkarahisar, Derviş Paşa, Dumlupınar, Burmalı, Tacı Ahmet, and Sümer neighborhoods, located in the old settlement area of the city center, share the common feature of using coal for heating and industry during the winter season.

*3.2.2.2 Getis-Ord G**

Using the Getis-Ord G* statistic, the winter period measurement data for the SO_2 and NO_2 parameters were used to examine whether hot and cold spot clusters formed in the study area and the significance levels of the clusters that formed.

When examining Figure 6, it is seen that no cold spot clusters formed, and only hot spot clusters formed at the 95% and 99% significance levels. Hot spot clusters formed at the 99% significance level in the neighborhoods of Tacı Ahmet, Burmalı, Dumlupınar, and Kanlıca, and at the 95% significance level in the neighborhoods of Osmangazi, Selçuklu, Hattatkarahisar, Dervişpaşa, Sümer, and Güvenevler.

Similar to the Local Moran's I clustering maps, the Getis-Ord G* Statistics results map also shows that the neighborhoods mentioned above, which have a high level of significance, share the common feature of high coal usage rates during the winter months. Another common feature of these neighborhoods in the city center is the lack of green spaces and open areas.

When examining Figure 7, cold spot clusters are observed at a 90% significance level, while hot spot clusters are observed at 95% and 99% significance levels. Cold spot clusters were observed in the Veysel Karani neighborhood, while hot spot clusters were observed at the 99% significance level in the Osmangazi, Selçuklu, Hattatkarahisar, and Tacı Ahmet neighborhoods and at the 95% significance level in the Dervişpaşa, Dumlupınar, Burmalı, and Sümer neighborhoods.

In both local clustering methods, high clusters are concentrated in neighborhoods in the city center. This indicates that the pollution rate in this area is higher than in other areas.

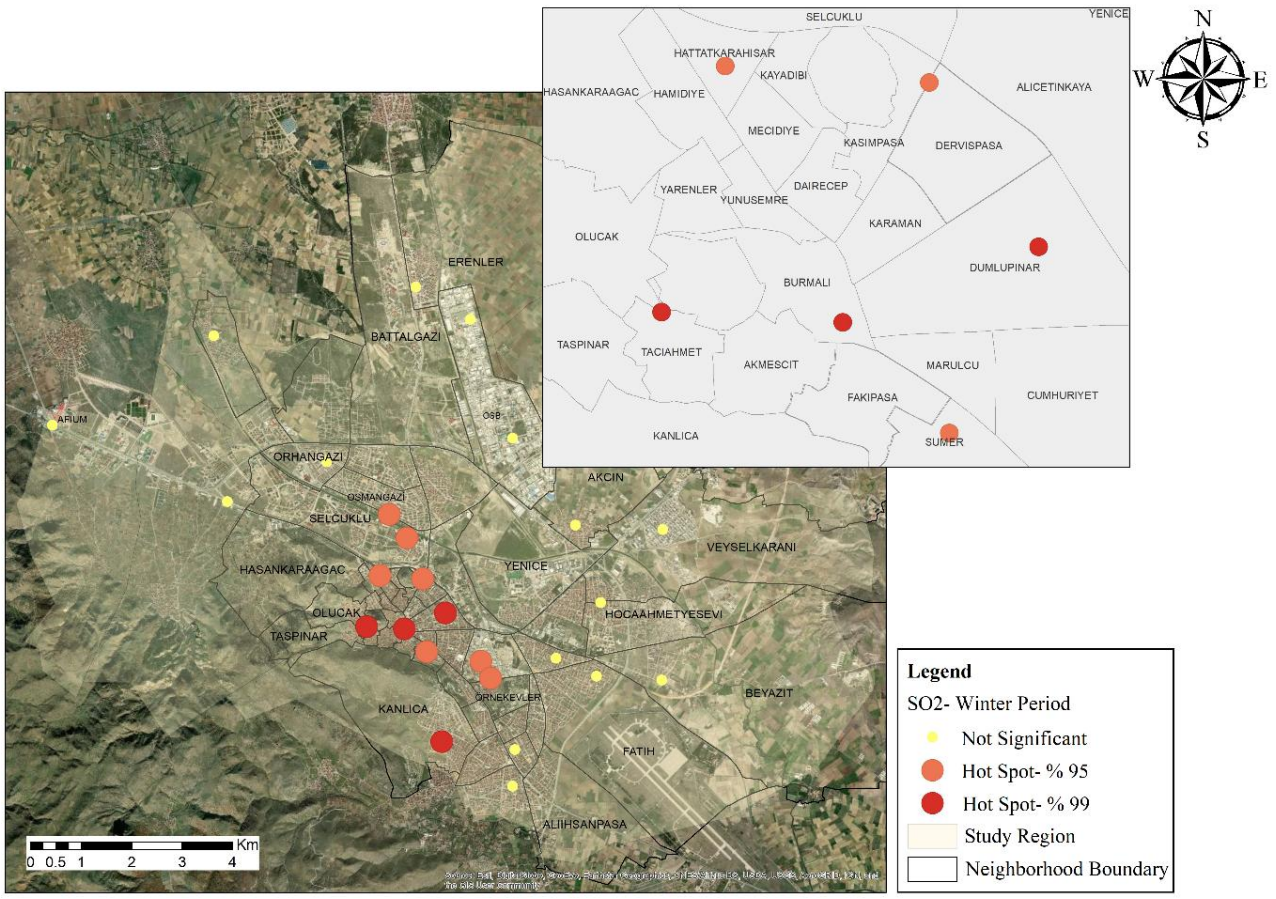


Figure 6. SO_2 parameter winter period Getis-Ord G* Statistics Result Map.

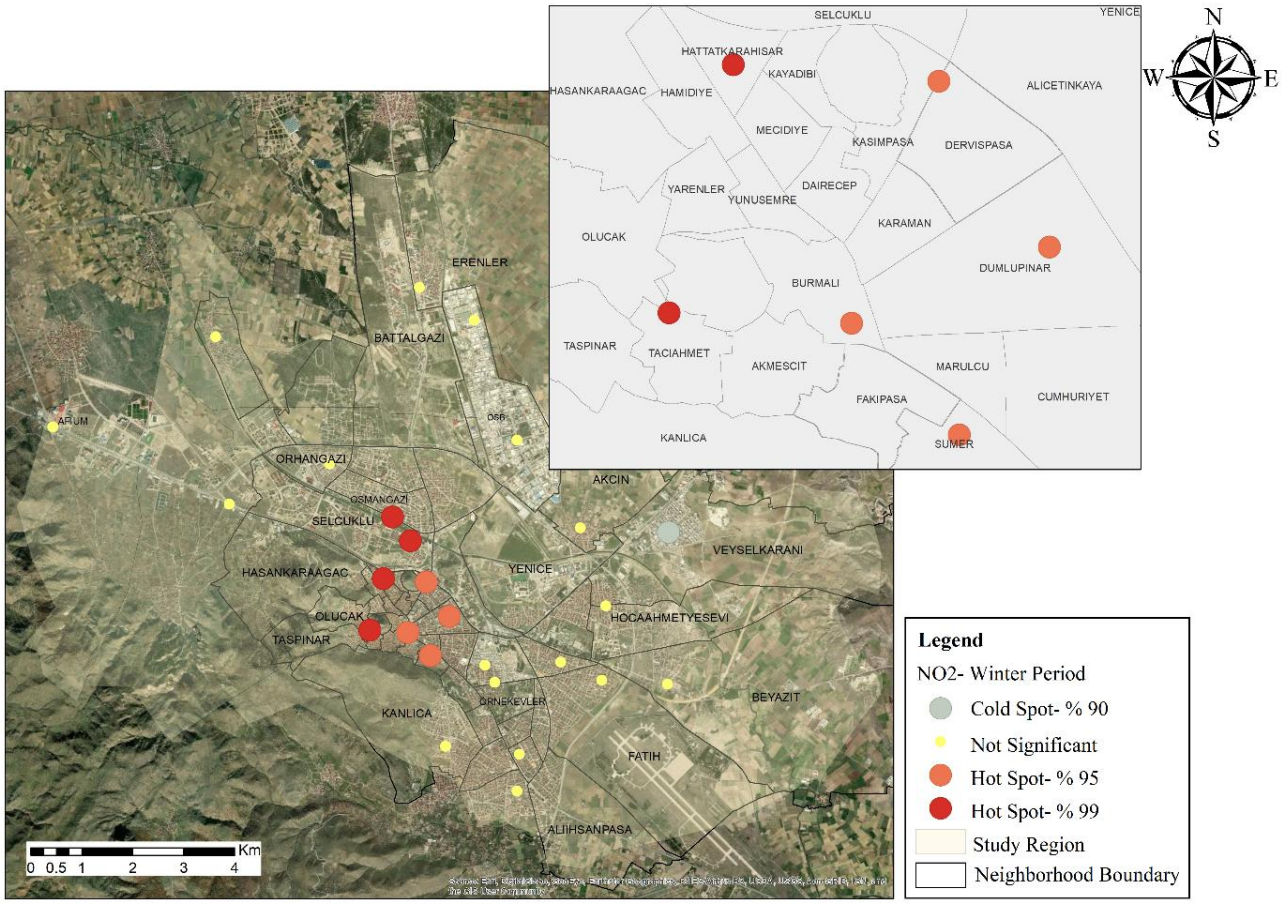


Figure 7. NO_2 parameter winter period Getis-Ord G* Statistics Result Map.

4. Discussion and Conclusion

Air pollution is recognized as a major environmental and public-health challenge worldwide due to its detrimental effects on all living organisms, including its potential to cause premature mortality. Numerous studies have demonstrated that exposure to air pollution disproportionately affects vulnerable groups such as infants, children, the elderly, and individuals with chronic illnesses, contributing to respiratory diseases, asthma, reduced lung function, psychological disorders, and early death (Boldo et al. 2011; Çapraz 2013; Kunay 2018). According to international assessments, Turkey ranks among the European countries with the highest number of premature deaths linked to air pollution, and WHO reports indicate that several of Europe's most polluted cities—including Afyonkarahisar—are located in Turkey (Yazıcı 2018). These factors highlight the critical need for detailed spatial assessment, monitoring, and identification of pollution sources to support effective air quality management.

In order to ensure that air quality levels are at the best possible levels, it is important to measure the concentration values of pollution parameters and identify the factors causing air pollution. In this context, many studies have been conducted. In this study, pollution distribution maps were created based on summer and winter seasons and annual average values covering all seasons, by investigating whether air pollution clusters in a specific area and whether there is a spatial dependence with pollutant parameters. SO_2 and NO_2 were selected as pollutant types from the pollution parameters measured at 26 points. Thus, a comprehensive data set was created with points surrounding the city center of Afyonkarahisar.

In the related literature, it has been determined that the level of SO_2, one of many pollutant types, is high in city centers, areas with increased residential and vehicle density, and regions where fossil fuels used in domestic heating and industrial production stages are burned, and therefore the season with the highest pollution level is winter (Başkır 1993, McPherson et al. 1994, Peng et al. 2005, Gül 2005, Daylan and İncecik 2002, Staelens et al. 2012, Özcan 2016, Altıkat 2020).

The study found that NO_2 levels, another pollution parameter selected for the study, were higher in residential areas close to main roads and road sections, in city centers, in areas with high traffic density, and especially in the summer season (Mayer 1999, Özen 2006, Vardoulakis and Kassomenos 2008, Elbir et al. 2010, Dergham et al. 2015, Cuci et al. 2015, Polat 2016).

The results of this study, which evaluated the measurement results obtained in winter and summer and the average of the measurement results obtained in all seasons, were consistent with the literature. According to the results of the study, winter was determined to be the season with the highest SO_2 pollutant concentration, and it was observed that the neighborhoods with high pollution included the neighborhoods that were the first settlements with unplanned construction and a high number of residences. The season with the highest NO_2 pollutant concentration was determined to be summer, and it was observed that pollution was higher in the city center, road intersections, and ring roads, where vehicle density increased. Spatial clustering analyses also determined that there were significant clusters in neighborhoods with high pollution in winter.

The limiting aspect of the study is that long-term measurements (on all days within the year) could not be made, and due to the method used, only SO_2 and NO_2 parameters could be used because not all pollutant parameters could be measured. This study is the first comprehensive study to identify the spatial pattern of air pollution in the city center of Afyonkarahisar, where 325,000 people reside, using GIS-based analyses. The results obtained are expected to guide future academic studies and the planning and work of relevant institutions/organizations. Local authorities should prioritize urban regeneration in identified hot-spot neighborhoods, reduce coal use through cleaner heating incentives, implement green traffic wave systems on main roads, and establish vegetation barriers in high-traffic corridors.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.
This study is derived from the master's/doctoral thesis titled "GIS-Based Investigation of the Spatial Dependency of Air Pollution: The Example of Afyonkarahisar" (thesis number: 672190), completed in 2021 under the supervision of Associate Professor Dr. Mustafa Yalçın.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft.
Author-2: Conceptualization, investigation, methodology and software, supervision and writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Datasets are available on request. The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.)

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5.References

Afyonkarahisar Çevre ve Şehircilik İl Müdürlüğü, 2020. Afyonkarahisar İli 2019 Yılı Çevre Durum Raporu,105s.

Alkan A, 2018, Hava Kirliliğinin Ciddi Boyutlara Ulaştığı Kentlere Bir Örnek: Siirt, Bitlis Eren Üniversitesi, Sosyal Bilimler Enstitüsü Dergisi, **7**, 41-666.

Altıkat A, 2020. Iğdır İli Partiküler Kirlilik Düzeyi ve Partiküler Kirliliğin Diğer Kirleticiler ile İlişkileri, Iğdır Üniversitesi, Fen Bilimleri Enstitüsü Dergisi, **10**, 878–887.

Ayturan Y A, 2019. Derin Öğrenme ile Havadaki Partikül Madde Konsantrasyonu Tahmini, KTO Karatay Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 72s, Konya.

Başkır H, 1993. Türkiye'de Jeotermal Enerjinin Isıtma Amaçlı Kullanım Potansiyeli ve Afyon Şehrinin Hava Kirliliğinin Azaltılmasında Jeotermal Enerjiden Yararlanma İmkânları, Yıldız Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 95s, İstanbul.

Bazoğlu B, 2017. Hava Kirliliği Raporu 2016,-, 19s.

Boldo E, Linares C, Lumbreras J, Borge R, Narros A, García-Pérez J, Fernández Navarro P, Pérez-Gómez B, Aragonés N, Ramis R, 2011. Health İmpact Assessment Of A Reduction in Ambient PM2.5 Levels in Spain, Environment International, **37**, 342–348.

Çapraz Ö, 2013. İstanbul'da 2007-2012 Yılları Arasında hava kirliliğinin ölümler Üzerindeki Etkilerinin Modellenmesi, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 112s, İstanbul.

Colvero, D. A., Gomes, A. P. D., da Cruz Tarelho, L. A., de Matos, M. A. A., & Dos Santos, K. A. 2018. Use of a geographic information system to find areas for locating of municipal solid waste management facilities. Waste Management, **77**, 500-515.

Cuci Y, Ergün Polat E, 2015. Gaziantep'in Trafik Kaynaklı Hava Kirliliğinin Belirlenmesi, KSU Mühendislik Bilimleri Dergisi, **18**, https://doi.org/10.17780/ksujes.12923

Daylan E, İncecik S, 2002. İstanbul'da Coğrafi Bilgi Sistemleri İle Hava Kalitesinin İncelenmesi, İTÜ Dergisi Mühendislik, 1, 51-62.

Demirarslan K O, Akıncı H, 2018. CBS ve Hava Kalitesi Verileri Kullanılarak Marmara Bölgesinin Kış Sezonunda Hava Kalitesinin Değerlendirilmesi, Doğal Afetler ve Çevre Dergisi, **4**, 11-27.

Dergham M, Lepers C , Verdin A , Cazier F , Billet S , Courcot D, vd., 2015. Temporal–spatial variations of the physicochemical characteristics of air pollution Particulate Matter (PM2.5–0.3) and toxicological effects in human bronchial epithelial cells (BEAS-2B), Environmental Research, **137**, 256-267.

Dokuz Y, Bozdağ A, Gökçek B, 2020. Hava Kalitesi Parametrelerinin Tahmini ve Mekansal Dağılımı İçin Makine Öğrenmesi Yöntemlerinin Kullanılması, Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi, **9**, 37-47.

Elbir T, Bayram A, Kara M, Altıok H, Seyfioğlu R, Ergün P, vd., 2010. İzmir Kent Merkezinde Karayolu Trafiğinden Kaynaklanan Hava Kirliliğinin İncelenmesi, DEÜ Mühendislik Bilimleri Dergisi, **12**, 1-17.

Erdoğan E, 2012. Sanayi Kaynaklı Hava Kirliliğinde Modellerin Kullanımının Karar Verme Sürecindeki Rolü, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 200s, İstanbul.

Garipağaoğlu N, 2015. Türkiye Ortam Sorunları Coğrafyası, Yeditepe Yayınları, 472s, İstanbul.

Getis A, 2010. Spatial Statistics in ArcGIS, Fischer M M, Getis A (Ed.), Handbook of Applied Spatial Analysis: Spatial Autocorrelation (255-275), Springer-Verlag Berlin Heidelberg, 801p, Berlin.

Górecki T, Namieśnik J, 2002. Passive Sampling, Trends in Analytical Chemistry, **21**, 276-291.

Gül N, 2005. Afyon'da Kömür Kullanımının Hava Kirliliğine Etkisi ve Çözüm Önerileri, Selçuk Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 49s, Konya.

Jumaah H J, Ameen M H, Kalantar B, Rizeei H R, Jumaah S J, 2019. Air quality index prediction using IDW geostatistical technique and OLS-based GIS technique in Kuala Lumpur, Malaysia, Geomatics, Natural Hazards and Risk, **10**:1, 2185-2199.

Kara B M, Tezel K B, 2017. Türkiye'deki SO2 Yer Ölçümlerinin Değerlendirilmesi ve SO2 Kirliliğinin Zamansal ve Mekânsal Değişiminin İncelenmesi, VII. Ulusal Hava Kirliliği ve Kontrolü Sempozyumu, 1-3 Kasım 2017, Antalya.

Karimi, H., Herki, B., Gardi, S. Q., Galalizadeh, S., Hossini, H., Mirzaei, K., & Pirsaheb, M. (2022). Site selection and environmental risks assessment of medical solid waste landfill for the City of Kermanshah-Iran. International journal of environmental health research, 32(1), 155-167.

Kavak Yürük R, 2010. Trafik Yoğunluğunun Enerji Tüketimi Ve Hava Kirliliğine Etkilerinin Analizi, Bahçeşehir Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 146s, İstanbul.

Keçebaş A, Kayfeci M, Gedik E, 2010. Afyonkarahisar da Ölçülen Sülfür Dioksit ve Partikül Madde Değişimleri

Üzerine Değerlendirme, Mühendis ve Makine, **51**, 14-19.

Kocaman Ö, 2010. Erzurum'da pasif örnekleme yöntemiyle alansal hava kalitesinin tahmini, Atatürk Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 58s, Erzurum.

Koç A, 2018. Kentsel Alan Kullanımlarının Zamansal Değişimlerinin Hava Kirliliği Üzerindeki Etkisi, Kent Akademisi, 11, 609-617.

Koç A, Yılmaz S, Mutlu E, 2016. Erzurum Kent Merkezinde Kitle Yeşil Alanların Hava Kalitesine Etkisi, Iğdır Üniversitesi Fen Bilimleri Dergisi, **6**, 109-112.

Kök F, 2018. Var Olan / Yeni Planlanacak Kentlerde Hava Kirliliğini Önleyecek/ Azaltacak Yöntem İçin Verilerin Toplanması, Hasan Kalyoncu Üniversitesi, Fen Bilimler Enstitüsü, Yüksek Lisans Tezi, 129s, Gaziantep.

Krochmal D, Kalina A, 1997. Measurements of nitrogen dioxide and sulphur dioxide concentrations in urban and rural areas of Poland using a passive sampling method, Environmental Pollution, **96**, 401-407.

Krupa S V, Legge A H, 2000. Passive sampling of ambient, gaseous air pollutants: an assessment from an ecological perspective, Environmental Pollution, **107**, 31-45.

Kunay Ş B, 2018. Manisa'da Hava Kirliliğinin Acil Servise Başvuran Çocuklarda Solunum Yakınmalarına Etkisi, Manisa Celal Bayar Ünversitesi, Tıp Fakültesi, Uzmanlık Tezi, 81s, Manisa.

Kyrkilis, G, Chaloulakou A, Kassomenos P A, 2007. Development of an aggregate Air Quality Index for an urban Mediterranean agglomeration: Relation to potential health effects, Environment International, **33**, 670-676.

Mayer H, 1999. Air pollution in cities, Atmospheric Environment, **33**, 3029-4037.

McPherson E G, Nowak D J, Rowntree R A, 1994. Chicago's Urban Forest: Results of the Chicago Urban Forest Climate Project, Northeastern Forest Experimental Station https://doi.org/10.2737/NE-GTR-186

Dereli M A, 2016. Trafik Kaza Kara Noktalarının Belirlenmesi İçin Coğrafi Bilgi Sistemleri (CBS) Destekli Mekânsal İstatistiksel Metotlar İle Bir Model Geliştirilmesi, Afyon Kocatepe Üniversitesi, Fen Bilimleri Enstitüsü, Doktora Tezi, 176 s, Afyonkarahisar.

Özcan N S, 2016. Kentsel Hava Kirliliğini Etkileyen ve Şehir Planlama İle Kontrol Edilebilen Fiziksel Faktörlerin Mekânsal İstatistik Yöntemleri ile İncelenmesi, Dokuz Eylül Üniversitesi, Fen Bilimleri Enstitüsü, Doktora Tezi, 209s, İzmir.

Özen M, 2006. Karayolu ulaşımının hava kirliliğine etkileri ve çözüm önerileri, Gazi Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 94s, Ankara.

Özer F, 2013. Karabük'te Doğalgaz Kullanımının Hava Kirliliğinin Azaltılmasına Etkisi, Karabük Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 85s, Karabük.

Öztürk G, 2006. Düzce İlinde Trafikten Kaynaklanan Hava Kirliliğinin Belirlenmesi, Zonguldak Karaelmas Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 78s, Zonguldak.

Peng R D, Dominici F, Pastor-Barriuso R, Zeger S L, Samet J M, 2005. Seasonal Analyses of Air Pollution and Mortality in 100 US Cities, American Journal of Epidemiology, **161**, 585-594.

Polat E E, 2016. Gaziantep'in Trafik Kaynaklı Hava Kirliliğinin Belirlenmesi Üzerine Bir Çalışma, Kahramanmaraş Sütçü İmam Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 89s, Kahramanmaraş.

Salem A A, Soliman A A, El-Haty İ A, 2009. Determination of nitrogen dioxide, sulfur dioxide, ozone, and ammonia in ambient air using the passive sampling method associated with ion chromatographic and potentiometric analyses, Air Quality, Atmosphere and Healt, **2**, 133-145.

Santiago J L, Borge R, Martin F, Paz D, Martilli A, Lumbreras J, Sanchez B, 2017. Evaluation Of A CFD-Based Approach To Estimate Pollutant Distribution Within A Real Urban Canopy By Means Of Passive Samplers, Science of The Total Environment, **576**, 46-58.

Staelens J, Wuyts K, Adriaenssens S, Avermaet P. V, Buysse H, Von den Bril B, vd., 2012. Trends in atmospheric nitrogen and sulphur deposition in northern Belgium. Atmospheric Environment, **49**, 186–196.

Sümer G Ç, 2014, Hava Kirliği Kontrolü: Türkiye'de Hava Kirliliğini Önlemeye Yönelik Yasal Düzenlemelerin ve Örgütlenmelerin İncelenmesi, Uluslararası İktisadi ve İdari İncelemeler Dergisi, **13**, 37-56.

Tağıl Ş, 2007. Balıkesir'de Hava Kirliliğinin Solunum Yolu Hastalıklarının Mekânsal Dağılışı Üzerine Etkisini Anlamada Jeo-İstatistik Teknikler, Coğrafi Bilimler Dergisi, **5**, 37-56.

Taş F, 2006. Hava Kirliliği ve Kastamonu Şehir Merkezi için Değerlendirme, Gazi Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 142s, Ankara.

Taylan E D, Damçayırı D, 2016. Isparta Bölgesi Yağış Değerlerinin IDW ve Kriging Enterpolasyon Yöntemleri ile Tahmini, İMO Teknik Dergi, **27**, 7551-7559.

Tuna G, Özgünerge Falay E, Altıok H, Kara M, Dumanoğlu Y, Bayram A vd., 2013. Bir Endüstriyel Bölgedeki Hava Kirliliğinin Mekansal Dağılımının Ağaç Bileşenlerindeki İz Elementler Yardımıyla İncelenmesi, Uluslararası Katılımlı V. Hava Kirliliği ve Kontrolü Sempozyumu, 1-4 Eylül 2013, Türkiye, 705-716.

Türkiye Toraks Derneği, 2016. Nefes Alamıyoruz: Hava Kirliliği, İklim Değişikliği ve Sağlık Sempozyumu, 15.10.2016, İstanbul.

Vardoulakis S, Kassomenos P,2008. Sources and factors affecting PM10 levels in two European cities: Implications for local air quality management, Atmospheric Environment, **42**, 3949–3963.

Wang H, Brimblecombe P, Ngan K, 2021. A numerical study of local traffic volume and air quality within urban street canyons, Science of the Total Environment, 791, 148138.

Wang, C., Zou, F., Yap, J. B. H., Tang, R., & Li, H. 2022. Geographic information system and system dynamics combination technique for municipal solid waste treatment station site selection. Environmental Monitoring and Assessment, **194**(7), 457.

Yalçın M, Kaya K, 2019. Türkiye'de Solunum Sistemine Bağlı Ölüm Oranlarının Mekansal Kümelenmelerinin İncelenmesi, Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, **19**, 750-761.

Yazıcı H, Koca N, Ekiz E, 2018. Topoğrafik, meteorolojik ve klimatolojik faktörlerin Afyonkarahisar şehrindeki hava kirliliği üzerine etkileri, Türk Coğrafya Dergisi, **71**, 63-68.

Zhang C, Luo L, Xu W, Ledwith V , 2008. Use Of Local Moran's I and GIS To İdentify Pollution Hotspots of Pb İn Urban Soils Of Galway, Ireland, Science of the total environment, **398**, 212-221.

Internet References

1. https://sim.csb.gov.tr/Intro/Uhkia , 20.11.2025
2.https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-how-spatial-autocorrelation-moran-s-i-spatial-st.htm, 20.11.2025