Artvin Çoruh Üniversitesi
Doğal Afetler Uygulama ve Araştırma Merkezi
Doğal Afetler ve Çevre Dergisi

Artvin Çoruh University
Natural Hazards Application and Research Center
Journal of Natural Hazards and Environment

Araştırma Makalesi / Research Article, Doğ Afet Çev Derg, 2025; 11(1): 181–193, DOI: 10.21324/dacd.1562860

Air Quality of Bursa: Temporal and Spatial Evaluation of PM10, PM2.5, NO2 and SO2 Pollutants Using IDW Geostatistical Technique

Duygu Arıkan İspir [1,*], Ferruh Yıldız[1]

[1]*Konya Technical University, Faculty of Engineering and Natural Sciences, Geomatics Engineering, 42075, Konya, Türkiye.*

Abstract

One of the most significant environmental issues is air pollution. Human health is negatively impacted by this issue in addition to the environment. In this study, spatial and temporal analysis of particulate matter 10 (PM10), particulate matter 2.5 (PM2.5), sulfur dioxide (SO2) and nitrogen dioxide (NO2) pollutants for 2022 was conducted within the provincial borders of Bursa, Turkey. The monthly and seasonal air pollution maps have been generated using 24-hour measurements obtained from air quality monitoring stations within the city. Data for PM10, PM2.5, SO2, and NO2 were utilized in the creation of these maps. The pollution maps were analyzed based on the criteria outlined in the World Health Organization (WHO) report, as well as the limit values set by the European Union and the national regulations. According to the results obtained, the amount of pollutants in summer is lower than in winter. While PM10 was on average 39.32 µg/m³ in the summer months, it exceeded the national legislation by 3.09% in the winter. When evaluated during the average summer season, the concentrations of PM2.5 and SO2 were observed to be 19.29 µg/m³ and 5.82 µg/m³, respectively. In contrast, during the winter season, the concentrations were found to be 47.30 µg/m³ for PM2.5 and 11.07 µg/m³ for SO2. There is no legal limit for PM2.5 in national legislation. SO2 was found to be below the specified legal regulations. While NO2 was on average 25.13 µg/m³ in the summer months, it exceeded the national legislation by 9.74% in the winter. The main sources of pollutants in the region were examined and according to the findings, factors such as the city being an industrial zone and high traffic density increased the pollutants. The results of this investigation show that air pollution poses a significant issue in Bursa.

Keywords
Air Quality, Atmospheric Particulate Matter, Inverse Distance Weighting, Temporal Evaluation, Spatial Evaluation

Bursa'nın Hava Kalitesi: IDW Jeoistatistik Tekniğini Kullanarak PM10, PM2.5, NO2 ve SO2 Kirleticilerinin Zamansal ve Mekansal Değerlendirilmesi

Özet

En önemli çevresel sorunlardan biri hava kirliliğidir. Bu sorun, çevreye ek olarak insan sağlığını da olumsuz etkilemektedir. Bu çalışmada, Türkiye'nin Bursa ili sınırları içinde 2022 yılına ait partikül madde 10 (PM10), partikül madde 2.5 (PM2.5), kükürtdioksit (SO2) ve azotdioksit (NO2) kirleticilerinin mekânsal ve zamansal analizi yapılmıştır. Şehirdeki hava kalitesi izleme istasyonlarından elde edilen 24 saatlik ölçümler kullanılarak aylık ve mevsimlik hava kirliliği haritaları oluşturulmuştur. Bu haritaların oluşturulmasında PM10, PM2.5, SO2 ve NO2 verileri kullanılmıştır. Kirlilik haritaları, Dünya Sağlık Örgütü (WHO) raporunda belirtilen kriterler ile Avrupa Birliği ve ulusal mevzuat tarafından belirlenen sınır değerler baz alınarak analiz edilmiştir. Elde edilen sonuçlara göre, yaz aylarında kirletici miktarı kış aylarına göre daha düşüktür. Yaz aylarında PM10 ortalama olarak 39.32 µg/m³ iken, kış aylarında ulusal mevzuatı %3.09 oranında aşmıştır. Ortalama yaz mevsiminde değerlendirildiğinde, PM2.5 ve SO2 konsantrasyonları sırasıyla 19.29 µg/m³ ve 5.82 µg/m³ olarak gözlemlenmiştir. Buna karşılık, kış mevsiminde PM2.5 ve SO2 konsantrasyonları sırasıyla 47.30 µg/m³ ve 11.07 µg/m³ olarak bulunmuştur. PM2.5 için ulusal mevzuatta yasal bir sınır bulunmamaktadır. SO2'nin belirlenen yasal mevzuatın altında olduğu tespit edilmiştir. NO2 yaz aylarında ortalama olarak 25.13 µg/m³ iken, kış aylarında ulusal mevzuatı %9.74 oranında aşmıştır. Bölgedeki kirleticilerin ana kaynakları incelenmiş ve bulgulara göre şehrin sanayi bölgesi olması ve yüksek trafik yoğunluğu gibi faktörlerin kirleticileri artırdığı belirlenmiştir. Bu araştırmanın sonuçları, Bursa'da hava kirliliğinin önemli bir sorun teşkil ettiğini göstermektedir.

Anahtar Sözcükler
Hava Kalitesi, Atmosferik Partikül Madde, Ters Mesafe Ağırlıklandırma, Zamansal Değerlendirme, Mekânsal Değerlendirme

1. Introduction

The increasing acceleration in population growth, coupled with the rapid industrialization bringing about economic challenges and unplanned urbanization issues exacerbated by uncontrolled migration, triggers problems. The escalation of these negative factors also adversely affects air quality. Air pollution is a condition in which the quantity of foreign or unwanted substances in the atmosphere exceeds normal levels, reaching elevated levels, ultimately impacting living

* Corresponding Author: Tel: +90 (332) 2051669 Faks: +90 (332) 2410635
E-mail: darikan@ktun.edu.tr (Arıkan İspir D.), fyildiz@ktun.edu.tr (Yıldız F.)
Gönderim Tarihi / Received : 07/10/2024
Kabul Tarihi / Accepted : 15/12/2024

organisms negatively. There are two types of air pollutants: primary and secondary. While secondary pollutants are caused by a combination of two or more primary pollutants or by common atmospheric components, primary pollutants are released straight from their sources (Yener & Demirarslan, 2022).

An increase in this pollution may be brought about artificially by human sources, or naturally by events like lightning, forest fires, and desert dust (Kampa & Castanas, 2008; Arikan & Yildiz, 2023). Air pollution that arises naturally is far less than that which exists artificially (Yağmur, 2022). Human activity-induced increases in air pollution have an adverse impact on people's quality of life as well (Demirarslan & Akıncı, 2016a). This situation causes an increase in health problems such as respiratory illness, stroke, lung cancer, and heart diseases in individuals (Suthar et al., 2024). According to the report published by the World Health Organization (WHO), the majority of the global population breathes highly polluting air. According to this report, 7,000,000 people die prematurely every year from indoor and outdoor air pollution (World Health Organization, 2022).

Various studies are conducted by researchers to monitor and simulate air quality, track the levels of pollutants, and determine the primary sources and causes of pollution. The effects of each pollutant parameter, its dispersion across the atmosphere and the events it causes were investigated. Hashim et al. (2004), investigated the primary pollutant conditions resulting from a forest fire in Indonesia in 1997. They utilized the Advanced Very High-Resolution Radiometer (AVHRR) satellite to monitor the quantity of 10 µm-sized particulate matter (PM10), one of the pollutants. Arikan and Yildiz (2023) similarly observed carbon monoxide (CO) and ultraviolet aerosol index (UVAI) values following a forest fire in Antalya in 2021. They used the Sentinel-5P TROPOMI satellite for observation and compared the results with data obtained from national air quality stations.

Various mathematical methods and artificial intelligence algorithms are employed to reduce the level of pollutants in the atmosphere or improve air quality. Among the preferred mathematical models for this purpose are physical or deterministic models based on atmospheric chemistry and physics principles. Additionally, statistical models, which predict future air quality based on past data, are commonly used. Source emission models, designed to determine the quantity of pollutants emitted from sources such as industrial facilities and transportation vehicles, also play a significant role. Dispersion models are utilized to ascertain the spread of pollutants in the atmosphere, analyzing how pollutants disperse and their effects. Finally, multi-criteria optimization methods can be applied to optimize these complex processes (Goyal & Kumar, 2011).

Studies on the assessment and prediction of air quality using different machine learning algorithms—a subfield of artificial intelligence—have been published in the literature. A subfield of artificial intelligence known as "machine learning" develops models of real-world problems and the data that has been received about them in order to extract knowledge (El Naqa & Murphy, 2015; Zhou, 2021). Yağmur (2022), estimated the amount of particulate matter for a metropolitan metropolis using Multiple Linear Regression (MLR), Random Forest (RF), Support Vector Machines (SVM), and Artificial Neural Networks (ANN). MLR yielded a worse outcome than other algorithms, however the RF method did the best. In a similar study by Bozdağ et al. (2020), Least Absolute Shrinkage and Selection Operator (LASSO), SVM, RF, K-nearest neighbor (kNN), eXtreme gradient boosting (XGBoost), ANN machine learning algorithms were used. Performance and error rates were calculated for each algorithm specified. According to the values they obtained, they obtained the best results using ANN with values of R^2 = 0.58, RMSE = 20.8, MAE = 14.4. These algorithms provide advantages in calculation and scenario simulation according to the characteristics of the input data. However, as these models were inadequate in determining particulate matter concentrations, deep learning algorithms began to be used. In their study, Chang et al. (2020), examined the spatiotemporal characteristics of the PM2.5 concentration status and implemented it on the Self-organizing map (SOM). Then, they tested the accuracy of the model by creating an ANN model. Zhou et al. (2019) combined mini-batch gradient descent, dropout neuron and L2 regularization models and designed Deep Multi-output LSTM (DM-LSTM) neural network models. With this model, PM2.5, PM10 and nitrogen oxides (NOx) pollutant parameters were estimated. They compared the new model results with the Shallow Multi-output Long Short-Term Memory (SM-LSTM) model. According to the results obtained, SM-LSTM achieved a mean squared error of 0.87, while DM-LSTM achieved 0.72. In addition to artificial intelligence algorithms, geographic information systems (GIS) are also used in modeling air quality. These systems contribute to finding solutions to environmental problems by collecting various geographical and attribute information on the earth's surface (Khan et al., 2019; Masroor et al., 2020; Bugdayci et al., 2023). With GIS, statistical and geostatistical analyses are feasible. For spatial interpolation, various techniques such as Kriging (a geostatistical method), and deterministic approaches including inverse distance weighted (IDW), weighted average interpolation, polynomial interpolation, multiquadric interpolation, linear interpolation in the network of triangles, small curvature surface interpolation, and nearest neighbor interpolation are commonly utilized (Arıkan et al., 2021; Roy, 2021; Kumar et al., 2022; Gokul et al., 2023; Samal et al., 2023; Zhou et al., 2023). Demirarslan and Akıncı (2016a) ve Demirarslan and Akıncı (2016b) used the Inverse Distance Weighting (IDW) technique to detect air pollution in the Eastern Black Sea region. In these studies, the IDW method was applied to visualize the spatial distribution of air pollution data, and density maps of the pollutants in the region were created using this method. These studies demonstrate that the IDW technique is an effective tool for air pollution analysis. Through the system based on the acquisition, analysis, and interpretation of data and information, important trends related to air quality can be identified. Pollution sources can be detected, and relationships between various environmental variables can be understood.

Consequently, more effective policy and intervention strategies can be developed for environmental sustainability goals, leading to positive impacts on public health and environmental quality. To achieve these objectives, a total of 365 air quality monitoring stations have been uniformly distributed throughout Turkey as of the year 2022 (Ministry of Environment, Urbanization and Climate Change, 2022a).

In this study, National air monitoring stations were utilized to assess the air quality of the city. The focus of the study was not only on the changes in particulate matter (PM10, PM2.5) but also on the status of other air pollutants, namely NO2 and SO2. Pollution conditions were examined on a monthly and seasonal basis. The aim of this study was to understand the trends of pollution in the summer and winter seasons by analyzing different temporal periods and to identify the main sources of pollutants. The city covers an approximate area of 10,819 km², with 9 distributed ground stations in 2022. Monitoring the air quality for the entire city is not possible with a limited number of stations. In the literature, numerous studies have utilized interpolation techniques, such as IDW, to generate air pollution maps and perform spatial analyses. These studies, however, often focus on larger scales or specific monitoring station data, without delving into localized urban characteristics. Unlike these broader studies, this research focuses on Bursa province, a major urban and industrial center in Turkey. By employing the Inverse Distance Weighting (IDW) technique, this study aims to estimate air pollutant concentrations not only at monitoring station locations but across the entire urban area, including regions without direct monitoring. In this study, the focus was expanded to detect air pollution in other parts of the city, not just at station locations. For this purpose, an Inverse Distance Weighting (IDW) analysis, an interpolation technique, was performed to visualize the concentration of air pollutants, and pollution maps were generated. At the core of the study, information explaining emissions from all relevant sources in the city, including emissions from residential heating, traffic, and industry, was collected to evaluate air pollution for the Bursa province.

2. Material and Method

2.1. Study Area

Bursa is a city located between the northern latitudes of 40°15’ and 41°38’ and the eastern longitudes of 28°40’ and 30°48’ (Figure 1). The city's average elevation above sea level is around 150 meters, and its population is approximately 3 million people (Turkish Statistical Institute, 2022). The population density is 291 people per square kilometer in the province. As an industrial city, Bursa's economy and population are increasing every year. Consequently, monitoring and tracking air quality become crucial.

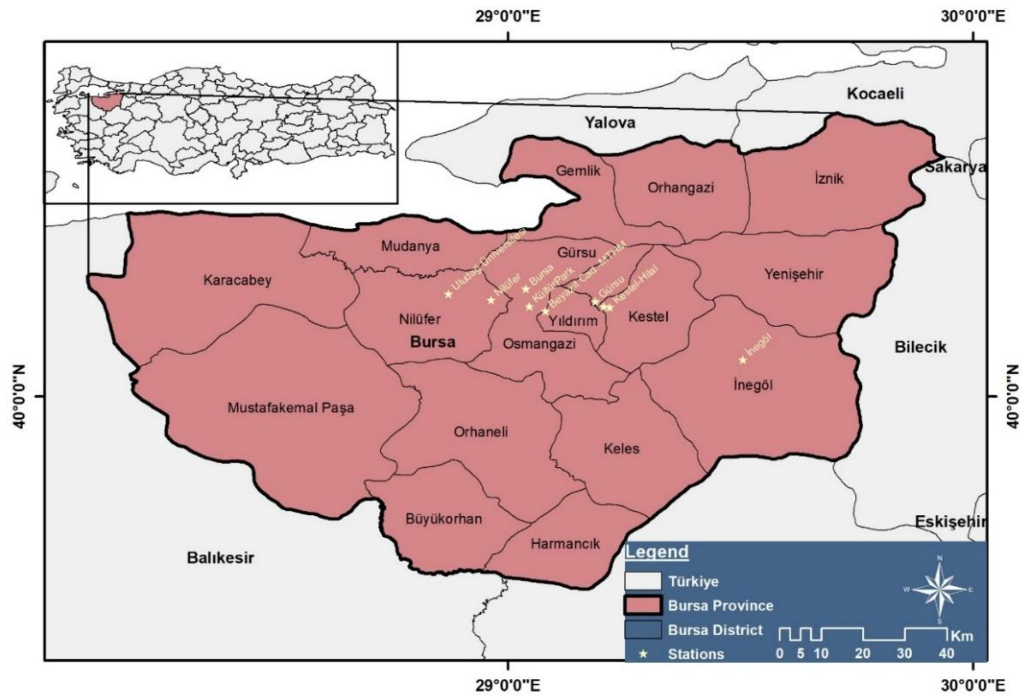

Figure 1: The map of Bursa Province

In the long term, economic growth depends on technological progress. Bursa, the fourth largest city in Turkey, has a share of more than 50% in the country's automotive industry, together with its main industry and sub-industry suppliers (Temel, 2023). Bursa is one of the cities with the highest sectoral diversity and in this sense, employment is divided into various industrial branches (Sungur & Yaman, 2021).

It comes in first for the automotive, metal, and machinery industries; second for the number of machinery and equipment manufacturers; third for food producers; fourth for exports from the defense sector industry; and fifth for quantity of industrial establishments (Görener & Görener, 2008; Turkish Statistical Institute, 2022; Albayrak, 2023; Temel, 2023). Being an industrial city is one of the factors that significantly affects urban structuring.

2.2. Data Collection

Since air pollution has significant effects on human health, great importance is given to air quality all over the world (Altıkat et al., 2011). To effectively conflict air pollution, raise public awareness, and develop methods for management, accurate recording of air pollution levels is essential. For this reason, 36 stations were established in 2005 by the Ministry of Environment, Urbanization and Climate Change in order to monitor air quality in Turkey (Bugdayci et al., 2023). Monitoring of air quality in Turkey is increasing day by day. The number of stations in Turkey has been steadily rising every day, as seen in Figure 2. While only 10 µm sized particulate matter PM10 and SO2 pollutant parameters can be collected from the first established stations, as of 2022, NO2, NOX, CO, ozone (O3) and 2.5 µm diameter particles PM2.5 parameters was also possible to collect. These compounds' general characteristics are described.

- Carbon monoxide (CO); Chemically, it is a structure formed as a result of the covalent bonding of two carbon atoms with oxygen (Şahin & Kubilay, 2023). In the event of insufficient oxygen during the combustion reaction, the carbon atom cannot be fully oxidized. As a consequence, carbon monoxide gas, a highly potent toxic gas, is released (Aydinoğlu et al., 2022). This colorless, odorless, and tasteless gas, when reaching levels around 30% in the air, can lead to respiratory obstruction, causing health problems (Şahin & Kubilay, 2023). Prolonged exposure can result in death because oxygen transported through the blood cannot reach the cells, leading to cellular death (Aydinoğlu et al., 2022).
- Sulfur dioxide (SO2); The main sources include coal used in thermal power plants, production activities in industries (such as raw material processing, petroleum refineries, cement factories, metallurgical industry), solid and liquid fuels used for residential and workplace heating in urban areas, and events originating from natural sources (such as forest fires, volcanic activities) (Zencirci & Işıklı, 2017; Kırbıyık, 2023). Since this gas dissolves in water, it largely affects the respiratory tract. It is a cough-inducing and throat-irritating gas (Bayrı, 2023).
- Nitrogen oxides (NOX); They are gases formed as a result of the reaction of nitrogen and oxygen in the atmosphere. These gases are produced especially during burning. When it reacts with water vapor in the atmosphere, it causes acid rain. This harms ecosystems (Erickson et al., 2020).
- Ozone (O3); It is a molecule formed by the combination of three oxygen atoms. Ultraviolet rays from the sun split O2 molecules into two separate oxygen atoms. The O3 molecule emerges as a result of the combination of free oxygen atoms in the atmosphere with other O2 molecules. In recent research, it has been determined that ozone in the air is not only in the formula O3, but also in the form of O4, O6....Ox, and is given the name Aran (Bayrı, 2023). While ozone gas has a protective effect in the upper layers of the atmosphere, it has negative effects on the environment and human health in the troposphere. As a result of the increase in ozone gas in the troposphere, people have to breathe less amount of oxygen. This situation causes asthma and cardiovascular diseases due to respiratory failure in individuals (Aydinoğlu et al., 2022).
- Particulate matter (PM); They are small solid or liquid particles suspended in the air consisting of many different components (Aydinoğlu et al., 2022). An aerodynamic diameter of 10 µm is called PM10, and a diameter of 2.5 µm is called PM2.5.

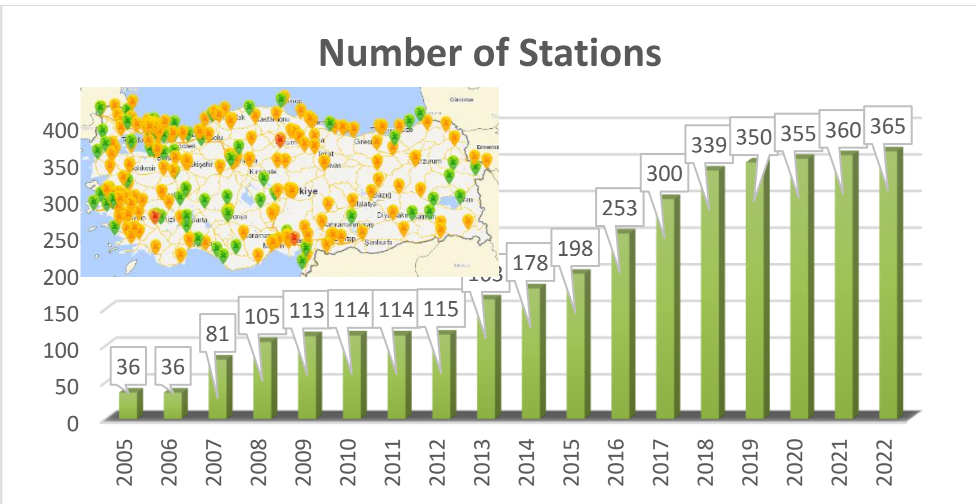

Figure 2: Number of national air quality monitoring station in Türkiye

These parameters are used to measure the concentrations of pollutants using specialized devices, and later converted to the Air Quality Index (AQI) through the use of specific algorithms. Globally, the air quality index consists of six categories ranging from good to hazardous, based on the concentration levels of pollutants present in the air (Aydinoğlu et al., 2022). Different colors are used to symbolize each group (Yağmur, 2022). The color scale starts from green and continues through yellow, orange, red, purple and burgundy. Each color represents the degree of cleanliness of the atmosphere. Green symbolizes the highest air quality, while other colors indicate that the air is respectively less clean. The values of pollutant parameters at the stations are open to sharing free of charge. Data is published in two ways: hourly and daily. Individuals and researchers working on these issues can access it via "www.havaizleme.gov.tr".

In the study, daily recorded air quality parameter results of 7 of 9 stations in Bursa between the dates 01.01.2022-31.12.2022 were provided. Stations used; Nilüfer, Bursa, Beyazıt Cad. - MTHM, Kestel-MTHM, İnegöl, Kültür Park, Uludağ University. Since the other two stations were newly established, they were not included in the study because there was not enough data. General information about the air quality stations used, such as minimum and maximum average values and availability of data, is given in Table 1. Days on which data were not recorded at the station were not included in the study. Except for the PM10 parameter of Nilüfer station, the availability of other data is over 90%.

Table 1: General information about data

	Parameter	Unit	Min. Value	Max Value	Average Value	Data Percentage
Nilüfer	PM10	µg/m³	24,15	192,97	64,47	83,56
Bursa			12,55	185,06	47,40	95,62
Beyazıt Cad.-MTHM			12,73	175,81	48,40	92,88
Kestel-MTHM			7,66	212,68	60,30	94,79
İnegöl			7,97	357,87	67,24	92,33
Nilüfer	PM2.5		15,35	112,93	37,21	90,68
Bursa			2,35	146,61	29,38	96,71
KültürPark			4,82	152,74	30,61	95,89
Uludağ Üniversitesi			1,71	90,05	21,34	95,89
Nilüfer	SO_2		3,31	28,60	8,67	90,32
Bursa			1,85	45,97	10,51	97,81
Beyazıt Cad.-MTHM			1,57	30,93	4,97	93,42
Kestel-MTHM			1,05	56,30	12,20	95,62
İnegöl			3,08	38,74	11,87	93,70
KültürPark			2,05	30,18	7,78	97,26
Uludağ Üniversitesi			1,38	20,08	4,35	97,26
Beyazıt Cad.-MTHM	NO_2		8,66	128,09	57,41	92,33
Kestel-MTHM			5,06	73,51	27,58	93,97
İnegöl			3,81	130,68	38,15	94,52
KültürPark			5,12	94,61	41,06	97,26
Uludağ Üniversitesi			3,10	59,99	18,69	93,70

In the study, GIS software ArcMap v.10.3 was used for spatial modeling of pollutant gases. Thanks to GIS technology, it is possible to access both spatial and attribute information of information on the earth's surface (Khan et al., 2019; Masroor et al., 2020). Based on this information, it is possible to use the monitoring and analysis of air quality, which is one of the factors contributing to global warming.

2.3. IDW Interpolation

In the study, the pollution status of areas around the station was addressed using the IDW method. The reason for choosing this method is its frequent preference in literature and its widespread use for spatial modeling of climatic data interpolation (Willmott & Matsuura, 1995; Jumaah, et al., 2019; Kumar et al., 2022). IDW, a spatial interpolation technique, relies directly on neighboring sampled values (Shepard, 1968). In other words, it involves predicting and calculating the unsampled value within a region based on the known points of sampled values. The IDW formula is given in Equation 1.

$$Z(x_0, y_0) = \frac{\sum_{i=1}^{n} w_i Z_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

Here, $Z(x_0, y_0)$) is the value of the predicted point, n is the number of points (stations) used, Z_i is the value of each point, w_i is the inverse distance weight of each point to (x_0, y_0). Since it is the inverse distance, w_i in the equation is expressed as follows.

$$w_i = \frac{1}{d_i} \quad (2)$$

Here d_i, (x_0, y_0) is the distance to the point.

3. Results

To evaluate the air quality of Bursa, the measurement results of air pollutant parameters were examined. Maps of pollutants (Figures 3, 4, 5 and 6) and the box chart in Figure 7 were evaluated according to the legislation. For PM10 parameter; Nilüfer, Bursa, Beyazıt Cad. - MTHM, Kestel-MTHM, İnegöl stations were used.

Figure 3 shows the monthly averages of PM10 air pollution for a year in 2022. Minimum, maximum, average and standard deviation values for each month are indicated. In the national legislation, the limit value for PM10 is set at 70 µg/m³, while EU member states have established a limit value of 50 µg/m³, and according to WHO, the recommended level is 15 µg/m³ (World Health Organization, 2021; World Health Organization, 2022). When the values were examined, the months in which the average value exceeded the national limit were determined as January, November and December. In addition, it is observed that EU member states' limit values are exceeded in February, March and April. In these months, it was determined to be above the EU member states limit value of 10-20 µg/m³. The month with the lowest average PM10 value (34.66 µg/m³) is July, while the month with the highest (80.54 µg/m³) is December. The maximum value in 2022 was 119.93 µg/m³ in January. The amount of PM10 tends to decrease starting from January, except for September, October, November and December. November, December and January are the coldest months of winter in Bursa. Therefore, there are increases in the amount of PM10 in the city during this period. The main reason for the increase in these months is due to warming activities. High concentration values were recorded at Kestel station in the months when there were no warming activities (May, June, July, August, September). The main reason for this is that the terrain is mountainous, and the station is close to the foot of the mountain. In this case, it makes it difficult for pollutant gases to disperse.

Apart from Kestel station, it was observed that the amount of PM10 was higher in the areas where Nilüfer station is located. It is known that industry is dominant in these regions, routes of transportation are mostly present, and fuels such as fuel oil and coal, other than natural gas, are used in industry.

The main factors that cause an increase in PM10 are various industrial activities, vehicle exhausts or energy production. As a result of these activities, the amount of PM10 increases in the atmosphere and negatively affects human health. These structures, with a diameter of 10 µm, have an effect that can cause respiratory diseases and heart diseases when they enter the human respiratory system.

The amount of PM10 in summer is lower than in winter. This decrease is due to the increase in air temperature. Because warm air is lighter than cold air, it causes surface pollutants to rise and disperse faster into the atmosphere. In some cases, pollutants may be transported by the wind.

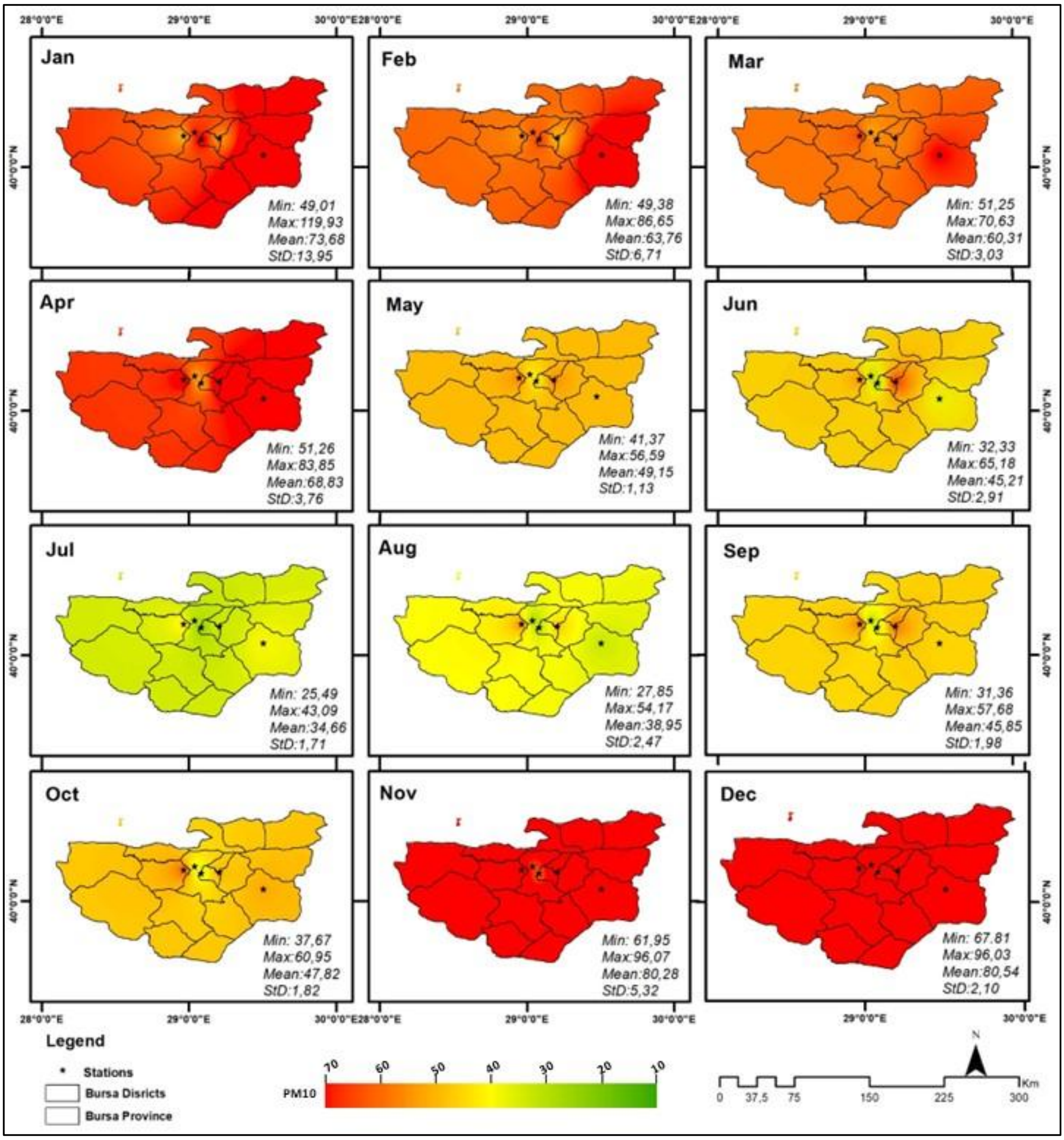

Figure 3: Spatial-temporal distribution of PM10 air pollutant concentrations in 2022

Figure 4 shows the temporal and spatial situation of PM2.5 air pollutants for 2022. For this pollutant, Nilüfer, Bursa, Kültür Park and Uludağ University stations were used.

According to the 2021 WHO report, it is recommended that the monthly average PM2.5 concentration should not exceed 5 µg/m³. This value is 5 µg/m³ less than the limit value determined in 2005 (World Health Organization, 2022). While it is stated that the EU member states limit value should not exceed 25 µg/m³, no limit value is specified for PM2.5 concentration in the "Air Quality Assessment and Management Regulation" published by the Ministry of Environment, Urbanization and Climate Change of the Republic of Turkey (Ministry of Environment, Urbanization and Climate Change, 2022b).

When the values are examined, it is seen that the average PM2.5 values in all months of the year are above the limit value that has not been determined by the World Health Organization. When EU member states are examined in terms of limit value, it is seen that it is below the limit value in all months. The month with the highest monthly average PM2.5 concentration is March with 53.88 µg/m³. During this month, depending on seasonal conditions, air temperatures are low and evaporation is reduced. In this case, it is due to the presence of more polluting particles in the atmosphere. The month with the lowest monthly average PM2.5 concentration is July with 17.08 µg/m³. Air temperatures increase in summer. The amount of moisture in the overheated air increases and the evaporated water creates precipitation. In this way, pollutant gases in the atmosphere are dissolved and their amount decreases.

When considering the map, it is observed that pollution, especially around the Nilüfer station, has increased. Particularly, values recorded from the Nilüfer station in January, March, and December exceed 50 µg/m³. In May, the highest concentration amount was recorded at Nilüfer station compared to other stations. In this month, the value was recorded as 17.63 µg/m³ at Bursa station, 17.92 µg/m³ at Kültürpark station, 13.43 µg/m³ at Uludağ University and 32.02 µg/m³ at Nilüfer station. There are various industrial establishments in Bursa's Nilüfer district. One of these is the automotive industry. Automotive parts are produced in many regions of Bursa. Processes such as paint, varnish and solvent are carried out in these facilities during production. During these processes, polluting gases and particles are dispersed into the atmosphere. There are also facilities that produce chemicals and various food products. These facilities also cause an increase in pollutants such as chlorine, acids, solvents, dust and smoke. The PM2.5 value taken from the air quality station at Uludağ University is lower than the values recorded at the other station. Given that the station is located at high altitude, it is a major factor in the dispersion of pollutant particles in the atmosphere.

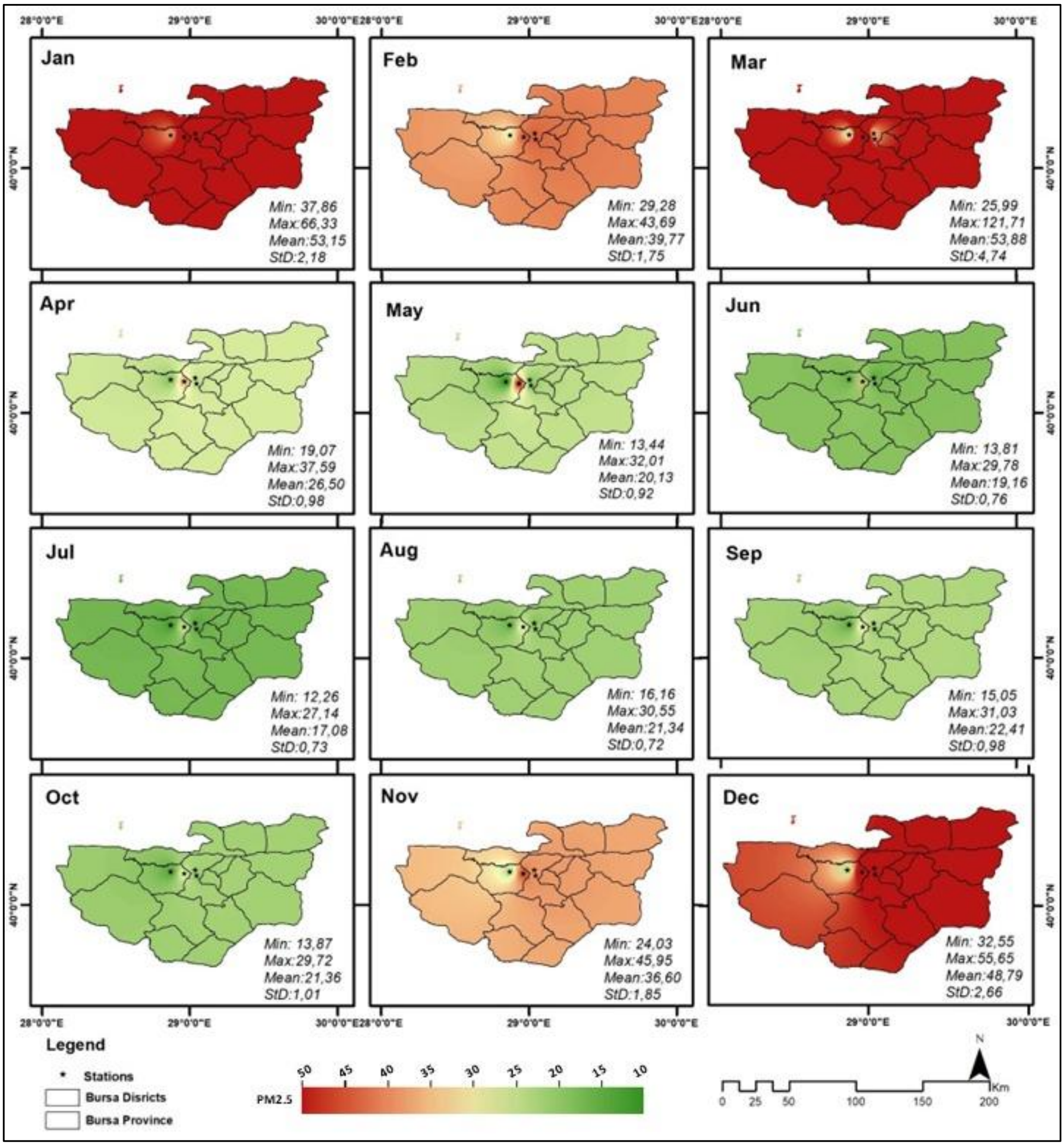

Figure 4: Spatial-temporal distribution of PM2.5 air pollutant concentrations in 2022

Figure 5 shows the temporal and spatial situation of SO2 air pollutant for 2022. A total of 7 stations were used for this pollutant. The names of these stations are Nilüfer, Bursa, Beyazıt Cad.-MTHM, Kestel-MTHM, İnegöl, KültürPark, Uludağ University. The national and EU member states limit value for SO2 in Turkey is 125 µg/m³ on an hourly average.

This value should not be more than 35 times in 1 year (Ministry of Environment, Urbanization and Climate Change, 2022b). According to WHO, this limit is determined as 40 µg/m³ (World Health Organization, 2022). According to the three legislations, it is possible to say that SO2 is below the specified limit and air quality is good in all months. However, when the maps are examined, it is seen that the SO2 concentration at Kestel station increased in January, February, March and April compared to the others. The observation of an increase, especially in the months corresponding to the winter season, may be associated with the fact that pollutants tend to remain in the atmosphere for longer periods of time in cold weather conditions. Kestel district, close to Bursa city center, is a region with industrial facilities, traffic density and high population. There are various industrial enterprises in this district, such as coal, cement and iron-steel. It is known that similar industrial facilities are also located in İnegöl. These facilities release polluting gases such as SO2, NOx and dust during their production processes. Considering all months, the concentration at İnegöl station is approximately 46% higher than the average value of other stations. Traffic density in İnegöl district has increased even more in recent years. Because highway and railway connections pass through this region.

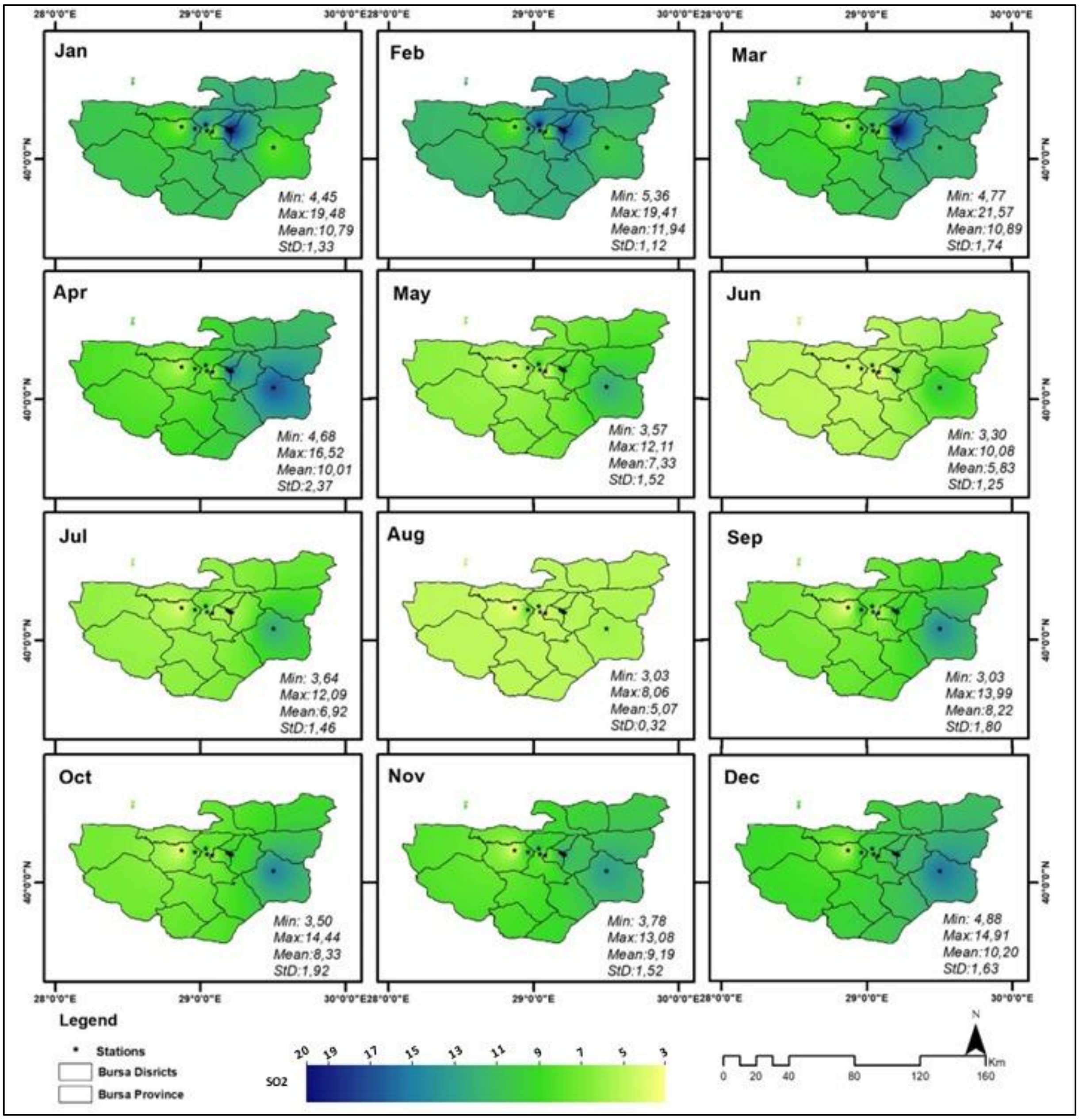

Figure 5: Spatial-temporal distribution of SO2 air pollutant concentrations in 2022

Figure 6 shows the temporal and spatial situation of NO2 air pollutant for 2022. For this polluting gas; Beyazıt Cad.-MTHM, Kestel-MTHM, İnegöl, KültürPark, Uludağ University stations were used. In national legislation in Turkey and in EU member states, the limit value for NO2 concentration is 40 µg/m³ on a daily average (Ministry of Environment, Urbanization and Climate Change, 2022b). According to WHO, this value is 25 µg/m³ (World Health Organization, 2021).

According to the average NO2 values, the limit value determined by WHO exceeded except for July and August. Months exceeding the limit value in national legislation and EU member states are January, February, November and December. NO2 concentration is high in Beyazıt Cad.-MTHM, KültürPark and İnegöl stations.

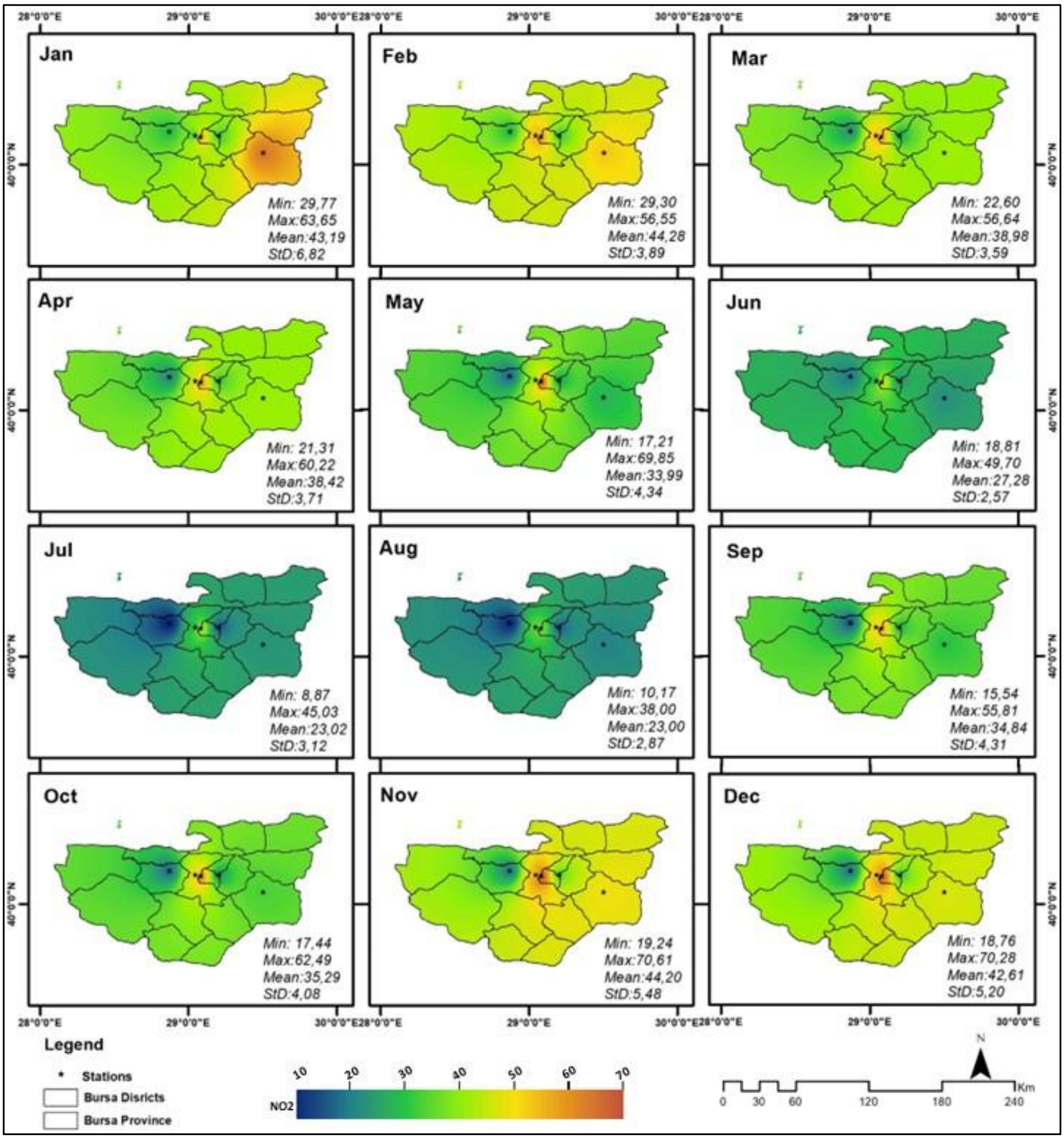

Figure 6: Spatial-temporal distribution of NO2 air pollutant concentrations in 2022

In order to determine seasonal average values, months are grouped according to seasons. All months are divided into seasons: summer (June, July, August), autumn (September, October, November), winter (December, January, February) and spring (March, April, May). For all gases examined, it was observed that a slight increase occurred in the autumn and winter seasons, while it remained at lower values in the spring and summer seasons. The main reason for this is that rainfall due to extreme temperatures in the summer reduces the amount of pollutants. The opposite is true for the winter season. Furthermore, the city's location near Uludağ's base keeps gas concentrations from spreading.

In Figure 7, a box plot illustrates the status of air quality stations and pollutant levels. When evaluating the graph for PM10, the average concentration is observed to be 62.84 µg/m³ for Nilüfer station, 47.60 µg/m³ for Bursa station, 48.50 µg/m³ for Beyazıt Cad.-MTHM station, 60.15 µg/m³ for Kestel-MTHM station, and 65.92 µg/m³ for İnegöl station. According to these data, İnegöl station has the highest PM10 concentration. The maximum recorded PM10 level at İnegöl station is 119.93 µg/m³ in January, while the minimum is in August at 33.19 µg/m³.

For the PM2.5 pollutant, data from four stations were used. The highest PM2.5 concentration is observed in the Nilüfer region, while the lowest is recorded in the Uludağ University region. In March 2022, the PM2.5 value reached 121.78 µg/m³, exceeding legal limits. The SO2 concentration has not exceeded legal limits at any station. The station with the maximum SO2 concentration is Kestel-MTHM, recorded at 21.57 µg/m³ in March. The station with the highest observed NO2 concentration is Beyazıt Cad.-MTHM, while the lowest is Uludağ University.

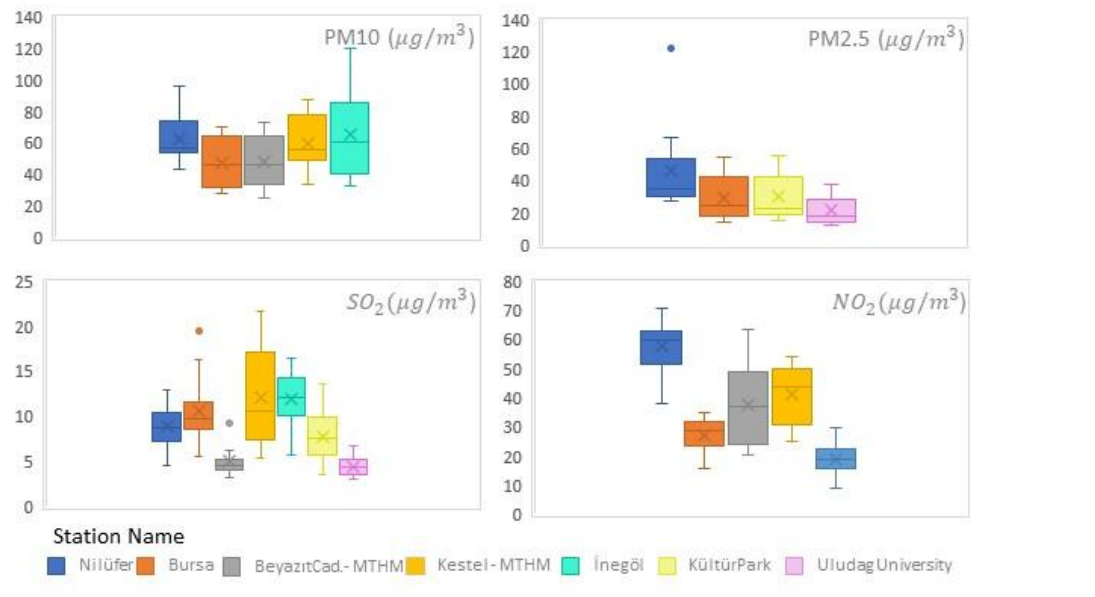

Figure 7: Air quality stations and pollutants quantities

4. Discussion

Better understanding air pollution in daily life is important for human health and ensuring a sustainable environment. For this, it is important to express the air pollution level in numbers, considering the density and exposure times of various pollutants from different sources. In this study, the amount of pollutants in Bursa was examined according to the national, EU member and WHO legal limits specified in Table 2.

Table 2: Limit values of some pollutants specified in the legislation

Air Quality Standards (24 h Average)	**PM10 µg/m³**	**PM2.5 µg/m³**	**SO2 µg/m³**	**NO2 µg/m³**
National legal limit value	70	-	125	25
EU member states limit	50	25	125	25
According to World health organization report	15	5	40	40

It has been determined that the districts of Nilüfer, Osmangazi, Yıldırım and Nilüfer are close to industrial areas and the population density is high. It has been determined that environmental problems are observed in these districts due to industry and population. In particular, it has been observed that air quality is above national limits. The presence of quarries close to the Kestel region also affects the measured values.

The following results have been observed in the study.

- It has been determined that during the summer season, the concentrations of air pollutants are lower compared to the winter season. November, December, and January are the coldest months in the city, experiencing winter conditions, with maximum levels of PM10, PM2.5, NO2, and SO2 gases leading to a greater increase in air pollution during these periods.
- Bursa, being a city with low temperatures during the winter season, causes the atmospheric pollutants to linger in the air for a longer duration. This situation has become a contributing factor to increased air pollution throughout the city.
- Pollutants were evaluated according to national air quality legislation, World Health Organization reports, and EU member states' limit values. While SO2 gas does not exceed the limit set by all three regulations, PM10, PM2.5, and NO2 gases have exceeded legal limit values in some months.

- Considering the spatial distribution of pollutant concentrations, an increase in pollution levels was observed, especially in the intersection areas of industrial zones and transportation routes.

Bugdayci et al. (2023), Suthar et al. (2024), Gokul et al. (2023) found similar results in their study. They determined that there was an increase in pollutant gas levels in months when the temperature dropped, such as October, November, December and January. Demirarslan and Akıncı (2016a) conducted a study in the Eastern Black Sea region and obtained similar results. Using the IDW technique, they analyzed the pollution levels in the region and found that the fuels used for heating during the winter months significantly increased PM10 concentrations. In another study by Demirarslan and Akıncı (2016b) the SO_2 levels were monitored, and it was highlighted that traffic and industrial activities were among the factors contributing to the increase in pollutant concentrations.

Another interpretation derived from this study is related to the location of the city. The polluted air coming from Istanbul is carried to the city. Makineci (2022) and Yağmur (2022) examined the air quality in the Istanbul region. Considering the values, air pollution in Istanbul is higher than in Bursa. Therefore, the polluted air coming from Istanbul further increases the air pollution level in Bursa. Cities such as Bursa and Istanbul are cities with a high level of industrialization. These factors cause air pollution to increase.

5. Conclusions

This study investigated the spatial-temporal variations of PM10, PM2.5, SO2, NO2, air pollutants recorded from 7 NAQS (National Air Quality Stations) throughout Bursa during the year 2022. The analysis reveals that the İnegöl station recorded the highest levels of PM10 pollution, with an average concentration of 65.92 µg/m³. The peak concentration of PM10 was observed in January, reaching 119.93 µg/m³. In contrast, the Nilüfer station exhibited the highest PM2.5 concentration, with a notable value of 121.78 µg/m³ recorded in March 2022. This concentration exceeded the legal limits set by both the European Union and the World Health Organization. Consequently, while İnegöl station experienced the highest PM10 pollution levels, Nilüfer station recorded the most significant PM2.5 pollution, surpassing critical health thresholds. Regarding other pollutants, no station exceeded the legal limits for SO2 concentrations. For NO2 concentrations, the Beyazıt Cad.-MTHM station recorded the highest value, while the lowest concentration was observed at the Uludağ University station.

The data obtained from the study help us understand the distribution and change over time of air pollutants in Bursa and cities in developing countries. This information can be used to develop more effective air quality policies. Considering findings, various measures can be taken to reduce the amount of polluting air in the city. For example; In order to make the automotive, textile, metal and machinery manufacturing industries in the city environmentally friendly, measures such as adopting more sustainable production methods, effective implementation of waste management and supporting investments to increase energy efficiency can be taken. The use of public transportation should be encouraged, the types of fuel used for domestic heating should be changed and the system should be switched to systems that consume less fuel. Afforestation efforts should be carried out in urban areas to ensure ecological balance. Most importantly, individuals should be made aware of air pollution and environmental protection.

References

Albayrak, B. (2023). *Türkiye'de zeytin üretiminin kümeleme yöntemi ile analizi* [Yüksek lisans tezi, Bursa Uludağ Üniversitesi]. YÖK Ulusal Tez Merkezi. https://tez.yok.gov.tr/UlusalTezMerkezi

Altıkat, A., Torun, F. E., & Bayram, T. T. (2011). Küresel kirlilik: Dünya, Avrupa Birliği ve Türkiye’de hava kirliliği örneği. *Erciyes Üniversitesi Fen Bilimleri Enstitüsü Fen Bilimleri Dergisi, 27*(2), 134–149.

Arikan, D., & Yildiz, F. (2023). Investigation of Antalya forest fire's impact on air quality by satellite images using Google earth engine. *Remote Sensing Applications: Society and Environment*, *29*, Article 100922. https://doi.org/10.1016/j.rsase.2023.100922

Arıkan, D., Yıldız, F., & Makineci, H. B. (2021). Hava lidari verilerine uygulanan farklı enterpolasyon yöntemlerinin SAM doğruluğuna etkisi. *Konya Journal of Engineering Sciences, 9*(2), 377–394. https://doi.org/10.36306/konjes.850250

Aydinoğlu, A. Ç., Bovkir, R., & Bulut, M. (2022). Akıllı şehirlerde büyük coğrafi veri yönetimi ve analizi: hava kalitesi örneği. *Geomatik, 7*(3), 174–186. https://doi.org/10.29128/geomatik.938855

Bayrı, F. (2023). Ankara Şehrinde Hava Kirlenmesi. *Bulletin of the Mineral Research and Exploration*, *63*(1964), 64–74.

Bozdağ, A., Dokuz, Y., & Gökçek, Ö. B. (2020). Spatial prediction of PM10 concentration using machine learning algorithms in Ankara, Turkey. *Environmental Pollution, 263*, Article 114635. https://doi.org/10.1016/j.envpol.2020.114635

Bugdayci, I., Ugurlu, O., & Kunt, F. (2023). Spatial analysis of SO2, PM10, CO, NO2, and O3 pollutants: the case of Konya province, Turkey. *Atmosphere, 14*(3), Article 462. https://doi.org/10.3390/atmos14030462

Chang, F. J., Chang, L. C., Kang, C. C., Wang, Y. S., & Huang, A. (2020). Explore spatio-temporal PM2. 5 features in northern Taiwan using machine learning techniques. *Science of the Total Environment, 736*, Article 139656. https://doi.org/10.1016/j.scitotenv.2020.139656

Demirarslan, K., & Akıncı, H. (2016a). Doğu Karadeniz Bölgesindeki partikül madde dağılımlarının coğrafi bilgi sistemleri yardımıyla belirlenmesi. *Doğal Afetler ve Çevre Dergisi, 2*(1), 30–45.

Demirarslan, K. O., & Akıncı, H. (2016b). Doğu Karadeniz Bölgesinde kükürtdioksit (SO2) dağılımlarının coğrafi bilgi sistemleri yardımıyla belirlenmesi. *Doğal Afetler ve Çevre Dergisi, 2*(2), 81–99.

El Naqa, I., & Murphy, M. J. (2015). *What is machine learning?.* Springer.

Erickson, L. E., Newmark, G. L., Higgins, M. J., & Wang, Z. (2020). Nitrogen oxides and ozone in urban air: A review of 50 plus years of progress. *Environmental Progress & Sustainable Energy, 39*(6), Article e13484. https://doi.org/10.1002/ep.13484

Gokul, P., Mathew, A., Bhosale, A., & Nair, A. T. (2023). Spatio-temporal air quality analysis and PM2. 5 prediction over Hyderabad City, India using artificial intelligence techniques. *Ecological Informatics, 76*, Article 102067. https://doi.org/10.1016/j.ecoinf.2023.102067

Goyal, P., & Kumar, A. (2011). Mathematical modeling of air pollutants: an application to Indian urban city. In D. Popovic (Ed.), *Air Quality-Models and Applications* (pp. 101–130). InTech. https://doi.org/10.5772/16840

Görener, Ö., & Görener, A. (2008). Otomotiv Endüstrisinin Türkiye Ekonomisindeki Yeri: Sektörel Bir İnceleme. *Elektronik Sosyal Bilimler Dergisi, 7*(26), 306–319.

Hashim, M., Kanniah, K., Ahmad, A., Rasib, A., & Ibrahim, A. (2004). The use of AVHRR data to determine the concentration of visible and invisible tropospheric pollutants originating from a 1997 forest fire in Southeast Asia. *International journal of remote sensing, 25*(21), 4781–4794.

Jumaah, H. J., Ameen, M. H., Kalantar, B., Rizeei, H. M., & 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.

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution, 151*(2), 362–367.

Khan, J., Kakosimos, K., Raaschou-Nielsen, O., Brandt, J., Jensen, S. S., Ellermann, T., & Ketzel, M. (2019). Development and performance evaluation of new AirGIS–a GIS based air pollution and human exposure modelling system. *Atmospheric Environment, 198*, 102–121. https://doi.org/10.1016/j.atmosenv.2018.10.036

Kırbıyık, B. (2023). *Antalya ili hava kalitesinin değerlendirilmesi ve 2021 yılı orman yangınlarının etkisinin araştırılması* [Yüksek lisans tezi, Konya Teknik Üniversitesi]. YÖK Ulusal Tez Merkezi. https://tez.yok.gov.tr/UlusalTezMerkezi

Kumar, A., Dhakhwa, S., & Dikshit, A. K. (2022). Comparative evaluation of fitness of interpolation techniques of ArcGIS using leave-one-out scheme for air quality mapping. *Journal of Geovisualization and Spatial Analysis, 6*(1), Article 9. https://doi.org/10.1007/s41651-022-00102-4.

Makineci, H. B. (2022). İstanbul İli Merkez İlçelerindeki NO2 ve CO Emisyonlarının Uzaktan Algılama ve Yersel İstasyon Verileri Kullanılarak İncelenmesi. *Türkiye Uzaktan Algılama Dergisi, 4*(2), 62–74. https://doi.org/10.51489/tuzal.1160333

Masroor, K., Fanaei, F., Yousefi, S., Raeesi, M., Abbaslou, H., Shahsavani, A., & Hadei, M. (2020). Spatial modelling of PM2. 5 concentrations in Tehran using Kriging and inverse distance weighting (IDW) methods. *Journal of Air Pollution and Health, 5*(2), 89–96.

Ministry of Environment, Urbanization and Climate Change. (2022a). *Ministry of Environment, Urbanization and Climate Change National Air Quality Monitoring Network (NAQMN)*. 20 Haziran 2024'de https://www.havaizleme.gov.tr/ adresinden alındı.

Ministry of Environment, Urbanization and Climate Change. (2022b). *Air Quality Bulletin September 2023 Report*. 10 Kasım 2023'de https://webdosya.csb.gov.tr/db/ced/icerikler/eylul-2023_bulten-raporu-20231110091236.pdf adresinden alındı.

Roy, A. (2021). Atmospheric pollution retrieval using path radiance derived from remote sensing data. *Journal of Geovisualization and Spatial Analysis, 5*, 1–11. https://doi.org/10.1007/s41651-021-00093-8

Samal, K. K. R. S., Babu, K. S., & Das, S. K. (2023). Spatial-temporal prediction of air quality by deep learning and kriging interpolation approach. *EAI Endorsed Transactions on Scalable Information Systems, 10*(5). https://doi.org/10.4108/eetsis.3325

Shepard, D. (1968, August 27 - 29). *A two-dimensional interpolation function for irregularly-spaced data* [Conference presentation]. 23rd ACM national conference, New York, United States.

Sungur, O., & Yaman, H. (2021). Bölgesel çeşitlilik mi uzmanlaşma mı? İllerin İmalat sanayinde çeşitlilik/uzmanlaşma düzeylerine göre sıralanması. *İdealkent, 12*(32), 76–94.

Suthar, G., Singhal, R. P., Khandelwal, S., Kaul, N., Parmar, V., & Singh, A. P. (2024). Annual and seasonal assessment of spatiotemporal variation in PM2. 5 and gaseous air pollutants in Bengaluru, India. *Environment, Development and Sustainability*, *26*, 20629–20652.

Şahin, O., & Kubilay, K. (2023). Bitlis İli, Güroymak ilçesi, Gölbaşı Beldesindeki Anadolu Mandası İşletmelerinde Barınak İçi Karbondioksit (CO2) Emisyonu Üzerine Barınak Hacmi ve Sürü Büyüklüğünün Etkisi. *Palandöken Journal of Animal Sciences Technology and Economics, 2*(2), 44–52. https://doi.org/10.5152/JASE.2023.1224595

Temel, K. (2023). *Yeni sınıf hareketleri ve mekânsal etkileri: Bursa örneği.* [Doktora tezi, Bursa Uludağ Üniversitesi]. YÖK Ulusal Tez Merkezi. https://tez.yok.gov.tr/UlusalTezMerkezi

Turkish Statistical Institute. (2022). Turkish Statistical Institute (TSI). 16 Aralık 2022'de https://www.tuik.gov.tr/ adresinden alındı

World Health Organization. (2021). *WHO global air quality guidelines: particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*: World Health Organization.

World Health Organization. (2022). World Health Organization. 20 Aralık 2024'de https://www.who.int/health-topics/air-pollution#tab=tab_1 adresinden alındı.

Willmott, C. J., & Matsuura, K. (1995). Smart interpolation of annually averaged air temperature in the United States. *Journal of Applied Meteorology and Climatology, 34*(12), 2577–2586.

Yağmur, E. Ç. (2022). Atmosferik partikül maddelerin makine öğrenmesi ile tahmini: Beşiktaş, İstanbul Örneği. *Konya Journal of Engineering Sciences, 10*(4), 807–826. https://doi.org/10.36306/konjes.1082866

Yener, İ., & Demirarslan, K. O. (2022). Determining the factors affecting air quality in marmara, turkey, and assessing it using air quality indices. *Journal of Natural Hazards and Environment, 8*(2), 383–395. https://doi.org/10.21324/dacd.1081167

Zencirci, S. A., & Işıklı, B. (2017). Hava kirliliği. *ESTÜDAM Halk Sağlığı Dergisi, 2*(2), 24–36.

Zhou, F., Wang, Y., Liu, J., Yang, X., Hu, Z., Guo, T., Han, Y. (2023). Influence of ship emission control area policy on air quality at Shanghai Port—local and regional perspectives. *Ecological indicators, 155*, 110951. https://doi.org/10.1016/j.ecolind.2023.110951

Zhou, Y., Chang, F. J., Chang, L. C., Kao, I. F., & Wang, Y. S. (2019). Explore a deep learning multi-output neural network for regional multi-step-ahead air quality forecasts. *Journal of cleaner production, 209*, 134–145. https://doi.org/10.1016/j.jclepro.2018.10.243

Zhou, Z. H. (2021). *Machine learning.* Springer Nature.