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FUJECE

Hava Kirliliği Dinamikleri ve Kalitesine İlişkin İçgörüler: Türkiye'deki Akademik Araştırmaların Kapsamlı Bir Analizi

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Öz

Hava kirliliği, insan sağlığı, sürdürülebilir çevre ve sosyo-ekonomik refah için uzun vadeli sonuçları olan ciddi bir küresel sorundur. Bu kapsamlı analiz, Türkiye'de 2022 ve 2023 yılları arasında DergiPark platformunda yayınlanan makalelerden elde edilen en son araştırma bulgularını birleştirerek hava kirliliğinin ve kalitesinin çok yönlü doğasına yer vermektedir. Çalışmamız, araştırma konularına göre makaleleri kategorize etmektedir. Temel bulgular, hava koşulları, şehirleşme, sanayinin hava kirliliği ve hava kalitesi üzerinde etkili olduğunu göstermektedir. Ayrıca, COVID-19 pandemisinin hava kalitesi dinamikleri ile etkileşime girdiği belirlenmiştir. Araştırmacılar, tahmin, değerlendirme ve modelleme için bir dizi yöntem kullanmışlardır. Bu konuda yenilikçi yaklaşımlarla üzerinde durulması gereken zorluklar devam etmektedir. Hava kirliliğini iklim değişikliği, kentsel gelişme ve ulaşım ile ilişkilendiren neden-sonuç yollarını araştırmak, sorunu daha iyi anlamamıza yardımcı olacaktır. Hava kirliliği ve kalitesinin insan sağlığı üzerindeki etkilerine ilişkin deneysel çalışma, bilinçli politika kararları almak özellikle savunmasız gruplar için önemlidir. Mevcut düzenlemelerin etkinliğini değerlendirmek ve yeni yaklaşımlar oluşturmak, etkili hava kalitesi yönetimine rehberlik edebilir. Sonuç olarak, bu makale, hava kalitesi ve kirliliği hakkında akademik araştırmaları derleyerek konunun yaygın etkisine dair kapsamlı bir inceleme sunmaktadır.

Anahtar kelimeler: Hava kirliliği, Hava kalitesi, COVID-19, İnsan sağlığı

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Insights Into Air Pollution Dynamics and Quality: A Comprehensive Analysis Of Scholarly Research In Türkiye

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Abstract

Air pollution affects human health, the environment, and the economy worldwide. This comprehensive analysis elucidates the intricate characteristics of air pollution and its quality by amalgamating the latest study outcomes derived from papers published on the DergiPark platform in Türkiye throughout the period spanning from 2022 to 2023. The papers in our study are classified according to their research themes. The main findings suggest that weather, urbanization, industry, and wildfires affect air pollution and quality. Additionally, the COVID-19 pandemic has affected air quality dynamics, requiring further study. Scientists have used various methods to forecast, evaluate, and simulate, but challenges remain that require new approaches. Investigating the causal pathways linking air pollution to climate change, urban development, and transportation will help us better understand the problem. Empirical study into the effects of air pollution and quality on human health is essential for making informed policy decisions, especially for vulnerable groups. Evaluating the efficacy of current regulations and establishing new approaches can help guide effective air quality. This paper is a comprehensive synthesis of scholarly studies pertaining to air quality and pollution, providing a comprehensive overview of the extensive ramifications associated with this subject matter.

Keywords: Air pollution, Air quality, COVID-19, Human health

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1. Introduction

Air pollution has become one of the most pressing global issues due to its significant impact on both environmental sustainability and public health. Defined by the World Health Organization (WHO) as the contamination of indoor or outdoor environments by any chemical, physical, or biological agent that modifies the natural characteristics of the atmosphere, air pollution remains a multidimensional challenge [1]. It stems from a variety of sources, including industrial processes, transportation, residential energy use, and agriculture. Some pollutants are directly emitted from combustion sources as primary pollutants, with elemental carbon being the main constituent of particulate matter (PM). Others are formed in the atmosphere as secondary pollutants, such as nitrates, sulfates, and organic carbon, through complex physicochemical processes involving gaseous precursors from combustion sources, agriculture (ammonia), various anthropogenic activities, and natural processes like biogenic emissions [2]. The most concerning pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3), have been linked to severe health outcomes, including respiratory and cardiovascular diseases [3], neurological damage [4], and even premature death [5]. The detrimental effects of poor air quality also extend to ecosystems, leading to biodiversity loss and harm to wildlife [6, 7]. In addition to other pollutants, exposure to volatile organic compounds (VOCs), which are widely found in gaseous form, has also been shown to be linked to serious health effects such as cancer, obesity and diabetes, and cardiovascular issues [8-10].

National and international authorities, such as the WHO, have implemented guidelines and regulations to mitigate air pollution and protect public health. These efforts have led to the establishment of air quality standards for key pollutants and the promotion of measures to reduce emissions. For instance, the World Health Organization's air quality guidelines have set threshold levels for pollutants including $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3. The 2021 guidelines specify an annual limit of 5 $\mu g/m^3$ for $PM_{2.5}$, 15 $\mu g/m^3$ for PM_{10}, and 10 $\mu g/m^3$ for NO_2. Additionally, the guidelines establish an 8-hour limit of 100 $\mu g/m^3$ for O_3, a 24-hour limit of 40 $\mu g/m^3$ for SO_2, and 4 $\mu g/m^3$ for CO, demonstrating the continuous updates made in response to new scientific evidence [11]. Exceeding these threshold levels can lead to serious health issues, environmental damage, and deterioration of air quality.

Clean air is a human right and fundamental to many of the United Nations' sustainable development goals, including good health, climate action, sustainable cities, clean energy, and the protection of life on land and in the sea [12]. In line with global efforts, Türkiye has incorporated air quality targets into its commitment to the United Nations Sustainable Development Goals (SDGs), aiming to reduce air pollution-related deaths and diseases by 2030 [13]. Achieving these goals will rely heavily on scientific research contributions.

The increasing urgency to address air quality has drawn attention from a wide range of disciplines, including chemistry, biology, environmental engineering, meteorology, public health, and economics. This multidisciplinary focus has resulted in a surge of studies on pollution sources, the spatial and temporal variations of air quality, interactions between pollutants and environmental parameters, and their impacts on human health and ecosystems. For example, in a study by Chen et al., there has been a marked increase in the number of publications on air pollution control over the past two decades, with a particularly rapid rise since 2018, demonstrating the continuous growth in academic interest in this field, as shown in Figure 1 [14].

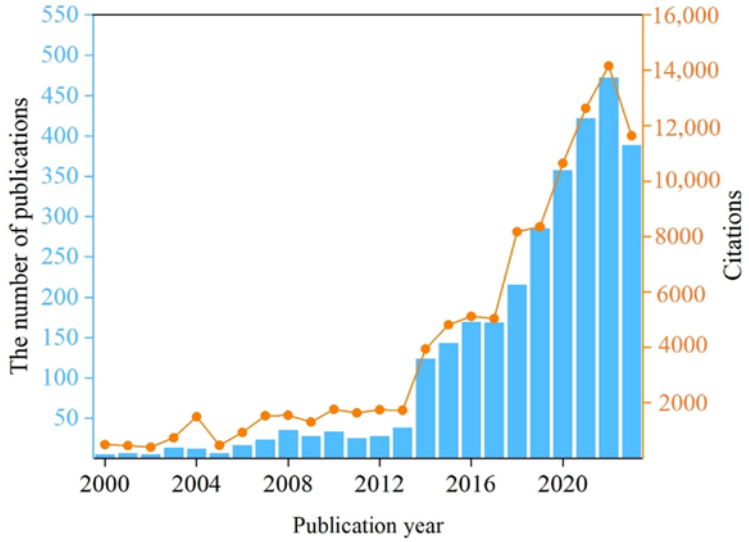

Figure 1. The annual number of publications on air pollution control [14]

In Türkiye, the understanding of the causes and consequences of air pollution, as well as the development of new technologies to prevent pollutant emissions, has become a focal point of scientific research. This review aims to present a compilation of the scientific contributions made by Turkish researchers between 2022 and 2023. By summarizing these works, the review provides insights into the latest developments in air pollution research in Türkiye, highlights the challenges and progress in this field, and aims to create a forecast for future studies.

This study specifically examines articles published on the DergiPark platform, hosted by TÜBİTAK ULAKBİM (The Scientific and Technological Research Council of Türkiye, Informatics and Information Security Advanced Technologies Research Center), which provides editorial management services for electronically published academic journals. We analyzed 50 articles addressing various aspects of air pollution, categorizing them by their topics and examining them under main headings. These articles offer a comprehensive perspective on air pollution, highlighting the complexity of the subject through discussions of various factors. Furthermore, examples from significant studies conducted in different regions of Türkiye are included to illustrate the broader context of air pollution research.

2. Methodology

This article constitutes a review encompassing significant studies identified through a search conducted on articles published in DergiPark between 2022 and 2023. The search criteria included articles with key terms "air pollution" or "air quality." Additionally, variations of these terms such as "Outdoor Air Quality," "Air Quality Index," "Daily Air Quality Index," "Urban Air Quality," and "Perception of Air Pollution" were included in the review. In some instances, articles were selected based on the combination of two of these keywords, as specified by the authors. Figure 2 illustrates the distribution of articles according to the selected keywords.

Figure 2. The distribution of articles classified by the selected keywords

Figure 3 illustrates the link between the articles' major phrases. Only terms that were unique to the relationship analysis file were removed to show the density of relationships between keywords. The visual depiction shows the additional keyword selections made by authors who chose 'Air Pollution' and 'Air Quality' for their publications.

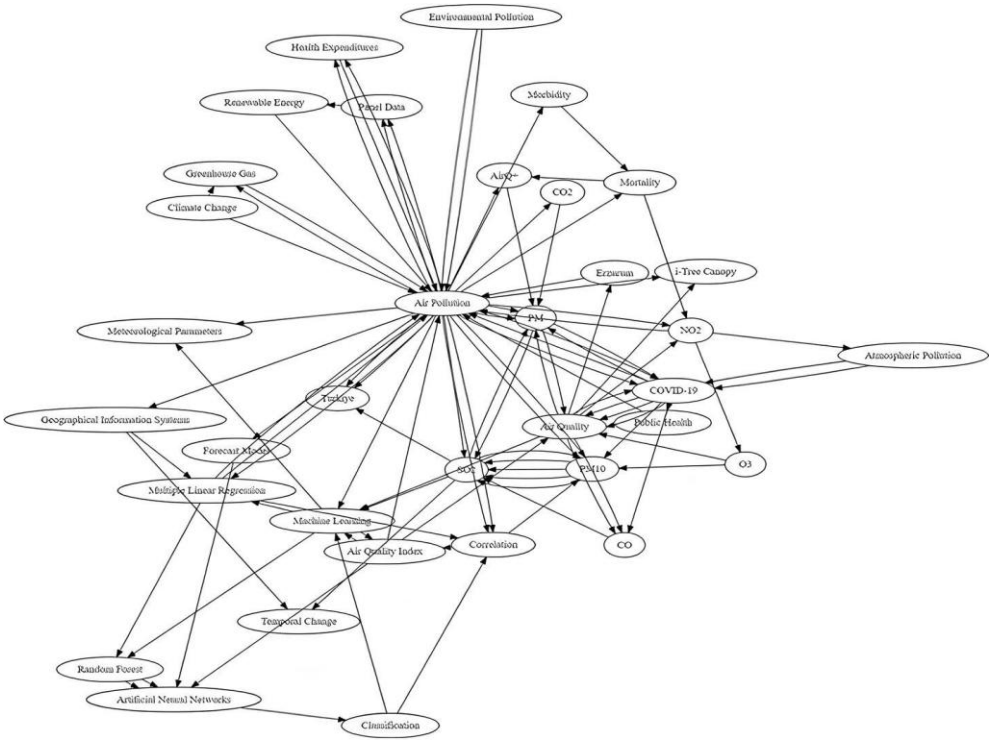

Figure 3. The keywords graph displays extra keywords chosen by authors who selected the 'Air Pollution' and 'Air Quality' keywords

Air pollution is an interdisciplinary topic that enables academics from numerous fields to collaborate. Interdisciplinary collaboration is critical for improving a complete understanding of air pollution challenges and contributing to the development of long-term remedies. The departments reported by the authors as affiliations in the analyzed publications were also investigated in this context. Figure 4 shows a graphic depiction of the reviewed articles that involved transdisciplinary studies.

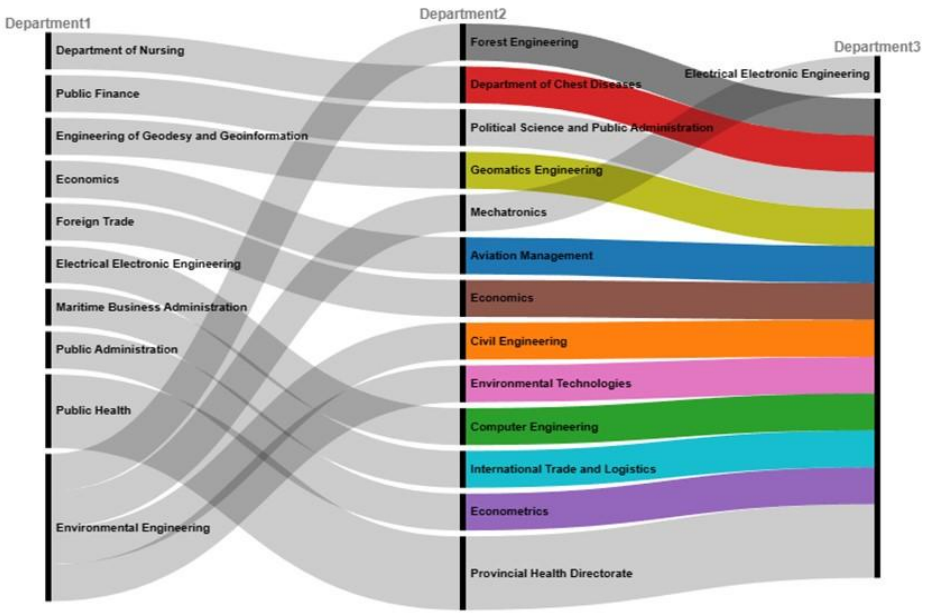

Figure 4. The distribution of studied articles across author affiliations in multidisciplinary air pollution articles

As depicted in Figure 4, researchers from the departments of Environmental Engineering, Mechatronics, and Electrical-Electronics Engineering have collaboratively contributed to studies on air pollution/quality.
Following all these preliminary assessments, all articles have been organized under six distinct headings: Temporal/spatial variations in air quality, the relationship between various parameters and air quality, air pollution/quality prediction, the relationship between air quality and health, COVID-19, and other studies and review articles.

2.1. Temporal and spatial analysis of air quality

An analysis was conducted on the temporal and spatial variations of air pollution in different provinces of Türkiye, using eight articles obtained from DergiPark. The study areas, pollutants examined, and meteorological parameters used are presented in Table 1. Meteorological parameters are of paramount importance in the field of air pollution research. Consequently, Table 1 presents studies that make use of meteorological data.

Table 1. Provinces where temporal and spatial changes in air quality are analyzed with pollutant and meteorological data

Location	Pollutants	Meteorological Data	Reference
Kocaeli	SO_2, CO, O_3, HCHO, NO_X, PM_{10}, Aerosol Index	-	[15]
Muş	PM_{10}, SO_2	-	[16]
Mardin	PM_{10}, SO_2	-	[17]
Bayburt	NO_X,NO, NO_2,O_3, SO_2, PM_{10}	wind direction, wind speed, pressure, relative humidity, temperature	[18]
Karabük	SO_2, CH_4, CO, CO_2, NO_X, O_3, $PM_{2.5}$, PM10, VOC	temperature, humidity, atmospheric pressure	[19]
Kütahya	PM (0.3, 0.5, 1, 2, 5, 10 µm), CO_2	-	[20]
Kocaeli	PM_{10}, SO_2	-	[21]
Erzurum	PM_{10}, SO_2	average temperature, wind speed, wind direction, relative humidity, precipitation	[22]

The initial study conducted in Kocaeli aimed to investigate the spatial distribution of pollutants released into the atmosphere and approximate elevation levels they reach. Utilizing Sentinel-5P satellite data and local station data, the research identified regions with significant air pollution, particularly along the coast of the Gulf of Izmit and specific districts. Moreover, it was revealed that pollutants concentrate within the range of 0-500 meters in elevation [15].

In another study focusing on Muş, researchers observed that between 2012 and 2021, the values of PM_{10} and SO_2 frequently exceeded the annual average values specified in the Air Quality Assessment and Management Regulation [16]. Another study focusing on pollution levels in Mardin between 2010 and 2021 revealed that both PM_{10} and SO_2 levels significantly exceeded the regulatory limits specified in both WHO and Turkish regulations during the specified period. This was proved by statistical analyses using Analysis of Variance (ANOVA) and multiple comparison (TUKEY) tests. The high levels of pollutant parameters in the summer and fall seasons compared to other seasons in the province were found to be related to the movement of desert dust [17]. Furthermore, the research by Hırca et al. in Bayburt city center employed statistical methods to analyze the temporal variations of air pollutants, their interactions with local meteorological parameters, and trends. According to the results of the Mann-Whitney U test, the averages of pollutant concentrations during the cold season were statistically significantly dissimilar to the averages during the warm season. Additionally, the Kruskal-Wallis test indicated a statistically significant difference in pollutant concentration averages across the years. Post-Hoc/Tamhane's T2 analysis was performed to identify the years that were significantly different. Furthermore, Spearman's rho (ρ) correlation analysis results demonstrated a statistically significant relationship between air pollutants and meteorological parameters. Using the Innovative Trend Analysis (ITA) method, a decrease in PM10 levels and an increase in other pollutants were observed in Bayburt [18]. Karabük province used a new air pollution measurement device designed to simultaneously measure numerous atmospheric parameters along with SO_2, CH_4, CO_2, CO, NO_X, O_3, $PM_{2.5}$, and Volatile Organic Compounds (VOC) pollutant parameters. The study demonstrated high concentrations exceeding the standards for SO_2, CO, NO_X, and $PM_{2.5}$. Additionally, the impact of seasonal variations and atmospheric parameters on pollution levels has been emphasized [19]. In his article on Kütahya, Işinkaralar identified high levels of pollution in the province, primarily caused by heating, fuel types, industrial activities, and transportation [20].

Kotan and Erener conducted a study examining temporal and spatial changes in air pollution using PM_{10} and SO_2 data in Kocaeli. Seasonal pollution maps created for the years 2008, 2014, and 2019 were subjected to overlay analysis, a Geographic Information Systems technique, revealing seasonal variations in pollutant concentrations across the province. Despite a decrease in concentration values from 2008 to 2019 throughout the province, localized areas exceeding the pollutant concentration limit values set by the European Union and national regulations were identified in 2019 [21]. A study examining the air quality in the city atmosphere of Erzurum from the winter of 1978-1979 to the period of 2018-2019 with SO_2 and PM_{10} parameters found that the use of natural gas led to a significant structural change in air quality in 2006 and 2009 [22].

2.2. The relationship between various parameters and air quality

Air quality can be influenced by various factors, including meteorological conditions [23], urbanization [24], transportation [25], industrialization [26], wildfires [27], vegetation [28], and many other parameters, all of which can contribute to or affect the formation or magnitude of air pollution. A detailed analysis of the air pollution parameters and their influencing factors is presented in Table 2, based on studies published in DergiPark.

Table 2. Comparative study of air quality indicators and their determinants

Location	Pollutants	Parameters	Findings	Ref.
Marmara	$PM_{2.5}$, PM_{10}, SO_2, O_3, CO, NOx	Spatial, meteorological, anthropogenic data	NOx and O_3 are influenced by anthropogenic factors, while PM is affected by meteorological and spatial factors.	[29]
Bolu	PM_{10}, SO_2, NO, NO_2, NO_X, CO	Temperature, pressure, wind direction/speed, humidity	Moderate correlation with temperature, pressure, and wind direction; low correlation with speed and humidity.	[30]
Muş	PM_{10}, SO_2	Temperature, wind speed/direction, pressure, humidity	PM_{10} is influenced by pressure (positive) temperature and wind speed (negative); SO_2 by temperature (negative) and humidity (positive).	[31]
Çanakkale	O_3	Temperature, wind speed/direction, solar radiation, humidity, total precipitation	Ozone levels have a positive correlation with temperature and solar radiation, and a negative correlation with relative humidity.	[32]
Balıkesir	SO_2, PM_{10}	Temperature, wind speed, humidity, pressure and mixing heights	PM_{10} levels are negatively correlated with wind speed and temperature, while SO_2 levels correlate negatively with temperature and mixing height.	[33]
Erzurum	SO_2, PM_{10}, CO, NO_X, NO, NO_2, O_3	Pressure, altitude, wind, temperature, natural gas/coal consumption, Sky View Factor	Fuel consumption is identified as the primary factor affecting air pollution, while secondary parameters include wind speed and street orientations.	[34]
Konya	CO	Urban Heat Island (UHI)	The amount of heat in the city is directly proportional to the increase in CO.	[35]
Adıyaman	SO_2, PM_{10}	Solar power plants daily electric energy values	There is a notable correlation between air pollution levels and solar energy efficiency.	[36]
Antalya	PM_{10}, $PM_{2.5}$, SO_2, CO, O_3	Wildfires data	The 2021 wildfires had no significant effect on air quality.	[37]
İstanbul	CO, NO_2, NOx, O_3 SO_2, $PM_{10,}$ $PM_{2.5}$	Traffic sensor data.	Increased vehicle numbers and traffic congestion raise AQI levels.	[38]
General Study	-	Information collected from various sources	Restrictions on ship speed will reduce CO_2, black carbon, nitrogen oxides, and nitrous oxide emissions.	[39]
Zonguldak	eCO_2	Types of vehicles, distances traveled, amounts of waste	Inspection station location affects carbon emissions.	[40]
Altınpark Ankara	O_3, NO_2, $PM_{2.5}$, SO_2, CO	Land/canopy cover data	Tree/shrub cover and species diversity significantly improve air quality.	[41]
Kuzguncuk İstanbul	CO_2 , CO, NO_2, O_3, SO_2, $PM_{2.5}$, PM_{10}	Land/canopy cover data	Tree/shrub cover helps remove pollutants and contributes economically.	[42]
APEC Countries	-	Economic and environmental indicators	A long-term relationship has been found between the welfare cost of premature deaths caused by ambient particulate matter, real Gross Domestic Product (GDP), trade openness, and renewable energy supply.	[43]
Türkiye	per capita PM	Economic growth, environmental patents, regulations	Economic growth increases pollution, while patents and regulations help reduce it.	[44]
General Study	PM_{10}	Health expenditure, GDP, population, information communication technologies data	The findings show that air pollution and mobile phone subscriptions have no effect on health expenditures, while internet subscriptions and index variables negatively impact health spending.	[45]

For instance, in a study investigating the impact of spatial, meteorological, and anthropogenic factors on air quality in the Marmara Region, it is emphasized that anthropogenic variables predominantly influence NO_x among the pollutants examined, while meteorological and spatial factors affect particulate matter levels [29]. During their study examining the impact of meteorological parameters on air pollution in Bolu province between 2017 and 2020, Ünal and Özel discovered that contaminants had a moderate association with temperature, air pressure, and wind direction, but a low relationship with wind speed and relative humidity [30]. Another study on the relationship between and air pollution and meteorological parameters was conducted for the province of Muş, revealing that temperature and wind speed (negative), pressure (positive), significantly influence the variations in PM_{10} levels, while for the SO_2 parameter, temperature (negative) and humidity (positive) were identified as the most influential variables [31]. A study in Çanakkale province examined how meteorological characteristics like temperature, wind speed, and relative humidity affect O_3. The study revealed that the most significant factors influencing ozone concentration levels in the province

are meteorological parameters and pollutants released into the atmosphere from anthropogenic sources (such as vehicles, industrial emissions, solvents, and volatile organic compounds (VOCs) emitted by industries) transported over long distances [32]. In another study focusing on the city center of Balıkesir as the study area, it was demonstrated that among meteorological parameters, wind speed and temperature exhibited the highest correlation coefficients concerning the variations in SO_2 and PM_{10} levels [33].

In a study conducted in Erzurum, various residential structures were examined in terms of emission rates and geographical variables triggering air pollution (pressure, altitude, wind, temperature) and physical variables (natural gas consumption, coal consumption and Sky View Factor), and recommendations related to residential structures were shared to mitigate pollution [34]. According to the results of the study examining the relationship between urban heat island and carbon monoxide concentration in three central districts of Konya, the urban heat island effect in the city has a positive correlation with carbon monoxide levels [35]. Investigating the influence of solar power plants on air pollution in Adıyaman province, researchers observed a notable correlation between air pollution levels and the energy efficiency derived from solar energy facilities [36].

Analyzing the impact of wildfires on air quality, researchers focused on Antalya, the most heavily affected province by wildfires in Türkiye in 2021. Comparing air quality data before and after the fire, the study concluded that the 2021 forest fire did not have a detrimental effect on air quality in Antalya and its vicinity [37].

Researchers examining the relationship between air quality and traffic through large-scale geographic data analysis have found that an increase in the number of vehicles passing through a point and a decrease in vehicle speeds due to traffic congestion result in an increase in Air Quality Index (AQI) value [44]. In another study, the European Green Deal has been evaluated in terms of air pollution caused by maritime transportation [38].

Ören and Kocabaş investigated the effect of vehicle inspection station location selection on carbon emissions in Zonguldak [39]. A research in Altınpark in Ankara found that tree and shrub canopy cover, as well as the variety and number of tree species present, significantly improves air quality [40]. A comparable study was undertaken for the Kuzguncuk Neighborhood of Istanbul, evaluating the quantity of removal of various air pollutants by tree-shrub cover and the economic contribution made by the removal of these pollutants [41].
There are certain factors influenced by air pollution. Many scholars are interested in the economic and social implications of pollution. Çetin and Bakırtaş examined the long-term effects of increased renewable energy supply on the welfare costs of air pollution-related premature deaths in Asia-Pacific Economic Cooperation (APEC) countries from 1990 to 2016 in their study. They found that the increase in renewable energy sources supply reduces the welfare costs of air pollution [42]. A research comparing the impacts of economic growth and environmental regulations on air pollution in Türkiye found that economic growth has a positive influence on air pollution, whilst the number of patents linked to environmental technologies has a negative effect on air pollution. The study also emphasizes the major influence of environmental rules on lowering air pollution in the short and medium term [43]. In their study, Özgür and Demirtaş stated that they could not find any significant effect of social capital on air pollution [45].

2.3. Air pollution and air quality prediction

The increasing data processing capacity of computers, combined with the integration of artificial intelligence technologies alongside statistical methods, has enabled faster and more accurate results with multidimensional data. A review study focusing on articles published worldwide from 1990 to 2021, which include keywords related to air pollution and machine learning, has been conducted. This study shows that research on air pollution using machine learning has drastically surged since 2017, as depicted in Figure 5. Furthermore, as reported in the same research, Türkiye is ranked 8th for the number of publications, placing it just behind the United Kingdom [46].

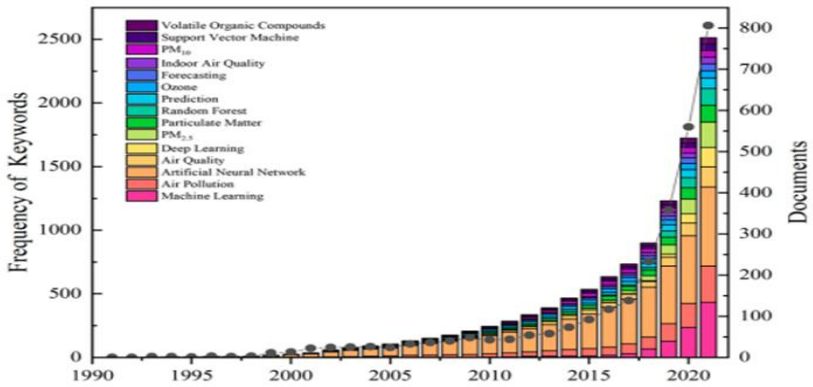

Figure 5. Trends in research on air pollution utilizing machine learning methods from 1990 to 2021 [46]

Between 2022 and 2023, 7 out of every 50 articles published on the DergiPark platform are on air pollution prediction or air quality indicators. One of the selected research regions is from another country, while the others are in Türkiye. Table 3 includes the study locations, pollutant characteristics utilized in the forecasts, projected pollutant information, meteorological data used in the predictions, and forecasting methodologies (Lognormal (LogD), Weibull (WD), and Gamma Distribution (GD), Multiple Linear Regression (MLR), Naive Bayes (NB), Decision Tree (DT), Deep Learning (DL), k-NN, Random Forest (RF), Artificial Neural Network (ANN), Support Vector Machines (SVM), k-NN, Logistic Regression (LR), Bagging, ANN, Multilayer Perceptron (MLPNN), Extreme Learning Machines (ELM)).

Table 3. Location-based analysis of pollutants, methodologies, and success criteria

Location	Pollutants	Other Data	Methods	Succes Criteria	Ref.
Van	PM_{10}	-	LogD, WD, GD	GD R^2: 0.9893	[47]
Ardahan, Kars, Erzurum, Iğdır	AQI	Meteorological data	MLR, NB, DT, DL, RF, k-NN	Accuracy Rates: MLR: 41.8%, NB: 68.91%, DT: 70.29%, DL: 73.05% k-NN: 73.35%, RF: 74.89%	[48]
Kocaeli	Seasonal PM_{10}, SO_2	Urbanization, industrialization, topography meteorological, and demographic data	MLR, ANN	For PM_{10} Best Model: ANN MAPE 4.91%-Spring For SO_2 Best Model: ANN MAPE: 21.76% Winter	[49]
USA	$PM_{2.5}$, PM_{10}, NO_2, O_3, CO, SO_2, AQI	Urbanization, transportation data	SVM, k-NN, NB, LR, RF, DT, Bagging, ANN	Best Model: 3-class models RF: 86.69% 5-class models RF: 81.61%	[50]
Başakşehir İstanbul	PM_{10}, CO, SO_2, NO, NO_2, NOx, O_3	Meteorological data	MLR, k-NN, SVM, RF, DT, MLPNN	Best Method: For PM_{10}, CO, SO_2, O_3 RF (MAPE: 0.28, 0.2, 0.418, 0.169 respectively) For NO_2 MLR (MAPE: 0.016)	[51]
Sıhhiye Ankara	PM_{10}, SO_2, CO, AQI	Meteorological data	ELM, ANN	AQI Classification Prediction Success Rate: ELM: 85.71% ANN: 71.43%	[52]
Beşiktaş İstanbul	$PM_{2.5}$, PM_{10}, NO_X, SO_2	Traffic density, and meteorological data	ANN, MLR, SVM, RF	Best Model: RF R^2: 0.675	[53]

The first paper on air pollution prediction chose Van province as its study region. The study focuses on Van province in Eastern Anatolia, Türkiye, and models PM_{10} levels, a crucial air pollutant, using lognormal,

Weibull, and Gamma distributions. The study also predicts PM_{10} concentrations that exceed legal limits, indicating that the Gamma distribution beat the other two in effectively modeling and predicting province-wide exceedances [47]. Akgün and Barlık examined several linear regression and machine learning algorithms (Deep Learning, K-Nearest Neighbors (k-NN), Naive Bayes, Decision Tree, Random Forest) to forecast air quality index in Ardahan, Kars, Erzurum, and Iğdır provinces. The Random Forest technique produced the highest accuracy in forecasting the Air Quality Index (AQI) [48]. In another study, artificial neural network and multiple linear regression approaches were used to forecast seasonal averages of PM_{10} and SO_2 levels in Kocaeli. The models drew on meteorological, pollution, urbanization, industrialization, topography, and demographic data. The study discovered that artificial neural networks beat multiple regression analysis in terms of performance [49]. Another study addressed the air quality classification problem by taking into account factors such as population, the quantity of concrete structures, green spaces, and transportation utilization ratios. Class assignments were based on the impact ratios of Air Quality Index (AQI) values on human health, which were divided into three categories (Good, Unhealthy, and Hazardous) and five categories (Good, Moderate, Unhealthy, Very Unhealthy, and Hazardous). The study used eight different classification algorithms (Bagging, Artificial Neural Networks Decision Trees, Logistic Regression, K-Nearest Neighbors (k-NN), Gauss Naive Bayes, Support Vector Machines and Random Forest) and found that the Random Forest algorithm produced the highest classification accuracy [50]. The Başakşehir area of Istanbul was used to forecast concentrations of NO_2, SO_2, CO, PM_{10}, and O_3 pollutants using Support Vector Machines, Multiple Linear Regression, K-Nearest Neighbors (k-NN), Random Forest, Multilayer Perceptron, and Decision Trees techniques. Notably, the Random Forest technique performed better in forecasting CO, SO_2, O_3, and PM_{10} concentrations than Multiple Linear Regression in predicting NO_2 [51]. A study used Artificial Neural Networks (ANN) and Extreme Learning Machines (ELM) algorithms to forecast the Air Quality Index (AQI) in Sıhhiye/Ankara. The results showed that the ELM algorithm outperformed the ANN algorithm in making more accurate predictions [52]. PM2.5 concentrations in Beşiktaş, Istanbul, were forecasted using various machine learning methods. While Random Forest achieved the highest accuracy on average, Multiple Linear Regression performed the worst [53].

2.4. Health implications of air pollution

Air pollution poses a significant threat to human health, with numerous studies linking exposure to harmful pollutants to a wide range of adverse health outcomes. Exposure to air pollutants such as $PM_{2.5}$, PM_{10}, SO_2, NOx, CO, and heavy metals has been linked to significant health risks, including respiratory issues [54], [55] and cognitive decline [56]. $PM_{2.5}$, in particular, has been associated with increased hypertension risk [57], adverse cardiovascular outcomes [58], and heightened cancer risk [54], [59] due to the presence of heavy metals. Airborne pollutants induce oxidative stress and inflammation, exacerbating conditions like asthma and contributing to chronic diseases that affect multiple organs [60]. Studies have also shown a connection between air pollution and increased mortality from respiratory and cardiovascular diseases [61].

Numerous research has been undertaken in Türkiye to investigate the relationship between air pollution and health, documenting the effects on major health indicators such as respiratory disorders, cardiovascular diseases, and mortality risk. During the research period, DergiPark published 7 research articles in Table 4 on the effects of air pollution on human health, the pollution-mortality relationship, and the cost of pollution-related health problems.

Table 4. Health impacts and health-related expenditures due to air pollution in Turkish cities and nationwide

Location	Pollutant	Findings	Ref.
Samsun	PM_{10}	Hospital admissions and hospitalizations increased by 1-3% for every 10 μg/m³ rise in PM_{10} levels.	[62]
Konya	$PM_{2.5}$	The study results show that premature deaths during the 3-year period could have been prevented if PM2.5 levels had stayed below 10 μg/m³.	[63]
Sakarya	NO_2	Increase in annual NO_2 concentrations in 2018 and 2019 led to a rise in mortality attributable to NO_2 for the age group of 30 and older.	[64]
Ankara	$PM_{2.5}$, PM_{10}	Calculations with $PM_{2.5}$ and PM_{10} did not show an effect of particulate air pollution on infant deaths in the first week.	[65]
Türkiye	SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, non-methane volatile organic compound (VOC)	The health costs arising from air pollution in Türkiye are estimated to be at least 25,845 million TL and up to 52,492 million TL.	[66]
Türkiye	PM_{10}	An increase of 1% in economic growth boosts healthcare spending by 2.018%, while a 1% rise in transportation-related air pollution increases costs by 0.266%.	[67]
Türkiye	PM_{10}	Results indicate that air pollution and mobile subscriptions do not affect healthcare spending, while internet subscriptions and index variables negatively impact costs.	[68]

A study conducted in Samsun Province found that a 10 μg/m³ increase in PM10 levels resulted in a 3% rise in respiratory system diseases, a 2% rise in cardiovascular diseases, a 1% rise in neurological and psychiatric diseases, and a 2% rise in respiratory system hospitalizations [62]. Two additional studies focusing on Konya and Sakarya revealed that air pollution increases mortality [63, 64]. Another study examined the association between particle air pollution and newborn mortality [65].

There are three studies looking at the health costs of air pollution from diverse angles. One study estimated that the health cost of air pollution in Türkiye ranged from 25.845 million TL to 52.492 million TL [66]. Another study discovered that a 1% increase in air pollution from mobility resulted in an increase in health expenses ranging from 0.266% to 0.381% [67]. In a study of the impact of Information and Communication Technologies (ICT) on health expenditures related to air pollution, it was demonstrated that air pollution and the number of mobile phone subscribers had no significant impact on health expenditures, whereas the number of internet subscribers and index variables had a negative impact on health expenditures [68].

2.5. COVID-19 pandemic and its influence on air quality

The COVID-19 epidemic, which has swept the planet since 2020, has provided new opportunities for researchers to evaluate the regional and global influence of human activities on air quality. The pandemic's restrictions on outdoor activities have resulted in major changes in pollution levels in the atmosphere. Numerous studies have been undertaken to assess the improvement in air quality when human intervention is reduced [69], [70]. Following numerous studies conducted worldwide on the effects of COVID-19, many studies have also been carried out in Türkiye during this period, and the findings summarized in Table 5 highlight the significant impacts of the pandemic on air pollutants in various regions.

Table 5. Impact of COVID-19 on Air Pollutants in Türkiye

Location	Pollutant	Findings	Ref.
Adana, Ankara, Antalya, Denizli, Edirne, Erzurum, Istanbul, Izmir, Kayseri, Kocaeli, Trabzon, Zonguldak	PM_{10}, NO_2, SO_2, CO, O_3	PM_{10}, NO_2, and SO_2 levels dropped by up to 75-80%, while CO and O_3 concentrations increased in many cities.	[71]
78 provinces including Ankara, Istanbul, Izmir	PM_{10}, SO_2	Based on population density, 87.6% and 70.2% of Türkiye's population benefited from reductions in PM_{10} and SO_2 levels, respectively.	[72]
31 Turkish provinces	PM_{10}, O_3, NO_2, SO_2	There was no significant change in SO_2, limited improvement in PM_{10}, a general decrease in O_3, and an overall increase in NO_2 levels.	[73]
Adana	SO_2, CO, NOx, NO, NO_2, O_3	The COVID-19 measures led to decreases of 0.35% in PM_{10}, 23.6% in SO_2, 84% in CO, 46.5% in NOx, 34.5% in NO, 63.1% in NO_2, and 68.4% in O_3 concentrations.	[74]
Şile Istanbul	PM_{10}	PM_{10} concentrations in Şile increased by approximately 16.90%	[75]
Adana, Mersin	NO_2	Industrial and commercial areas have the highest NO_2 concentrations, with Adana generally showing higher levels than Mersin, and significant decreases in NO_2 during COVID-19 lockdowns were observed across both cities.	[76]
Marmara Region	NO_2	Tropospheric NO_2 in the Marmara Region was analyzed using Sentinel-5P images, confirming its effectiveness in monitoring air pollution with a high correlation (r=0.85) to ground data.	[77]

Significant reductions in PM_{10}, NO_2, and SO_2 concentrations were recorded in an article that covered cities such as Adana, Ankara, Antalya, Denizli, Edirne, Erzurum, Istanbul, Izmir, Kayseri, Kocaeli, Trabzon, and Zonguldak. However, the same study discovered an increase in O_3 and CO concentrations in some cities, which was linked to meteorological conditions impacting secondary air pollutants formed by the oxidation of primary pollutants [71]. A study of 78 provinces, including Ankara, Istanbul, and Izmir, assessed the favorable impact of lower PM_{10} and SO_2 levels during the epidemic as a proportion of Türkiye's entire population. The computed ratios for the population in areas positively affected by the reduction are 87.6% for PM_{10} and 70.2% for SO_2 [72]. Yıkıcı and Ünal found that COVID-related actions improved air quality in 31 Turkish provinces [73]. A research done for the province of Adana also yielded similar results [74]. During the pandemic-related restrictions, the rise in PM_{10} concentrations in the Şile (İstanbul) district was linked to traffic and human movement driven by migration from neighboring areas [75]. Another study used satellite images from the COVID-19 period to investigate the association between air quality and pandemic measures in the cities of Adana and Mersin. In particular, higher tropospheric NO2 concentrations were found in industrial and commercial areas [76]. An analysis of Sentinel-5P satellite images from the Marmara Region during Türkiye's COVID-19 pandemic emergency measures revealed that a decrease in NO2 concentrations was associated with reduced fossil fuel use [77].

2.6. Other studies and review articles

The various studies and review articles on air pollution in Türkiye, summarized in Table 6, highlight significant findings and contributions to the understanding of this critical issue.

Tablo 6. Other studies and review articles on air pollution in Türkiye

Article Type	Topic	Details	Ref.
Research Article	Air Pollution Survey	Investigated university students' perceptions of air pollution in Eastern Anatolia; significant effects from study field, father's education/profession, and monthly expenditure on health opinions.	[78]
Review Article	Impact of Air Pollution on Health in Türkiye	Examines national studies on air pollution's health impact and changes during the COVID-19 pandemic.	[79]
Review Article	Municipal Approaches to Climate and Air Quality	The evolving roles of municipalities in Türkiye, particularly in Bursa, emphasize the necessity for enhanced funding and strategies to combat climate change and air pollution.	[80]
Review Article	Link Between Air Pollution and COVID-19	The review highlights the potential roles of particulate matter (PM) in COVID-19 transmission, inflammation, and oxidative stress, alongside the impacts of air pollutants like NO2 and O3, and the effects of lockdown measures on air quality.	[81]

In addition to articles organized by topic, one article reports on the findings of an air pollution survey. The survey was undertaken with university students studying in the Eastern Anatolia Region to investigate their perceptions of air pollution. Researchers discovered that students' primary field of study, father's educational level/profession, and monthly expenditure all had a statistically significant effect on their opinion of air pollution's negative impact on health [78].

Three publications were screened as review articles for DergiPark. The first review article examines many national studies on the impact of air pollution on health in Türkiye. Furthermore, the publication includes studies that assess the changes and impacts of outdoor air pollution during the COVID-19 pandemic [79]. Another review article explores the changing roles and new responsibilities of municipalities in Türkiye from the Republic period to the present, examining environmental protection and climate change reduction, adaptation, and waste goals within the budgets of municipalities, with a specific focus on the Bursa Metropolitan Municipality from 2018 to 2022 [80]. In the final paper, the authors synthesize research from multiple sources without regard to year, investigating the link between air pollution and COVID-19 [81].

3. Conclusions

This comprehensive review of recent air pollution and air quality research in Türkiye, spanning 2022 to 2023, reveals significant progress in understanding the complexities of air pollution dynamics while highlighting persistent challenges and areas requiring further investigation.

The synthesis of studies from various regions of Türkiye provides a multifaceted perspective on air quality issues, encompassing temporal and spatial variations, influential parameters, prediction models, health impacts, and the unprecedented effects of the COVID-19 pandemic. This body of research underscores the intricate interplay between air pollution and factors such as meteorology, urbanization, industrial activities, and natural phenomena like wildfires.

Several key findings emerge from this analysis. Persistent exceedances of regulatory limits for various pollutants, particularly PM_{10} and SO_2, in multiple Turkish cities indicate an ongoing public health concern. The significant influence of meteorological conditions, seasonal variations, and local topography on pollutant concentrations and dispersion patterns is evident. There is a growing application of advanced statistical methods, machine learning algorithms, and remote sensing techniques in air quality assessment and prediction. The complex relationship between air pollution and human health is becoming clearer, with emerging evidence linking poor air quality to various health outcomes. The temporary improvement in air quality during COVID-19 lockdowns provided valuable insights into the potential for rapid air quality changes under reduced anthropogenic activities.

However, this review also illuminates critical gaps in current research and areas requiring further attention. Long-term epidemiological studies investigating the chronic health effects of air pollution exposure, particularly on vulnerable populations, are needed. Comprehensive assessments of the effectiveness of current air quality regulations and policy interventions are essential. In-depth exploration of the intricate

relationships between air pollution, climate change, and urban development is crucial. The development of more accurate, high-resolution air quality prediction models integrating multiple data sources and advanced AI techniques should be prioritized. Investigation of innovative pollution control technologies and sustainable urban planning strategies to mitigate air pollution in rapidly growing cities is necessary. Expansion of air quality monitoring networks to cover a broader range of pollutants, including emerging contaminants of concern, would provide more comprehensive data.

As Türkiye continues to grapple with air quality challenges while striving to meet its commitments to the United Nations Sustainable Development Goals, the role of rigorous scientific research becomes increasingly crucial. This review underscores the need for sustained, interdisciplinary research efforts to inform evidence-based policies, enhance public awareness, and ultimately improve air quality and public health across the nation.
Future research should focus on addressing these identified gaps, fostering collaborations between academic institutions, government agencies, and international partners. Moreover, efforts should be made to translate research findings into actionable policies and public health interventions. By building on the foundation of knowledge synthesized in this review, researchers and policymakers can work towards a future where clean air is a reality for all citizens of Türkiye, contributing to improved public health, environmental sustainability, and overall quality of life.

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5. Author contribution statement

Author 1 contributed to the writing of the original draft, methodology, visualization. Author 2, conceptualized the study and was involved in writing, reviewing and editing.

6. Ethics Committee Approval and Conflict of Interest

There is no conflict of interest with any person/institution in the prepared article.

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