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Traffic-Impacted Soils Containing Oil and Grease and PAHs: Distance-Based Monitoring, PAH Cancer Risk Assessment, and Source Apportionment

Melike Büşra BAYRAMOĞLU KARŞI1[1]✍
[1]Innovative Food Technologies Development Application and Research Center (YENIGIDAM), Bolu Abant Izzet Baysal University, 14030 Bolu, Türkiye
[1]https://orcid.org/0000-0003-3162-8119-0000
✉: melikebayramoglu@ibu.edu.tr

ABSTRACT

In this study, surface soil samples were collected from agricultural land located in the Bolu region along the D-100 highway—which connects Turkey's populous cities, Istanbul and Ankara—at distances ranging from 0 to 100 meters from the road. Measurements of oil and grease (OG) and dissolved organic carbon (DOC) were conducted, and the concentrations, distribution, sources, and potential health risks of polycyclic aromatic hydrocarbons (PAHs) were assessed. The results showed that OG concentrations ranged from 259.04 to 910.80 μg kg^{-1} dry weight (dw), with the highest values detected at the roadside and the lowest at 100 meters away, reflecting the direct impact of vehicle-related pollution. DOC concentrations varied between 43.68 and 105.98 mg kg^{-1} dw, but no statistically significant relationship with distance was found, suggesting that DOC may have been transported across and beyond the area by factors such as rainwater and runoff. Total PAH concentrations were measured between 123.30 and 606.50 ng g^{-1} dw and exhibited a strong negative correlation with distance (r=–0.85, p<.05), confirming that PAH sources are predominantly linked to traffic activities. Source analysis using isomer ratios indicated that PAH contamination largely originated from diesel and liquid fossil fuel combustion. Lifetime incremental cancer risk (ILCR) assessment revealed that exposure to these soils poses a significant health risk for all population groups (ILCR>10^{-4}). This study highlights the significant impact of highway traffic on surface soil pollution and emphasizes the importance of regular monitoring of roadside soils to implement necessary measures aimed at reducing environmental and human health risks.

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Trafikten Etkilenmiş Topraklarda Yağ ve Gres ile PAH'lar: Mesafeye Dayalı İzleme, PAH Kaynaklı Kanser Riski Değerlendirmesi ve Kaynak Belirleme

ÖZET

Bu çalışmada, Türkiye'nin en kalabalık iki şehri olan İstanbul ve Ankara'yı birbirine bağlayan D-100 karayolu güzergâhında, Bolu bölgesinde yer alan tarım arazilerinden yüzey toprak örnekleri toplanmıştır. Örnekler yoldan itibaren 0 ila 100 metre mesafeler arasında alınmıştır. Toprak örneklerinde yağ ve gres (OG) ile çözünmüş organik karbon (DOC) ölçümleri gerçekleştirilmiş; polisiklik aromatik hidrokarbonların (PAH'lar) ise konsantrasyonları, dağılımları, kaynakları ve potansiyel sağlık riskleri değerlendirilmiştir. Elde edilen sonuçlara göre OG konsantrasyonları kuru ağırlık (ka) başına 259,04 ile 910,80 μg kg^{-1} arasında değişmekte olup, en yüksek değerler yol kenarında, en düşük değerler ise 100 metre uzaklıkta tespit edilmiştir. Bu durum, araç kaynaklı kirliliğin doğrudan etkisini yansıtmaktadır. DOC konsantrasyonları 43,68 ile 105,98 mg kg^{-1} ka arasında değişmekle birlikte mesafe ile istatistiksel olarak anlamlı bir ilişki göstermemiştir. Bu durum, DOC'nin yağmur suyu ve yüzey akışı gibi çevresel etkenlerle alan boyunca taşınmış olabileceğini düşündürmektedir. Toplam PAH konsantrasyonları

Toprak bilimi

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Anahtar Kelimeler
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Polisiklik aromatic hidrokarbon
Yağ gres
Trafik emisyonu
Risk değerlendirmesi

123,30 ile 606,50 ng g^{-1} ka arasında ölçülmüş ve mesafe ile güçlü negatif korelasyon göstermiştir (r=–0,85, p<,05). Bu bulgu, PAH kaynaklarının büyük ölçüde trafik faaliyetleriyle ilişkili olduğunu doğrulamaktadır. İzomer oranlarına dayalı kaynak analizleri, PAH kirliliğinin ağırlıklı olarak dizel ve sıvı fosil yakıtların yanmasından kaynaklandığını ortaya koymuştur. Yaşam boyu artan kanser riski (ILCR) değerlendirmesi, bu topraklara maruz kalmanın tüm nüfus grupları için önemli düzeyde sağlık riski oluşturduğunu göstermiştir (ILCR>10^{-4}). Bu çalışma, karayolu trafiğinin yüzey toprağı kirliliği üzerindeki önemli etkisini ortaya koymakta ve çevresel ve insan sağlığı risklerini azaltmaya yönelik gerekli önlemlerin alınabilmesi için yol kenarı topraklarının düzenli olarak izlenmesinin önemini vurgulamaktadır.

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INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs), composed of two or more fused aromatic rings of carbon and hydrogen, are organic contaminants of significant environmental concern due to their carcinogenic potential and widespread presence in the environment. Owing to their persistent and hydrophobic nature, PAHs tend to accumulate in soils, where they can remain for extended periods, making soils a primary environmental reservoir and a critical indicator of both pollution levels and potential human exposure (Wang et al., 2013; Dikmen et al., 2020). Human exposure to PAHs primarily occurs through the inhalation of contaminated air and tobacco smoke, ingestion of polluted water and smoked foods, direct contact with contaminated soils, and dermal absorption from substances such as soot, tar, and oil (Agarwahl, 2009). Consequently, investigating PAH contamination in soils is essential for mitigating associated environmental and health risks.

Total Petroleum Hydrocarbons (TPH) are used not only to classify aliphatic hydrocarbon substances but also to collectively describe a vast array of chemical compounds—numbering in the hundreds—originating from crude oil (Almeida et al., 2013). The concept of OG encompasses a range of non-polar compounds, including both naturally occurring fatty substances and those synthesized from petrochemical sources (Banan Khorshid et al., 2021). When these compounds enter surface or groundwater systems, they can contribute to environmental degradation and create significant risks to public health (Farmaki et al., 2007). Following the release of petroleum and its refined products into the environment, numerous chemical, physical, and biological processes act to alter their composition, toxicity, and bioavailability (Sun et al., 2021). Petroleum hydrocarbon contamination in soils represents a major ecological concern due to its harmful impacts on the soil's biological activity, chemical composition, and physical structure (Azmi et al., 2024). Despite their environmental significance, OG and TPH compounds have often been underrepresented in integrated traffic-related soil pollution studies, especially in agricultural contexts. In this study, the inclusion of OG alongside polycyclic aromatic hydrocarbons (PAHs) aims to provide a broader assessment of petroleum-derived pollution in roadside soils.

Numerous studies in the literature have investigated particulate-phase PAHs in urban polluted areas and near heavily trafficked roads (Pandey et al., 1999; Kume et al., 2007; Jiang et al., 2009; Singh et al., 2011). High-traffic land uses, such as highways, are recognized for releasing higher amounts of OG compared to lower-traffic areas like residential zones. The roadside agricultural soil system serves as a significant reservoir for PAHs, posing risks to agriculture and food safety through plant uptake and subsequently to human health via transfer through the food chain. Accurately identifying PAH sources in agricultural soils is essential for reducing PAH pollution along road networks. To date, numerous studies have conducted source apportionment of soil PAHs using qualitative or semi-quantitative methods such as diagnostic ratios, multivariate statistical analyses, and positive matrix factorization (PMF) receptor models (Li et al., 2016; Suman et al., 2016; Zhang and Chen, 2017). Examining PAH and OG concentrations in soils of roadside agricultural lands is also of significant importance.

In this study, surface soil samples were collected from agricultural land located in the Bolu region along the D-100 highway, which connects Turkey's two most populous cities, Istanbul and Ankara, at distances ranging from 0 to 100 meters from the road. The aim was to investigate the impact of highway traffic on soil quality. Concentrations of contaminants such as OG, dissolved organic carbon (DOC), and PAHs were measured, and their distribution,

sources, and potential health risks were analyzed. Additionally, statistical methods were used to examine correlations between contaminants relative to their distance from the road. Although previous studies have examined traffic-related soil pollution in urban and industrial areas, there is limited research focusing specifically on roadside agricultural soils in Türkiye, especially with an integrated assessment of OG, DOC, and PAHs combined with health risk evaluation. This study aims to fill this gap by providing distance-based contamination data and assessing pollutant sources using isomeric ratios, along with the potential human health risks using incremental lifetime cancer risk (ILCR) calculations. The primary objective of this study is to determine the effects of traffic-related pollution on agricultural soils and to assess the associated environmental and human health risks.

MATERIAL and METHOD

Sampling site and sample collection

Bolu, located in the northwestern part of Türkiye at an elevation of 730 meters above sea level (Fig. 1), is surrounded by high-altitude mountains that promote stagnant air over the urban area; combined with limited wind activity, low mixing heights sometimes dropping to 150 meters, and frequent temperature inversions during colder months, these conditions make the city highly vulnerable to severe air pollution (Bayramoğlu Karşı et al., 2018). The city is surrounded by high-altitude mountain ranges, which restrict atmospheric circulation and contribute to air stagnation over the urban area. Minimal wind movement, shallow atmospheric mixing layers—sometimes as low as 150 meters—and frequent temperature inversions during colder periods make the region particularly vulnerable to significant air pollution events (Bayramoğlu Karşı et al., 2018).

In Bolu, despite the relatively limited industrial activity, the main sources of pollution are major international transportation routes like the TEM and D-100 highways, combined with urban traffic and residential heating. Although Bolu has relatively limited industrial activity, major pollution sources include heavy traffic from international transport corridors such as the TEM and D-100 highways, along with emissions from residential heating, of which approximately 50% relies on natural gas, 45% on coal, and 5% on fuel oil and LPG (Bayramoğlu Karşı et al., 2018).

Figure 1. Sampling site
Şekil 1. Örnekleme alanı

In this study, surface soil samples were collected from the vicinity of Çivril in Bolu Province, located along the D-100 highway — a major transportation corridor connecting Türkiye's two most populous cities, Istanbul (nearly 16 million people) and Ankara (approximately 6 million people) (TUIK, 2024). Surface soil samples were taken from the 0–10 cm layer at distances of 0, 2.5, 5, 7.5, 10, 25, 50, and 100 meters from the roadside, with three replicate samples collected at each distance. Since pollutant concentrations are generally higher near roadways and tend to decrease with increasing distance, shorter intervals were selected for locations closer to the road to better capture the contamination gradient. The selection of distances also considered the specific characteristics of the study area, which extended up to 100 meters from the roadside—beyond which another agricultural field began. To minimize the risk of environmental contamination, the samples were initially wrapped in aluminium foil, placed in labelled polyethylene zip-lock bags, and transported to the laboratory. For comparative purposes, a reference sample was collected from an agricultural area far from traffic (40.7731862 N, 31.7039033 E) and direct pollution sources, and subjected to the same OG, DOC, and PAH analyses as the roadside samples.

Upon arrival at the laboratory, the samples were first cleaned of coarse debris such as litter, stones, and cigarette butts. They were then sieved through 1 mm mesh sieves, and the material passing through the sieve was retained. All subsequent analyses and experimental procedures were conducted using these sieved samples.

Chemicals and reagents

All reagents used were of analytical grade or higher and obtained from Sigma Aldrich. Sixteen PAH mix standard compounds, PAH-mix-9, containing 10 ng/µl individual PAH compounds, namely, Naphthalene (NaP), Acenaphthylene (Ace), Acenaphthene (Acy), Fluorene (Flr), Phenanthrene (Phe), Anthracene (Ant), Fluoranthene (Flu), Pyrene (Py), Benz(a)anthracene (BaA), Chrysene (Chr), Benzo(b)fluoranthene (BbF), Benzo(k)fluoranthene (BkF), Benzo(a)pyrene (BaP), Dibenz(a,h)anthracene (DahA), Benzo(g,h, i)perylene (BghiP), and Indeno(1,2,3-cd)pyrene (IcP) was obtained from Dr. Ehrenstorfer (GmbH). All the standard solutions were stored in amber glass vials at -20 ^{o}C.

OG analysis with Fourier Transform Infra-Red Spectroscopy (FT-IR)

Analyses were conducted by using Shimadzu IR Prestige21 Fourier Transform Infrared Spectroscopy with a 1 cm path length quartz cuvette, and IR solutions software. The FT-IR method was selected due to two main reasons: first, it requires less solvent and provides faster analysis compared to traditional solvent extraction methods; second, it enables the use of environmentally friendly alternative solvents instead of hazardous ones like Freon 113. All the FT-IR measurements were performed at a resolution of 8 cm-1, apodization Happ-Genzel, scan range 2700-3200 cm^{-1}, and number of scans 20. For sample analysis, approximately 15 grams of soil samples were placed into a 50 mL centrifuge tube for the determination of oil and grease contents. Subsequently, 2 g of anhydrous granular sodium sulfate (Na_2SO_4) and 20 mL of tetrachloroethylene (C_2Cl_4) were added on top and then vortexed for 2 minutes. 2.5 mL of 50% sulphuric acid (H_2SO_4) was added and then again vortexed for 2 minutes. The samples were kept in an ultrasonic bath at 50°C for 1 hour. After each specified time interval, the samples were centrifuged (Isolab Laborgeraete GmbH) at 5000 rpm for 6 minutes. After that, the C_2Cl_4 phase, extracted from the samples using a syringe, was placed in sealed glass bottles to await FT-IR analysis. The samples were kept in the dark at +4°C until analysis. Before analysis, the samples were allowed to stand at room temperature, and the quantitative analyses were conducted using the maximum peak height values between 3020-2800 cm^{-1} for both standards and samples (Bayramoğlu Karşı, 2014). The OG calibration standards were prepared using a mixture of isooctane and octanoic acid. Specifically, 0.72 mL of isooctane and 0.55 mL of octanoic acid were combined and diluted to a final volume of 10 mL with C_2Cl_4, yielding a stock solution with a concentration of 100 mg/mL. Calibration solutions ranging from 25 to 350 ppm were then prepared by appropriate dilution of this stock solution. The standard deviation of the peak heights at the lowest calibration level (25 ppm) was calculated. The limit of detection (LOD) was determined as 2.36 ppm by multiplying the standard deviation by 3, while the limit of quantification (LOQ) was calculated as 7.87 ppm by multiplying it by 10. Additionally, the method detection limit was determined as 4.72 ppm, and the method quantification limit was calculated as 15.75 ppm.

Dissolved organic carbon (DOC) analysis with a total organic carbon analyzer

Approximately 15 grams of sample were weighed into 50 mL centrifuge tubes with caps, and 30 mL of deionized water was added. The tubes were shaken for 2 hours using a New Brunswick Excella E24R model shaking incubator. Subsequently, the samples were centrifuged (Hettich Rotanta 460R, Germany) at 900 rpm at 20°C for 30 minutes, and the supernatant was decanted. The filtration was passed through Macherey-Nagel MN64 DE filters (110 mm diameter) and transferred into the containers of a Teledyne Tekmar (USA) Lotix TOC analyzer. These samples were designated as water-extractable organic carbon (WEOC) first. The entire procedure was then repeated from the beginning, and the resulting samples were designated as WEOC second. A similar extraction procedure was performed on the same samples using 25 mL of 0.125 M sodium pyrophosphate solution, adjusted to pH 5.0, as the extraction solution. The subsequent processing steps were identical, and the resulting samples were designated as pyrophosphate-extractable organic carbon (PEOC) (Erich et al., 2012). The behavior and environmental fate of hazardous persistent organic pollutants (POPs) are strongly influenced by both soil organic matter (SOM) and climatic conditions (Wilcke and Amelung, 2000). Dissolved organic carbon (DOC) analysis was conducted by subjecting each soil sample to a sequential three-step extraction protocol (Erich et al., 2012). The first extraction (WEOC-1), using deionized water, targeted the most labile fraction of soil organic matter (SOM) which is composed of a complex and heterogeneous assemblage of low-molecular-weight compounds that are highly bioavailable and are known to play critical roles in ecological processes such as nutrient mobilization, metal transport, and carbon cycling (Zsolnay, 1996; Chantigny, 2003). The second extraction (WEOC-2) aimed to recover a less mobile, water-soluble organic fraction, which is more tightly bound to soil particles and thus less readily available for microbial activity or leaching. In the third step, a pyrophosphate solution (PYRO) was applied to

release DOC complexed with aluminum and iron oxides, which are commonly associated with organo-mineral interactions in soil systems (Schnitzer & Schuppli, 1898; Wattel-Koekkoek et al., 2001). This stepwise approach provides a more detailed characterization of DOC pools with differing mobilities and ecological functions.

PAHs with high-performance liquid chromatography (HPLC-DAD)

For the determination of PAHs, approximately 25 g of soil was placed into capped centrifuge tubes, followed by the addition of 20 mL of tetrahydrofuran (THF). The samples were vortexed for 2 minutes to ensure thorough mixing and then subjected to shaking in a Wise Stir WSB-18 shaking water bath (DAIHAN Scientific, Daegu Gyeongbuk Branch Co., Ltd.) at 40°C and 150 rpm for 2 hours. After extraction, the samples were centrifuged at 4000 rpm for 6 minutes using an Isolab centrifuge (ISOLAB Laborgeräte GmbH), and the supernatant was carefully transferred into screw-capped glass test tubes. The solvent was evaporated using a nitrogen evaporator until the final volume was reduced to 1–3 mL.

A clean-up procedure was then applied to purify the extracts. For this step, glass wool (previously washed and dried with n-hexane) was packed at the bottom of a 1 cm diameter column, followed by 2 g of silica gel and 1 g of anhydrous Na_2SO_4. The column was sequentially rinsed with 15 mL of n-hexane and 15 mL of dichloromethane (DCM). The concentrated sample was then loaded onto the column, eluted with 4 mL of n-hexane, and further washed with 6 mL of a 1:1 n-hexane/DCM mixture to collect the PAH fraction. The eluates were further concentrated to approximately 1–2 mL using a nitrogen evaporator and transferred into amber vials. Subsequently, 50 µL of dimethylformamide (DMF) was added to each sample, followed by vortexing for 30 seconds to ensure complete dissolution of the PAHs in DMF. The samples were then evaporated under high-purity nitrogen gas to near dryness (approximately 50 µL, matching the DMF volume added). Finally, the volume was adjusted to 1 mL by adding 950 µL of acetonitrile, vortexed again for 30 seconds, and stored at +4°C until analysis (Karakaş and Pekey, 2005).

The analysis of polycyclic aromatic hydrocarbons was performed using a Shimadzu LC Prominence model high-performance liquid chromatography system, equipped with a diode array detector (DAD). The HPLC system consisted of the following components: DGU-20A5 degasser, LC-20AD pump, SIL-20AHT autosampler, CTO-20A column oven, SPD-M20A diode array detector. High-performance liquid chromatography with diode array detection (HPLC-DAD) was selected for PAH analysis due to its proven sensitivity, suitability for complex environmental matrices, and availability within our laboratory facilities. For the analytical conditions, a modified method based on Gratz et al. (2011) was used. HPLC analyses were performed using an ACE HPLC column with a C18 stationary phase (250 × 4.6 mm i.d.) as the analytical column. The flow rate was set at 1.3 mL/min, and the injection volume was 10 µL. The mobile phase consisted of acetonitrile (ACN) and water (H_2O), with the following gradient program: 0–13.39 min: ACN:H_2O (60:40), 13.40–18.74 min: ACN:H_2O (90:0), 18.75–28.00 min: ACN:H_2O (100:0), 28.01–32.00 min: ACN:H_2O (60:40).

The calibration standards were prepared using a PAH mix at concentrations of 62.5, 125, 250, 500, and 1000 ppb. The method detection limit (MDL) was calculated as three times the standard deviation of the lowest calibration standard, while the method quantification limit (LOQ) was calculated as ten times this standard deviation. Both MDL and LOQ values were expressed in the same units as the analytical results obtained from the method (Bayramoğlu Karşı, 2025).

Isomer ratios

For all samples, the sources of PAH compounds were determined using diagnostic ratios reported in the literature, including BaP/BghiP, BbF/BkF, Flu/(Flu+Py), IcP/(IcP+bghiP), BaA/(BaA+Chr), and LMW/HMW (low molecular weight PAHs/high molecular weight PAHs). The specific ratios applied are summarized in Table 2 (Akyüz & Çubuk, 2010; Oliveira et al., 2011; Zhang et al., 2008; Katsoyiannis et al., 2007).

Risk assessment

Incremental Lifetime Cancer Risk (ILCR), which quantifies the increased probability of developing cancer due to exposure to potentially carcinogenic chemicals, was applied in this study to assess the exposure risk of environmental PAHs, following the standardized models established by the United States Environmental Protection Agency (USEPA, 2006). The assessed population was divided into six groups according to age and gender: children (2–15 years), adolescents (15–24 years), and adults (24–74 years), with each age group further subdivided into male and female cohorts. The measured concentrations of BaP, as well as the toxicity equivalent concentrations (TEQs), were calculated using the following equation:

$$TEQs = \sum C_i \, x \, TEF_i \qquad \text{(Eq. 1)}$$

where Ci represents the concentration of the ith target PAH, and $TEFi$ is the toxic equivalency factor assigned to the ith compound. For BaP, the TEF is set to 1 (Yu et al., 2008). In the context of soil systems, three primary pathways of human exposure to BaP are considered: ingestion of BaP via contaminated plants, inhalation of BaP present in the air, and ingestion, dermal contact, and inhalation of BaP directly from soil.

Table 1. Linearity, method detection limit, limit of quantification for the 16 PAH compounds.
Çizelge 1. 16 PAH bileşiği için doğrusallık, yöntem tespit sınırı ve kantitasyon sınırı.

	Linearity R^2	*MDL (ng g^{-1})*	*LOQ (µg L^{-1})*
NaP	0.9973	4.33	22.10
Ace	0.9979	15.16	20.89
Acy	0.9995	20.41	22.31
Flr	0.999	7.49	11.42
Phe	0.9995	35.75	36.96
Ant	0.9984	8.90	16.21
Flu	0.9983	9.55	15.29
Py	0.9972	2.86	42.00
BaA	0.999	7.52	8.71
Chr	0.9964	2.05	5.47
BbF	0.9992	5.14	6.74
BkF	0.9989	10.31	14.57
BaP	0.999	14.70	27.95
DahA	0.997	3.88	34.36
BghiP	0.999	5.83	9.51
IcP	0.9984	3.20	18.76

Table 2. Diagnostic ratios used in the study.
Çizelge 2. Çalışmada kullanılan diagnostik oranlar

BaP/BghiP	<0.6	non traffic	Katsoyiannis et al., 2007
	>0.6	traffic	
BbF/BkF	>0.5	diesel	Oliveira et al., 2011
	0.22-0.55	gasoline	
Flu/(Flu+Py)	0-0.4	petroleum	Akyüz & Çubuk, 2010
	0.4-0.6	liquid fossil fuel	
IcP/(IcP+BghiP)	0.35-0.7	diesel	Oliveira et al., 2011
BaA/(BaA+Chr)	0.35-0.68	diesel	Oliveira et al., 2011
LMW/HMW	<1	pyrogenic	Zhang et al., 2008
	>1	petrogenic	

The variables used in the risk assessment are defined as follows:

CS: concentration of PAHs in soil (mg kg^{-1}), corresponding to the TEQ value of PAHs in soil (ng g^{-1}); CSF: carcinogenic slope factor for various exposure routes (mg kg^{-1} day^{-1});BW: body weight of the exposed individual childhood male 21.4, female 20.55; adolescence male 71.1, female 58.4; adulthood male 80.8, female 71.7 kg; AT: average lifetime, 70 years; EF: exposure frequency, 350 days $year^{-1}$; ED: exposure duration 2 years for childhood, 7 years for adolescence and adults; IRinhalation: inhalation rate 5 m^3/day for childhood, 20 m^3 day^{-1} for adolescence and adults; IRsoil: soil ingestion rate 114 mg day^{-1}; SA: dermal contact surface area 1800 cm^2 day^{-1} for childhood and adolescence, 5000 cm^2 day^{-1} for adults; AF: dermal adherence factor 0.2 mg cm^{-2} for childhood, 0.07 mg cm^{-2} for adolescence and adults; ABS: dermal absorption fraction, 0.13 (dimensionless); PEF: particle emission factor 1.36x109 m^3 kg^{-1}; CSFingestion, CSFdermal, CSFinhalation: carcinogenic slope factors for ingestion, dermal, and inhalation exposures to BaP; 7.3, 25 and 3.85 (mg kg^{-1} day^{-1}) respectively (USEPA, 1996; CHSA, 2006; Peng et al., 2011; TUIK, 2022).

$$ILCR_{Soilingestion} = \frac{TEQs\ x \left(CSF_{ingestion}\ x \sqrt[3]{\frac{BW}{70}} \right) x\ IR_{soil}\ x\ EF\ x\ ED}{BW\ x\ AT\ x\ 10^6} \qquad (Eq.\ 2)$$

$$ILCR_{Soildermal} = \frac{TEQs\ x\ \left(CSF_{dermal}\ x\ \sqrt[3]{\frac{BW}{70}} \right) x\ SA\ x\ AF\ x\ ABS\ x\ EF\ x\ ED}{BW\ x\ AT\ x\ 10^{6}} \quad (Eq.3)$$

$$ILCR_{Soilinhalation} = \frac{TEQs\ x\ \left(CSF_{inhalation}\ x\ \sqrt[3]{\frac{BW}{70}} \right) x\ IR_{air}\ x\ EF\ x\ ED}{BW\ x\ AT\ x\ PEF} \quad (Eq.4)$$

$$ILCR_{Soil} = ILCR_{Soilingestion} + ILCR_{Soildermal} + ILCR_{Soilinhalation} \quad (Eq.5)$$

Statistical analysis

Statistical analyses were conducted using Statgraphics Centurion XV V.15.2.11 software, encompassing correlation assessments and hypothesis testing. The choice of statistical tests—including independent samples t-tests, one-way analysis of variance (ANOVA), and Pearson correlation analyses—was guided by the distributional characteristics of the data. Pearson correlation analyses were employed to evaluate relationships among the measured pollutants as well as to investigate interrelationships among individual polycyclic aromatic hydrocarbons (PAHs). The influence of distance from the roadside on pollutant concentrations was rigorously assessed through one-way ANOVA. A significance threshold of 0.05 was maintained throughout all analyses.

Other analysis

In a representative sample taken from the central points of the study area, pH was analyzed using the Horneck et al. (1989) method (1:2.5 soil-to-water mixture), electrical conductivity (EC) was measured in saturation (water-saturated soil), lime content was determined according to TSE EN ISO 10693, soil texture was analyzed using the Bouyoucos (1928) hydrometer method, and organic matter content was assessed using the Walkley-Black method (Mylavarapu et al., 2014). All sample moisture determinations were performed using a Kern DBS-60 moisture determination device until a constant weight was achieved at 105°C. Soil physiochemical properties are shown in Table 3.

Table 3. Soil physiochemical properties
Çizelge 3. Toprağın fizikokimyasal özellikler

pH	EC	Calcium carbonate ($CaCO_3$)	Sand	Silt	Clay	Organic matter
7.08	11.68 dS m^{-1}	47.67%	56.10%	29.10%	14.80%	7.37%

RESULTS and DISCUSSION

OG results

The concentrations of OG detected in surface soil samples ranged from 259.04 µg kg^{-1} dw to 910.80 µg kg^{-1} dw, with a median value of 315.11 µg kg^{-1} dw. The highest concentration was observed in the sample collected at 0 meters from the road, whereas the lowest concentration was found in the surface soil sample collected 100 meters away from the road.

The relationship between the measured concentrations and the distance from the road was evaluated using a simple linear regression analysis based on a single factor. Although the highest OG concentration was detected at the closest distance and the lowest concentration at the farthest distance, the *p*-value was equal to or greater than 0.05 at the 95% confidence level, indicating that the relationship between OG and distance is not statistically significant. However, the R-squared (R^2) statistic shows that the model explains 28.75% of the total variance in OG concentrations. The correlation coefficient is −0.54, indicating a moderately strong negative relationship between the two variables.

DOC results

The total DOC concentrations detected in surface soil samples ranged from 43.68 to 105.98 mg/kg, with a mean value of 72.52 mg kg^{-1}. The relationship between the measured DOC concentrations and the distance of the sampling points from the road was statistically evaluated. Since the p-value obtained from the ANOVA table was greater than 0.05 at the 95% confidence level, no statistically significant relationship was found between DOC concentrations and distance. The R-squared statistic indicates that the fitted model explains 11.81% of the variability in distance. The correlation coefficient was calculated as -0.34, suggesting a relatively weak relationship between the two variables.

Table 4. DOC results (mg kg^{-1} dw) based on extraction fractions as a function of distance (m)
Çizelge 4. Mesafeye (m) bağlı olarak ekstraksiyon fraksiyonlarına dayalı DOC sonuçları (mg kg^{-1} ka*).*

Distance, m	*WEOC-1*	*WEOC-2*	*PYRO*	*Total DOC*
0	0.80 ± 0.47	42.22 ± 17.06	0.66 ± 0.18	43.68
2.5	0.69 ± 0.17	73.56 ± 42.16	0.74 ± 0.15	75.00
5	1.04 ± 0.51	104.42 ± 16.85	0.51 ± 0.10	105.98
7.5	0.50 ± 0.32	84.44 ± 29.73	0.60 ± 0.21	85.54
10	1.97 ± 2.76	81.22 ± 26.26	1.40 ± 1.34	84.60
25	1.27 ± 0.70	62.71 ± 4.44	0.71 ± 0.33	64.69
50	5.10 ± 2.97	46.55 ± 2.44	0.80 ± 0.10	52.46
100	3.01 ± 4.47	64.67 ± 18.77	0.56 ± 0.20	68.24

When examining the DOC concentrations determined according to the extraction steps, the WEOC-2 results accounted for between 88% and 98% of the total DOC in all samples (Table 4). As mentioned above, the WEOC-2 fraction comprises water-extractable organic carbon compounds that are more tightly bound to soil particles. Compared to WEOC-1, these carbon forms are more resistant to microbial activity and leaching processes. The agricultural field from which the samples were taken has not been subjected to any cultivation activities for many years, nor has it undergone tillage practices such as plowing or hoeing. In other words, the surface soils have not been mechanically disturbed or inverted by anthropogenic intervention. The considerably lower WEOC-1 levels relative to WEOC-2 can be attributed to the fact that the soils have remained undisturbed for an extended period. Additionally, the surface layer of this field has likely not been significantly affected by rainwater or percolating water over time, which may have limited the leaching of more labile organic carbon forms (WEOC-1). This suggests a predominance of more stable and strongly retained organic carbon compounds (WEOC-2) in the soil matrix. Soils represent the largest reservoir of organic carbon within terrestrial ecosystems, storing approximately three times more carbon than the atmosphere and nearly four times more than global vegetation (IPCC, 2013). As a result, even minor alterations in soil organic carbon (SOC) stocks can substantially influence atmospheric CO_2 concentrations (Kirschbaum, 2004).

PAH results

The 16 PAH compounds classified as priority pollutants by the United States Environmental Protection Agency (US EPA) were analyzed in surface soil samples (n = 24). The total PAH concentration levels ranged from 123.30 to 606.50 ng g^{-1} dw, with a median value of 367.30 ng g^{-1} dw. The highest concentration was detected in the sample collected at zero distance from the roadside, measured as 606.50 ± 505.5 ng g^{-1} dw, while the lowest concentration was found in the sample collected at the farthest distance from the road (100 meters), measured as 123.30 ± 45.3 ng/g dw.

The statistical results for surface soil samples are given in Table 5. The standardized skewness and kurtosis values provided in the table were used to examine whether the dataset follows a normal distribution. Values outside the range of -2 to +2 indicate significant departures from normality (bold values at Table 5). The values in bold in Table 5 represent data sets that deviate from the normal distribution.

In the current study, the total PAH concentrations in surface soil samples ranged from 155.22 to 613.36 ng/g, with a median value of 411.67 ng/g. According to Maliszewska-Kordybach's classification (1996), this level corresponds to "weak contamination" (200–600 ng/g). When compared to the reference soil sample collected from an agricultural site distant from anthropogenic activity (59.98 ng/g), the concentrations found in the current study are significantly higher, suggesting the influence of diffuse pollution sources. (Table 6).

A study by Yang et al. (2021) conducted in agricultural areas along Shanghai's road network reported PAH levels ranging from 17.2 to 3775 ng/g, with an average of 339 ± 591 ng/g; nearly 44% of samples were classified as moderately to heavily contaminated. Jia et al. (2021) reported PAH concentrations ranging from 130.1 to 359.3 ng/g (average 204.7 ng/g) in similarly impacted agricultural soils. In contrast, Al-Nasir et al. (2022) found substantially lower PAH levels in Jordanian agricultural soils, with an average concentration of 28.72 ng/g and a range between 10.65 and 21.77 ng/g. Ailijand et al. (2023) measured approximately 33.7 ng/g PAH in northwestern China. Earlier European and American studies also reported broad PAH ranges in soil: 0.01–0.6 mg/kg in Switzerland (Bucheli et al., 2004), 0.04–11.20 mg/kg in the UK (Mielke et al., 2004), and 0.91–7.29 mg/kg in urban soils from the USA (Nam et al., 2008). These findings collectively confirm that PAH contamination levels in soil are highly dependent on local emission sources, land use, and proximity to traffic and industrial zones.

Regarding OG, the present study determined concentrations between 259.04 and 910.80 µg/kg (median 315.11 µg/kg), which are markedly lower than most reported values from contaminated areas. For instance, Rauckyte et

al. (2010) found OG concentrations ranging from 100 to 2400 mg/kg (average 701 ± 829 mg/kg) in soils near petroleum refinery zones. Fei-Baffoe et al. (2025) measured OG concentrations of 139.71 mg/kg and total petroleum hydrocarbons (TPH) of 39.35 mg/kg in similarly impacted sites. Paíga et al. (2012) reported extremely high OG levels near a Portuguese oil refinery (9230 ± 322 mg/kg), while no OG was detected in samples from natural or agricultural locations. Additionally, Abdulsalam et al. (2011) found 141 g/kg OG in soil from a long-term automotive repair site. (Table 6).

Table 5. Summary statistics for individual PAHs
Çizelge 5. Bireysel PAH'ların istatistiksel sonuçları

	Count	*Average*	*Standard deviation*	*Minimum*	*Maximum*	*Range*	*Stnd. skewness*	*Stnd. kurtosis*
NaP	20	46.10	35.82	2.60	121.47	118.87	1.06	-0.20
Ace	17	56.26	64.14	8.32	228.32	220.00	**3.69**	**3.47**
Acy	19	5.57	5.76	1.31	23.82	22.51	**4.53**	**5.50**
Flr	19	2.11	1.07	0.50	4.87	4.37	1.40	0.95
Phe	17	3.42	1.21	1.92	5.37	3.45	0.04	-1.36
Ant	19	6.12	4.37	0.71	19.62	18.91	**3.06**	**3.68**
Flu	17	123.89	103.97	1.67	349.16	347.49	0.91	-0.44
Py	16	134.64	69.16	26.19	261.92	235.73	0.02	-0.63
BaA	19	1.24	0.54	0.47	2.44	1.97	1.42	0.23
Chr	14	0.82	0.65	0.14	2.15	2.01	1.36	-0.33
BbF	19	1.41	1.17	0.37	4.31	3.94	**2.55**	1.21
BkF	14	1.11	0.43	0.52	1.82	1.30	-0.05	-0.82
BaP	12	2.39	1.14	0.91	4.32	3.41	0.63	-0.58
DahA	18	40.80	104.22	1.11	449.83	448.72	**6.89**	**14.11**
BghiP	17	1.02	0.58	0.37	2.33	1.96	1.95	0.65
IcP	17	5.80	15.34	0.20	64.79	64.59	**6.74**	**13.70**

In comparison, Bayramoğlu Karşı (2025) reported OG concentrations between 2.4 and 15.9 mg/kg in surface soils from various locations across the same region, including recreational areas, areas adjacent to gas stations, and both urban and rural environments. Thus, the OG levels detected in the present study can be considered representative of background or slightly impacted conditions, far below those typically observed in industrial or heavily polluted settings (Table 6).

Table 6. Comparison of Soil PAH, OG, and TPH Concentrations Reported in the Literature
Çizelge 6. Literatürde Bildirilen Toprak PAH, OG ve TPH Konsantrasyonlarının Karşılaştırılması

Pollutant	*Sample*	*Concenration*	*Referance*
16PAH	soil	median 411.67 ng.g^{-1}, range 155.22-613.36 ng.g^{-1}	This study
		average 204.7 ng.g^{-1}, range 130.1-359.3 ng.g^{-1}	Jia et al. (2021),
		average 339±591 ng.g^{-1}, range 17.2-3775 ng.g^{-1}	Yang et al. (2021)
		average 28.72 ng.g^{-1}, range 10.65-21.77 ng.g^{-1}	Al-Nasir et al. (2022)
		range 0.01-0.6 mg.kg	Mielke et al., 2004
		range 0.04-11.20 mg kg^{-1}	Bucheli et al., 2004
		range 0.91-7.29 mg. kg^{-1}	Nam et al., 2008
		average 33.7 ng.g^{-1}	Ailijand et al. (2023)
OG	soil	median 315.11 ug.kg^{-1}, range 259.04-910.80 ug.kg^{-1}	This study
		average 701+-829 mg.kg^{-1}, range 100-2400 mg kg^{-1}	Rauckyte et al., 2010
		range 2.4-15.9 mg.kg^{-1}	Bayramoğlu Karşı, 2025
		average 139.71 mg.kg^{-1}	Fei-Baffoe et al., 2025
	sediment	range 15.25-18.08 mg kg^{-1}	Khozanah & Wulandari, 2021
TPH	soil	average 39.35 mg.kg^{-1}	Fei-Baffoe et al., 2025
		average 9230+-322 mg.kg^{-1}	Paiga et al. 2012

The total individual PAH concentrations detected in the surface soil samples revealed that among the 16 PAHs the highest concentration was that of Py (143.38 ng g^{-1} dw), followed by Flu (142.52 ng g^{-1} dw), and NaP (51.75 ng

g^{-1} dw). While the lowest concentration was observed for BghiP (1.01 ng g^{-1} dw) (Figure 2).

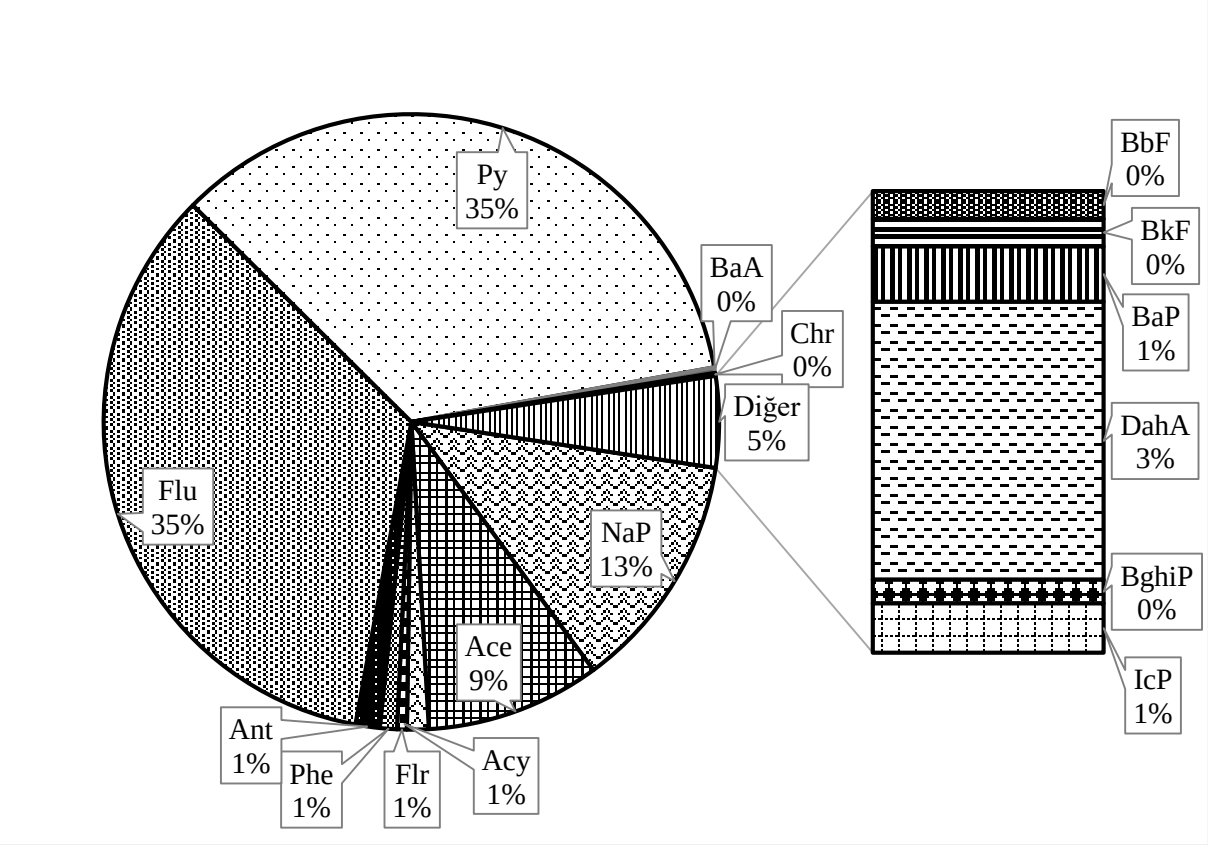

Figure 2. Mean concentrations percentage of individual PAH compounds for surface soil samples
Şekil 2. Yüzey toprağı örnekleri için bireysel PAH bileşiklerinin ortalama konsantrasyon yüzdeleri

The variation in total PAH concentrations with respect to the distance of the sampling points from the intercity highway was statistically evaluated using a one-way regression analysis. Since the *p*-value in the ANOVA table was less than 0.05 at a 95% confidence level, a statistically significant relationship was identified between the variables. The R-squared statistic indicates that the fitted model explains 72.5% of the variability in total PAH concentrations. The correlation coefficient was calculated as -0.85, indicating a moderately strong negative relationship between the variables. The negative value of the correlation coefficient indicates that as the distance from the road to the sampling point increases, the total PAH concentration decreases, with the highest concentration observed at the location closest to the road.

The Pearson correlation coefficients reported in Table 7 quantify the strength and direction of linear associations between individual variables. Statistical significance was assessed at the 95% confidence level, with *p*-values < 0.05 indicating significant non-zero correlations. As shown in Table 7, except for Flu, BaA, and Ant compounds, the concentrations of the other individual PAHs were found to exhibit strong negative correlations with increasing distance from the road.

Source identification of PAHs with diagnostic ratios

The PAH concentrations determined in this study were used for source identification based on selected diagnostic ratios reported in the literature, as summarized in Table 2 and illustrated in Figure 3. The IcP/(IcP+BghiP) ratio was found to range between 0.035 and 0.7 across all samples, indicating diesel as the predominant source (Oliveira et al., 2011). According to the literature, the Flu/(Flu+Pyr) ratio values between 0 and 0.4 suggest petroleum sources, while values between 0.4 and 0.6 indicate liquid fossil fuel sources (Akyüz & Çubuk, 2010). Based on this ratio, one sample was identified as petroleum-derived, whereas all other samples were attributed to liquid fossil fuel sources. The BaA/(BaA+Chr) ratio ranged from 0.35 to 0.68, and approximately 85% of the samples were identified as being of diesel origin (Oliveira et al., 2011). The ratio of low molecular weight (LMW) PAHs to high molecular weight (HMW) PAHs greater than 1 is indicative of petrogenic sources (Zhang et al., 2008), and all calculated values in this study exceeded 1. A BaP/BghiP ratio greater than 0.6 also indicates traffic-related sources (Katsoyiannis et al., 2007). According to the diagnostic ratio analysis, PAH contamination in the study area was primarily attributed to traffic-related sources.

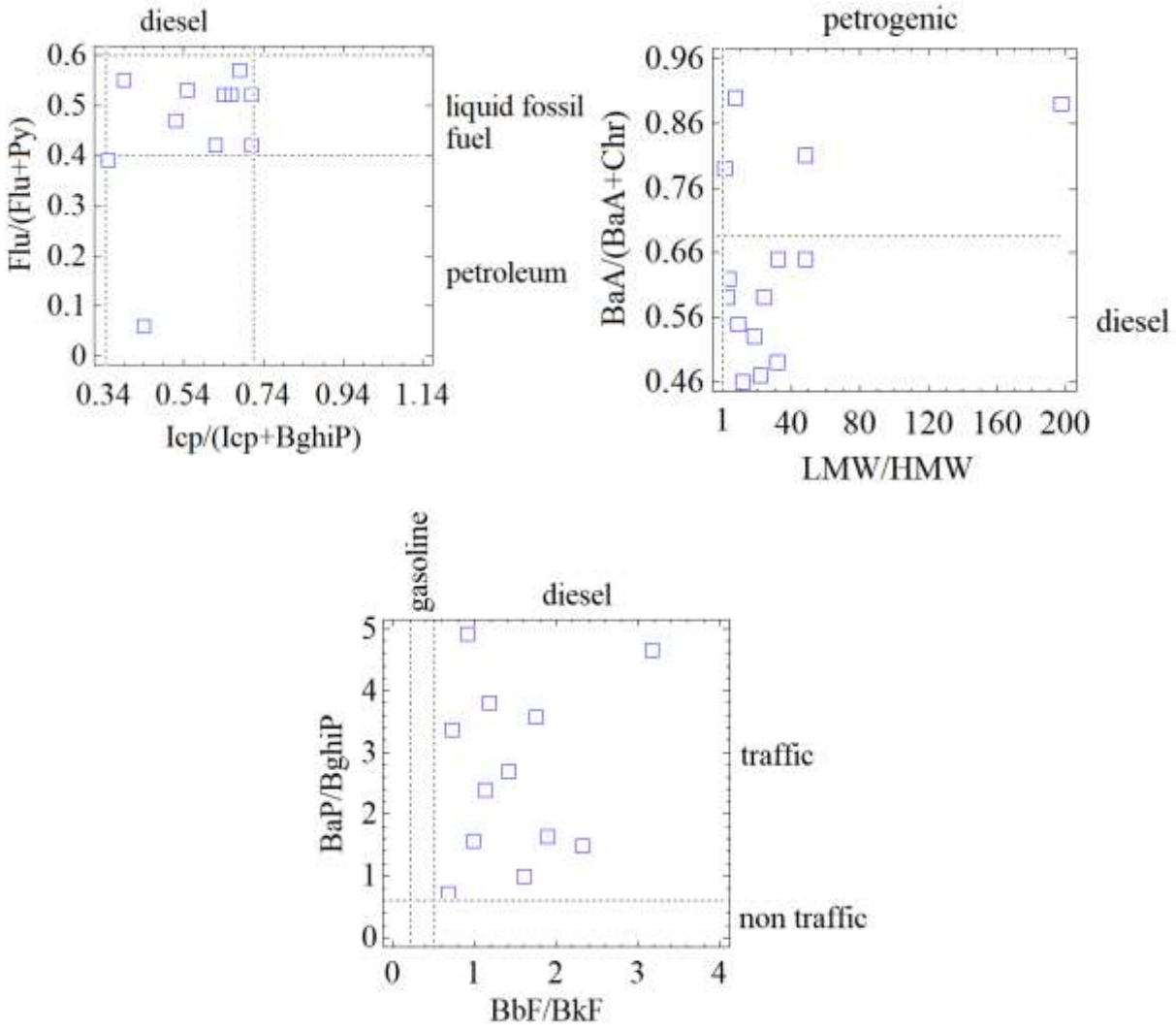

Figure 3. Diagnostic ratios
Şekil 3. Diagnostik oranlar

Risk assessment of PAHs

To assess the carcinogenic potential of PAHs in soil, benzo[a]pyrene equivalent (BaPeq) concentrations were calculated using toxic equivalency factors (TEFs) specific to benzo[a]pyrene.

The ILCR values for human exposure to PAHs in soil ranged from 1.46×10^{-3} to 2.31×10^{-3} (Table 8). Among the exposure pathways, dermal contact posed the highest carcinogenic risk for both children and adults, whereas ingestion was the predominant route for adolescents. The cancer risk for adults was higher than that for children and adolescents, primarily due to differences in ingestion rates, dermal absorption, and inhalation parameters across population groups. The highest ILCR value was observed in adults, which can be attributed to higher exposure frequency (EF) and exposure duration (ED). ILCR values via inhalation were found to be relatively similar among different population groups. According to Jia et al. (2018), an ILCR value of $\leq 10^{-6}$ indicates an acceptable or negligible risk, values between 10^{-6} and 10^{-4} represent a low potential health risk, while values $\geq 10^{-4}$ indicate a serious potential health concern. Based on the ILCR calculations derived from soil data in this study, all population groups exhibited serious health risks, with total ILCR values in the order of 10^{-3}. Although the incremental lifetime cancer risk (ILCR) values calculated in this study provided important insight into the carcinogenic potential of PAHs in traffic-impacted soils, it is essential to acknowledge that cancer is not the only health concern associated with these pollutants. PAHs are also known to exert various chronic toxic effects, including genotoxicity, endocrine disruption, immunotoxicity, developmental toxicity, and neurotoxicity, as evidenced in previous toxicological studies (ATSDR, 1995). Therefore, future research should aim to incorporate additional toxicological endpoints to comprehensively assess the broader health risks posed by PAH exposure in environmental matrices. A more holistic evaluation beyond cancer risk will enhance understanding of the full spectrum of potential long-term effects.

Table 7. Pearson correlation between individual PAH concentrations (ng g^{-1} dw) and distance from the road
Çizelge 7. Bireysel PAH konsantrasyonları (ng g^{-1} ka) ile yoldan olan mesafe arasındaki Pearson korelasyonu.

	Distance	NaP	Ace	Acy	Flr	Phe	Ant	Flu	Py	BaA	Chr	BbF	BkF	BaP	DahA	BghiP
Distance																
NaP	-0,78															
Ace	-0,56	0,02														
Acy	-0,62	0,17	0,97													
Flr	-0,50	0,33	0,37	0,51												
Phe	-0,60	0,64	0,16	0,33	0,76											
Ant	-0,48	0,02	0,83	0,85	0,67	0,56										
Flu	-0,01	0,32	-0,17	-0,04	0,07	0,62	0,19									
Py	-0,68	0,23	0,89	0,90	0,52	0,54	0,94	0,21								
BaA	-0,29	0,25	0,20	0,32	0,63	0,88	0,69	0,74	0,59							
Chr	-0,79	0,78	0,34	0,40	0,18	0,66	0,37	0,55	0,61	0,49						
BbF	-0,80	0,43	0,85	0,87	0,41	0,53	0,81	0,23	0,96	0,49	0,77					
BkF	-0,67	0,56	0,47	0,59	0,65	0,92	0,76	0,63	0,80	0,88	0,78	0,80				
BaP	-0,67	0,67	0,10	0,22	0,73	0,95	0,47	0,47	0,48	0,79	0,66	0,49	0,84			
DahA	-0,52	0,92	-0,21	-0,05	0,02	0,40	-0,29	0,35	-0,06	0,02	0,65	0,17	0,30	0,39		
BghiP	-0,70	0,77	0,39	0,55	0,38	0,75	0,48	0,65	0,64	0,59	0,89	0,76	0,85	0,62	0,66	
IcP	-0,85	0,68	0,56	0,68	0,72	0,88	0,74	0,41	0,82	0,73	0,80	0,85	0,95	0,84	0,40	0,86

Table 8. ILCR values of soils for childhood, adolescence and adulthood through ingestion, dermal contact, and inhalation
Çizelge 8. Topraklar için yutma, deri teması ve soluma yoluyla çocukluk, ergenlik ve yetişkinlik dönemlerine ait ILCR (Artan Yaşam Boyu Kanser Riski) değerleri.

	Childhood		*Adolescence*		*Adulthood*	
	Male	Female	Male	Female	Male	Female
ILCRsoilingestion	6,23E-04	6,41E-04	9,80E-04	1,12E-03	9,00E-04	9,75E-04
ILCRsoildermal	8,75E-04	9,01E-04	4,82E-04	5,50E-04	1,23E-03	1,33E-03
ILCRsoilinhalation	1,06E-08	1,09E-08	6,67E-08	7,60E-08	6,12E-08	6,63E-08
ILCRs	**1,50E-03**	**1,54E-03**	**1,46E-03**	**1,67E-03**	**2,13E-03**	**2,31E-03**

Relationship between OG, PAH, and TOC

Pearson correlation analysis was performed to examine the relationships between distance and the concentrations of total PAHs, 2–3 ring, 4-ring, 5-ring, and 6-ring PAHs, as well as OG and DOC in surface soil samples. (Table 9). Statistical significance was assessed at the 95% confidence level, with p-values < .05 indicating significant non-zero correlations.

When the correlation with distance was examined, all parameters—except for 6-ring PAH compounds—exhibited negative correlations with increasing distance, regardless of whether the correlation strength was low or high. The correlation between DOC and distance was identified as the weakest, with a coefficient of –0.34. The decreasing concentrations of OGs and PAHs with increasing distance from the road can be attributed to both transport limitations and source-related dilution. Specifically, the hydrophobic nature of OGs and the low aqueous solubility of PAHs limit their mobility via runoff and leachate, thereby restricting their long-range transport. In contrast, DOC is more soluble in water and can be transported more easily through surface or subsurface flow. Therefore, its concentration is more likely influenced by factors such as topography and water movement rather than by distance from the source alone. OG concentrations showed a strong correlation with total PAHs 0.78) and an even higher correlation with 5-ring PAH compounds (0.93), while the correlations with 2–3 ring and 4-ring PAHs were relatively lower (0.50 and 0.55, respectively). Low correlations were observed between DOC and both 2–3 ring and

Table 9. Pearson correlation coefficients between distance and the concentrations of total PAHs, PAH Ring Groups, OG, and DOC.

Çizelge 9. Mesafe ile toplam PAH'lar, PAH halkalı grupları, OG ve DOC konsantrasyonları arasındaki Pearson korelasyon katsayıları.

	Distance	OG	PAH	DOC	2-3 ring	4 ring	5 ring	6 ring
Distance								
OG	-0.54							
PAH	-0.87	0.78						
DOC	-0.34	-0.20	0.31					
2-3 ring	-0.67	0.50	0.80	0.44				
4 ring	-0.92	0.55	0.93	0.46	0.67			
5 ring	-0.43	0.93	0.62	-0.38	0.21	0.40		
6 ring	0.86	-0.24	-0.55	-0.12	-0.40	-0.68	-0.20	

4-ring PAH compounds. This can be explained by the relatively higher solubility of lower-ring PAHs compared to those with higher ring numbers, which makes them more similar in behavior to DOC in terms of mobility and distribution. The scatter plot of the measured variables is presented in Figure 4. In the soil environment, organic pollutants undergo diverse biological, chemical, and physical transformations that lead to the formation of various degradation products. Both the parent compounds and their degradation byproducts disperse through processes such as volatilization, leaching, bioaccumulation, and other soil-internal mechanisms (Khan et al., 2018). The soil ecosystem, composed of a wide variety of organisms including bacteria, fungi, invertebrates, and plants, plays a vital role in nutrient cycling and food production. However, the introduction of total petroleum hydrocarbons (TPH) into this environment can disrupt its natural balance, causing alterations in both micro- and macrobiotic communities (Bayramoğlu Karşı, 2025). Therefore, understanding the ecological implications and risks posed by contaminated soils to these biological receptors is essential. Among these, soil microbiota play a significant role in the biological degradation of organic pollutants such as oil, grease (OG), and polycyclic aromatic hydrocarbons (PAHs). Through enzymatic activities that vary depending on environmental conditions, these microorganisms help reduce the toxicity of contaminants and contribute to the restoration of soil quality (Cerniglia, 1992; Haritash & Kaushik, 2009).

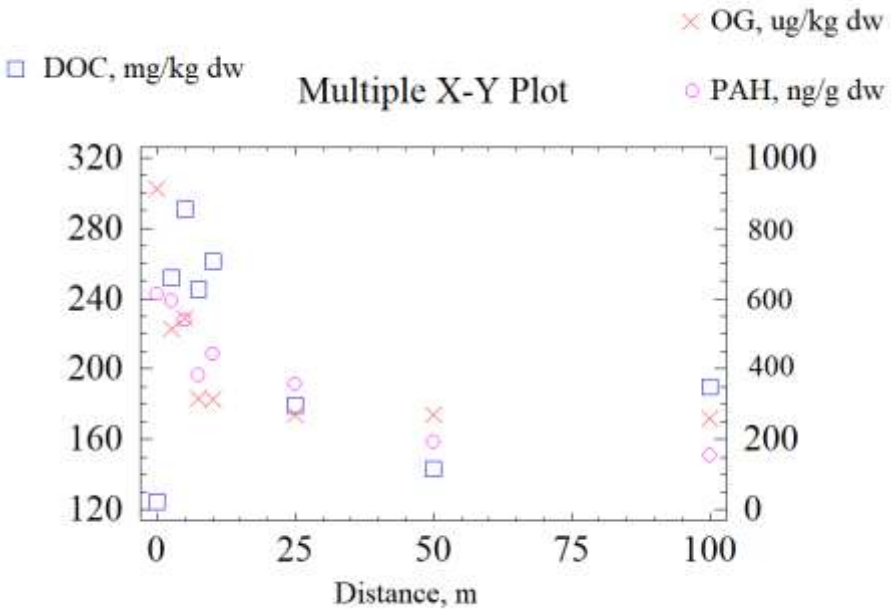

Figure 4. The scatter plots of the measured variables, including DOC concentrations (mg kg^{-1} dw) on the left y-axis, OG (µg kg^{-1} dw), and PAH (ng g^{-1}dw) on the right y-axis, plotted against distance (meters) on the x-axis.

Şekil 4. Ölçülen değişkenlerin saçılım grafikleri: x ekseninde mesafe (metre) olmak üzere; sol y ekseninde DOC konsantrasyonları (mg kg^{-1} ka), sağ y ekseninde ise OG (µg kg^{-1} ka) ve PAH (ng g^{-1} ka) değerleri gösterilmiştir.

CONCLUSION

The agricultural use of contaminated soils poses significant risks to human health due to the potential contamination of crops with pollutants. In particular, the accumulation of organic pollutants such as PAHs, oil, and grease not only reduces soil fertility but also adversely affects the quality and safety of agricultural products. Therefore, comprehensive risk assessments should be conducted prior to agricultural production on contaminated sites, and appropriate remediation strategies must be implemented.

A comprehensive and multifaceted approach is essential to reduce traffic-related air and soil pollution. Primarily, the strengthening and enforcement of emission control policies are crucial. This includes updating vehicle exhaust emission standards, implementing effective periodic inspection systems, and promoting the use of environmentally friendly fuels. In addition, planting green barriers (trees, shrubs) along roadsides and residential areas can help capture particulate matter and other pollutants from the atmosphere, thereby limiting the spread of pollution. Increasing green spaces contributes not only to improving air quality but also to mitigating urban heat island effects. Sustainable transportation solutions such as enhancing public transport systems, expanding bicycle lanes, and supporting the use of electric vehicles are also effective in reducing traffic-related pollutants. Finally, raising public environmental awareness and fostering collaboration with relevant stakeholders are necessary for long-term success.

This study demonstrated that traffic emissions along the D-100 highway significantly affect the contamination levels of surface soils in adjacent agricultural areas, particularly for OG and PAHs. The strong spatial gradient of PAHs linked to traffic-related sources underscores the urgent need for targeted pollution mitigation measures. Despite no significant correlation found between DOC and distance, the varying transport behaviors of different pollutants highlight the complexity of roadside soil contamination. The elevated lifetime cancer risk (ILCR) associated with these pollutants necessitates proactive environmental management to protect public health, especially vulnerable populations such as children and immunocompromised individuals.

In light of these findings, it is recommended that regular environmental monitoring programs be established for roadside soils to track pollution trends and the effectiveness of mitigation strategies. Moreover, adopting pollution control policies that limit vehicular emissions, such as stricter fuel quality standards and promotion of cleaner transportation technologies, could substantially reduce soil contamination. Finally, integrating population-specific exposure assessments in future risk evaluations will enable more comprehensive protection measures tailored to at-risk groups. Furthermore, more comprehensive studies supported by additional measurements, such as assessing seasonal variations and concentration differences in rural and semi-rural areas, are needed to provide a more holistic evaluation on this subject.

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Contribution Rate Statement Summary of Researchers

Melike Büşra Bayramoğlu Karşı: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – Original draft.

Conflict of Interest

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

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