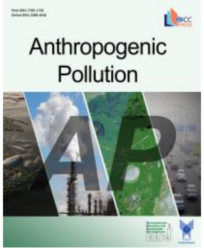

J. Anthropog Pollut 2025; 9(2): Article 21

Anthropogenic Pollution (AP)

https://doi.org/10.57647/J.AP.2025.0902.21

Research Article

Evaluation of Phthalate Concentration in Landfill Leachate in the West of Guilan Province, Iran

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Article History:

Received:
24 July 2025

Revised:
28 September 2025

Accepted:
31 December 2025

Published in Issue:
31 December 2025

Abstract

Landfill leachate contains pollutants, including phthalates, which pose significant risks to the environment and human health. This study aimed to investigate the phthalates concentration in landfill leachate from three cities in western Guilan: Astara, Talesh, and Anzali. Samples were collected from three designated stations during both the rainy and dry seasons. Physicochemical parameters such as pH, electrical conductivity (EC), organic matter content, and phthalate concentrations were measured using the standard extraction method EPA Method 8061A, with gas chromatography-mass spectrometry (GC-MS). The results revealed that the average total phthalate concentration in landfill leachate across the three cities was 455.46 ppb, with significant seasonal variation between the rainy and dry seasons ($P < 0.05$). Astara exhibited the highest phthalate concentration, measuring 239.50 ppb. Throughout both seasons, bis (2-ethylhexyl) phthalate (BEHP) accounted for the most significant proportion, comprising 73.2% of total phthalates, followed by dioctyl phthalate (DOP) at 13%, dimethyl phthalate (DMP) at 6.4%, and isobutyl phthalate (IBP) at 5.5%. Diethyl phthalate (DEP), dibutyl phthalate (DBP), and benzyl butyl phthalate (BBP) were less prevalent, representing 1.1%, 0.5%, and 0.2%, respectively. Health risk assessments indicated that the contamination factor (CFi) was highest at the Talesh station (80.30), followed by Anzali (45.52) and Astara (10.69). Similarly, the Pollution Load Index (PLI) was greatest at Talesh (32.32), followed by Astara (20.24) and Anzali (11.32). These findings underscore the critical need for continuous monitoring and effective management of landfill leachate, as well as further investigation into the health and environmental impacts of phthalate contamination.

Keywords: Environmental Pollution; Emerging Pollutants; Waste Leakage; Waste Management

Cite this article: Nemati Gaskaminjan S., Shariati F., Mohammadi Galangash M., Ooshaksaraei L., (2025). Evaluation of phthalate concentration in landfill leachate in the west of Guilan province, Iran. *Journal Anthropog Pollut, 9(2),* Article 21. https://doi.org/10.57647/J.AP.2025.0902.21

1. Introduction

The increasing volumes of municipal solid waste are ultimately disposed of in open dumps and landfills, leading to the continuous generation of landfill leachate (Ren et al., 2025; Wijekoon et al., 2022). Landfill leachate is a complex organic wastewater produced during the sanitary landfill process (Teng et al., 2021). It arises from the secondary products of solid organic decomposition processes (Abdel-Shafy et al., 2024) and forms when rainwater infiltrates landfills, mixing with liquids generated during the degradation of organic matter in the waste (Baucom and Ruhl, 2013). This leachate is characterized by its dark colour and pungent odour, containing high levels of dissolved organic matter, a variety of inorganic compounds, heavy metals, and organic substances (Matike and Ngole-Jeme, 2024; Ward et al., 2005). With the combined effects of economic growth, urbanization, population increase, and changing lifestyles, global municipal solid waste production is projected to exceed 2.2 billion tons by 2025 (Kaza et al., 2018; Wijekoon et al., 2022).

The generation of leachate presents a significant environmental challenge (Abdel-Shafy et al., 2024; Alao et al., 2025; Ma et al., 2022). Numerous factors influence the production process and the variable quantity and quality of leachate from landfills. These factors include annual precipitation (Chen, 1996), runoff (Kuusik et al., 2014), climate (Abunama et al., 2021), waste composition and density (Moody and Townsend, 2017), as well as the initial moisture content and depth of the landfill (Zhang et al., 2023). Waste leachate is particularly hazardous due to its high oxygen demand and elevated levels of organic and inorganic chemicals, including ammonium, phytate, heavy metals, and phenols. These compounds can significantly degrade water and soil quality, creating serious risks for human health and the environment (Hasnine et al., 2022; Naveen et al., 2017; Podlasek et al., 2023). Phthalates are chemical compounds that are widely present in everyday materials (Matike and Ngole-Jeme, 2024; Shen et al., 2025). They represent the most prevalent plasticizers employed across construction materials, medical devices, cosmetics, surfactants, pesticide formulations, and household appliances (Bulbul et al., 2022). Effluents from municipal wastewater treatment plants, the textile industry (Fekri et al., 2021), and leachates from municipal solid waste are significant sources of phthalates entering natural waters (Kotowska et al., 2020). The most commonly used phthalates in consumer products include dimethyl phthalate (DMP), diethyl phthalate (DEP), dibutyl phthalate (DBP), bis(2-ethylhexyl) phthalate (BEHP), benzyl butyl phthalate (BzBP), and di-n-octyl phthalate (DNOP) (Wang et al., 2019). Significant studies have been conducted in Iran regarding environmental pollution. Gholaminejad et al. (2024) investigated the contamination of phthalate esters in soil, water, and leachate near a landfill close to the sea. Mohammadi et al. (2022) focused on analyzing the occurrence, seasonal distribution, and ecological risk assessment of microplastics and phthalate esters in leachate from a landfill near the marine environment in Bushehr Port. Nasrabadi et al. (2024) also examined landfill leachate as a critical source of emerging phthalic acid ester pollutants, identifying their characteristics, fate, and transport. Additionally, Mohammadi et al. (2022) investigated the occurrence and ecological risks of phthalate esters and microplastics in solid waste at a landfill near the Persian Gulf. A systematic review by Momeniha et al. (2025) examined phthalic acid ester concentrations in waste processing and management facilities while outlining future research directions. In this context, Ateş and Argun (2023) studied the fate of phthalate esters in landfill leachate under different conditions. Guilan Province, located along the southern coast of the Caspian Sea, contains 41 landfills covering a total official area of approximately 105 hectares, with nearly 1,600 tons of waste deposited in these sites daily (Sadeghi Poor Sheijany et al., 2021). According to the Iranian Environmental Organization, municipal waste collection from landfills has been underway in the cities of Anzali, Talesh, and Astara since 2005, 1989, and 1985, respectively. These coastal cities, serving as vital tourism and economic hubs in western Guilan, play a central role in the province's development. Their attractive beaches, abundant natural resources, and rich cultural heritage draw thousands of domestic and international visitors each year. Furthermore, the presence of Anzali Port—one of the most important maritime centers in northern Iran—promotes trade and shipping activities across the Caspian region. The purpose of this study is to investigate the occurrence of phthalates in landfill leachate collected from the cities of Astara, Talesh, and Anzali. These areas face serious environmental challenges due to rapid population growth and solid waste generation. The significance of this research lies in elucidating the adverse effects of phthalates on both public health and ecosystems. These compounds can seriously degrade water and soil quality and contribute to various health hazards. The novelty of this study is to detect and quantify phthalates in landfill leachate and to assess their seasonal variations across different coastal zones of Guilan. This approach enables the identification of temporal patterns in phthalate contamination. Despite the environmental and economic importance of these coastal cities, there is a notable lack of research on phthalates in urban landfill leachate in Guilan Province. Therefore, this study aims to fill existing knowledge gaps and provide new insights to support improved environmental management and protection strategies in the region.

2. Materials and Methods

This experimental and descriptive field-scale study was conducted in 2023 in Guilan Province, northern Iran, which has a temperate climate and covers 14,044 square kilometers. The study focused on three landfill sites located in the cities of Astara, Talesh, and Anzali, situated in the western part of Guilan Province adjacent to the Caspian Sea (Figure 1).

2.1. Sampling

Leachate samples were collected during the dry (summer) and wet (winter) seasons of 2023 from three landfills of Astara, Anzali, and Talesh in western Guilan province using pre-cleaned steel buckets. The containers were washed with hexane one day before sampling and heated to 70°C. At each site, three samples were combined to form a composite sample. The samples were transferred to dark glass bottles with metal caps and wrapped in aluminum foil (Lee et al., 2019).

pH was measured using a pH meter (CLEAN 14091937, China) based on ASTM D2216. Biochemical oxygen demand (BOD) was determined via the standard 5-day BOD (BOD_5) method. Samples were stored in the dark at 20 °C for five days to prevent photodegradation. BOD was calculated as the difference in dissolved oxygen before and after incubation. All procedures adhered to APHA standard methods. The results were used to evaluate leachate quality and its environmental impact.

2.2. Sample extraction

The standard method (EPA Method 8061 A) was used to analyze the extracted phthalate samples. For preparation, 5 ml of the sample was placed on a shaker with 10 ml of methanol for 5 minutes. Then, it was placed in an ultrasonic device at room temperature for 24 minutes. After centrifugation, 5 ml of the solution was removed and placed in a new Falcon tube. Then, 1 ml of hexane and 1 ml of saturated saline were added to the mixture and stirred well for 2 minutes to extract the hexane phase. Finally, the hexane phase was transferred into a vial and injected into the device. The phthalate extracted from the samples was measured using a gas chromatography device equipped with a quadruple mass detector, model 5975, from Agilent Technologies, USA. Separation was performed using a 0.25 mm x 30 m I.D. polydimethylsiloxane (HP-5 MS (5%-95%) capillary column made of silica with a film thickness of 0.25 µm. Perfluoro-tert-butylamine (PFTBA) was used for tuning the mass spectrometer. SIM card analysis was used for each phthalate. In this mode, rather than scanning all m/z values across a broad range, the instrument selectively monitors only a few m/z values with the highest intensities as designated by the user. The parent ion exhibiting the highest intensity was chosen based on the data presented in Table 1 (Durand et al., 2025).

For enhanced measurement sensitivity, an appropriate amount of helium with 99.99% purity was used as the carrier gas at a flow rate of 1 mL min^{-1} to achieve optimal separation of chromatographic peaks at different temperatures. The column and carrier gas inlet flow programs were configured using the splitless inlet mode in the MSD ChemStation software (version E.02.01.1177).

The GC–MS temperature program was set as follows: the injector temperature was maintained at 290 °C. The oven temperature was initially set to 70 °C and held for 1 min, then ramped to 300 °C at a rate of 10 °C min^{-1} and held for an additional 7 min. The transfer line temperature was kept at 300 °C. The ion source temperatures were maintained at 230 °C and 150 °C, respectively. The electron beam energy of the spectrometer was set to 70 eV.

2.3. Quality Control

To ensure the quality of the leachate samples, 100 mL of HPLC-grade ultrapure water was spiked with 5 µL of a phthalate standard mixture. The solution was then stirred thoroughly, extracted with solvent, and subsequently injected into the GC–MS system. Extraction efficiency results are provided in Table 2. To evaluate repeatability, one sample was extracted and injected three consecutive times. This analytical procedure involved assessing key performance parameters—including calibration range, linearity, limits of detection and quantification, and recovery—to guarantee accurate and reliable extraction and measurement of phthalate esters in the samples. The calibration range (DLRa) was consistent across all phthalate compounds, spanning 5–1000 ng/mL. The coefficient of determination ($R^2 > 0.99$) for all analytes confirms excellent linearity of the calibration curves. The limits of detection (LOD) and quantification (LOQ) varied among compounds, but their low values (within the ng/g range) demonstrate the high sensitivity of the method. Recovery values ranged from 78.7% to 90.6%, reflecting good accuracy and precision. All PAE standards (DMP, DEP, DBP, BEHP, BBP, and DNOP) were obtained from Sigma-Aldrich (USA) with a purity of 99.99%.

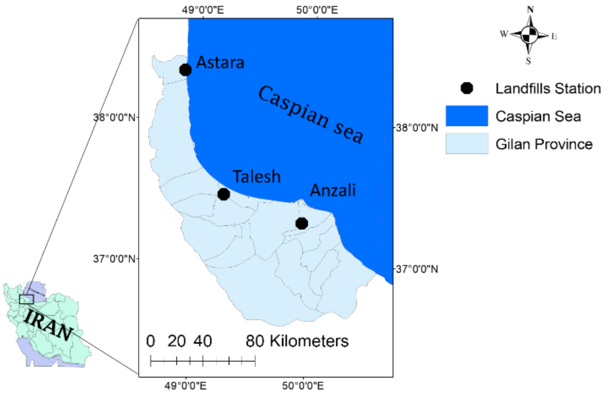

Figure 1. Locations of leachate sampling in Guilan province, Iran 2022

2.4. Risk Assessment

According to the formula proposed by Huang et al. (2025), the contamination factor (CFi) is the ratio of the concentration of each phthalate at each sampling point (Ci) to the minimum concentration of phthalate found in the present study (Coi). PLI indicates the level of phthalate contamination at each point (Huang et al., 2025) Equations 1, 2, and 3 are used to calculate the PLI value:

$$\mathrm{CF_i} = \frac{\mathrm{ci}}{\mathrm{coi}} \qquad (1)$$

$$\mathrm{PLI} = \sqrt[n]{\mathrm{CFi}} \qquad (2)$$

$$\text{PLI Landfill's} = \sqrt[n]{\mathrm{PLI\ 1 + PLI\ 2\ + PLI\ 3\ \ldots .\ PLI\ n}} \qquad (3)$$

2.5. Data Analysis Method

SPSS 23 software was used to analyze the data. First, the data were checked to ensure normal distribution using the Shapiro-Wilk test. Due to normal distribution, one-way analysis of variance (ANOVA) was used to compare phthalates. Also, independent t-test was used to examine pairs in groups. The principal component analysis (PCA) was used for alignment and correlation between variables using Canoco version 5software.

3. Results

The findings of this study, presented in Table 3, reveal varying concentrations of phthalate compounds in landfill leachate across three distinct cities: Astara, Anzali, and Talesh. In Astara, BEHP exhibited the highest average concentration at 160.36 ppb, while butyl benzyl phthalate (BBP) showed the lowest at 0.37 ppb.

Additionally, diethyl phthalate (DEP) and diisobutyl phthalate (IBP) averaged 3.67 ppb and 10.03 ppb, respectively.

Table 1. Selection of major ions for quantitative analysis of phthalates

Analyte	Abbreviations	Retention time (min)	Confirmation ions (*m/z*)	Quantification ion (*m/z*)
Di Methyl Phthalate	DMP	13.4	77,135, 163, 194	163
Di Ethyl Phthalate	DEP	15.8	121, 149, 177, 222	149
Di Buthyl Phthalate	DBP	21.3	121, 149, 205, 223	149
Bis (2-Ethylhexyl) Phthalate	BEHP	26.3	45, 72, 121, 149	149
Butyl Benzyl Phthalate	BBP	28.5	91,149, 206, 238	149
Di N-Octyl-Phthalate	DNOP	30.4	149,179,261, 79	149
Diiso buthyl Phthalate	IBP	16	205,278,223	149

Table 2. Quality control analytical method

PEs	DLRa (ng mL^{-1})	R^2	LOD^b (ng g^{-1})	LOQ^c (ng g^{-1})	Recovery
DMP	5-1000	0.993	1.68	5.56	90.6
DEP	5-1000	0.995	0.86	2.84	78.7
DBP	5-1000	0.990	0.75	2.46	80.6
BEHP	5-1000	0.991	0.10	0.34	79.2
BBP	5-1000	0.992	1.67	5.50	80.1
DNOP	5-1000	0.996	2.11	6.97	84.3

In contrast, Anzali displayed generally lower concentrations compared to Astara, with BEHP recorded at an average of 42.57 ppb and DEP at 0.88 ppb. For Talesh, BEHP again presented the highest average concentration at 130.71 ppb, and BBP the lowest at 0.53 ppb. Overall, the results indicate that the diversity and concentration range of phthalates, particularly BEHP, are notably more significant in Astara, whereas Anzali and Talesh exhibit considerably lower and more uniform concentrations.

The independent t-test revealed significant differences in the mean concentrations of phthalates DMP, DEP, and DOP between high- and low-rainfall seasons ($P < 0.05$). The highest average phthalate concentration was observed for BEHP at 111.21 ± 70.35 ppb, while BBP had the lowest average concentration of 0.34 ± 0.30 ppb. Moreover, the average total phthalate concentration during the low-rainfall season (50.78 ± 21.54 ppb) was significantly higher than that in the high-rainfall season (31.49 ± 21.83 ppb) ($P < 0.05$).

The results indicate notable seasonal variations in phthalate concentrations across the cities of Astara, Anzali, and Talesh. In Astara, BEHP concentration peaked at 203.30 ppb during the high-rainfall season, decreasing to 117.42 ppb in the low-rainfall season. Conversely, DEP concentration in Astara increased from 2.18 ppb in the high-rainy season to 5.17 ppb in the low-rainy season. In Anzali, BEHP concentration rose from 23.91 ppb in the high-rainy season to 61.23 ppb in the low-rainy season, indicating increased pollution during the drier period. Similarly, in Talesh, BEHP concentration was 182.26 ppb in the high-rainy season and dropped to 79.16 ppb in the low-rainy season (Figure 2).

The results of this study (Figure 3) illustrate the frequency distribution of phthalate compounds—including DOP, BEHP, BBP, DBP, IBP, DEP, and DMP—across three regions: Anzali, Astara, and Talesh. For DOP, Astara exhibited the highest frequency at 81.68%, while Talesh recorded the lowest at 18.32%. BEHP was most prevalent in Astara (48.00%), followed by Talesh (39.23%) and Anzali (12.77%). Regarding BBP, significant frequencies were observed in Talesh (58.89%) and Astara (41.11%). Astara also showed the highest proportion of DBP at 56.78%, compared to 15.25% in Anzali. For IBP, Talesh had the greatest frequency (43.13%), with Astara and Anzali accounting for 39.76% and 17.11%, respectively. DEP was predominantly found in Astara (70.78%), with lower frequencies in Anzali (16.98%) and Talesh (12.14%). DMP exhibited the highest value in Astara (53.05%) and the least in Talesh (6.76%). Statistical analysis confirmed significant differences in the istribution of these compounds among the regions ($P < 0.05$).

Overall, BEHP represented the largest proportion of phthalates detected, accounting for 73.2% of the total. This was followed by DOP (13.0%), DMP (6.4%), and IBP (5.5%). Conversely, DEP (1.1%), DBP (0.5%), and BBP (0.2%) constituted the lowest percentages.

In examining the inconsistencies observed in the data, two key factors stand out. First, the effect of rainfall on pollutant leaching could lead to a decrease in DMP, DOP, and DEP concentrations on rainy days, as rainfall can leach these compounds from different surfaces and contribute to their dilution. At the same time, IBP and BEHP may be specifically associated with suspended particles in water or soil sediments, and their concentrations may decrease on days with low rainfall due to higher accumulation. Second, different sources of pollutants also play an important role; for example, DMP, DOP, and DEP may originate more from industrial or consumer sources, which decrease on rainy days due to reduced human activities or source leaching. In contrast, IBP and BEHP may originate from domestic wastewater, which accumulates more on dry, low-rainfall days. These factors clearly indicate the complexity of pollutants behavior in different environmental conditions.

The results of this study (Figure 4) demonstrate significant seasonal variations in pH and biochemical oxygen demand (BOD). As shown in Figure 4A, the Anzali station exhibited a significantly higher pH during the winter compared to the summer season ($P < 0.05$). Figure 4B illustrates that the Talesh station recorded the highest BOD values in both seasons, peaking at 5700 mg/L in summer. Anzali station also presented notably elevated BOD levels, particularly in winter, with a value of 3520 mg/L. In contrast, the Astara station consistently showed the lowest BOD concentrations, remaining below 500 mg/L across both seasons ($P < 0.05$).

In the case of BOD, the observed discrepancy is because Astara has a lower BOD value than Anzali and Talesh, despite the high distribution of phthalate-derived pollutants. This phenomenon could be due to differences in the type and composition of pollutants; such that inorganic pollutants or other organic compounds that have a lower impact on BOD may be more prevalent in Astara. In addition, environmental activities such as biological decomposition and ecosystem conditions in these areas could also contribute to the reduction of BOD in Astara. In other words, the specific composition of pollutants and environmental conditions in each of these areas could have different effects on BOD and explain these discrepancies.

The results of the principal component analysis (PCA) (Figure 5) indicate a significant inverse correlation between pH and BOD and the concentrations of the compounds DOP, BEHP, BBP, DBP, IBP, DEP, and DMP ($P < 0.05$).

Table 4 presents the health risk assessment for three monitoring stations: Astara, Anzali, and Talesh. The contamination factor (CFi) values reflect the degree of contamination at each site, with Talesh exhibiting the highest value of 80.30, followed by Anzali at 45.52 and Astara at 10.69.

Similarly, the Pollution Load Index (PLI) was highest at the Talesh station (32.32), indicating a substantial potential risk to public health in this area. In comparison, Astara and Anzali stations showed lower PLI values of 20.24 and 11.32, respectively, suggesting comparatively reduced health risks. Figure 6 shows two chromatograms of samples of leachate from a landfill in western Guilan province, which identified, separated, and confirmed seven different phthalates: DMP, DEP, DBP, IBP, BBP, BEHP, and DOP.

Table 3. Concentrations of phthalate compounds in landfill leachate of Astara, Anzali and Talesh cities (ppb)

City	phthalate	Mean	Maximum	Minimum	Standard Deviation	Variance
Anzali	DMP	12	23	1	15	237
	DEP	0.88	1.00	0.75	0.18	0.03
	IBP	4.31	5.41	3.21	1.55	2.41
	DBP	0.36	0.72	nd	0.51	0.26
	BBP	nd	nd	nd	-	-
	BEHP	42.57	61.23	23.91	26.39	696.40
	DOP	nd	nd	nd	-	-
Astara	DMP	15	29	2	19	355
	DEP	3.67	5.17	2.18	2.12	4.48
	IBP	10.03	17.17	2.89	10.10	101.97
	DBP	1.34	2.68	nd	1.90	3.59
	BBP	0.37	0.73	nd	0.52	0.27
	BEHP	160.36	203.30	117.42	60.73	3687.73
	DOP	48.25	95.67	0.82	67.06	4497.60
Talesh	DMP	2	2	2	nd	nd
	DEP	0.63	0.89	0.37	0.37	0.14
	IBP	10.85	16.46	5.25	7.92	62.77
	DBP	0.66	1.00	0.32	0.49	0.24
	BBP	0.53	0.64	0.43	0.15	0.02
	BEHP	130.71	182.26	79.16	72.91	5315.17
	DOP	10.80	21.59	nd	15.27	233.10

nd: Not detected.

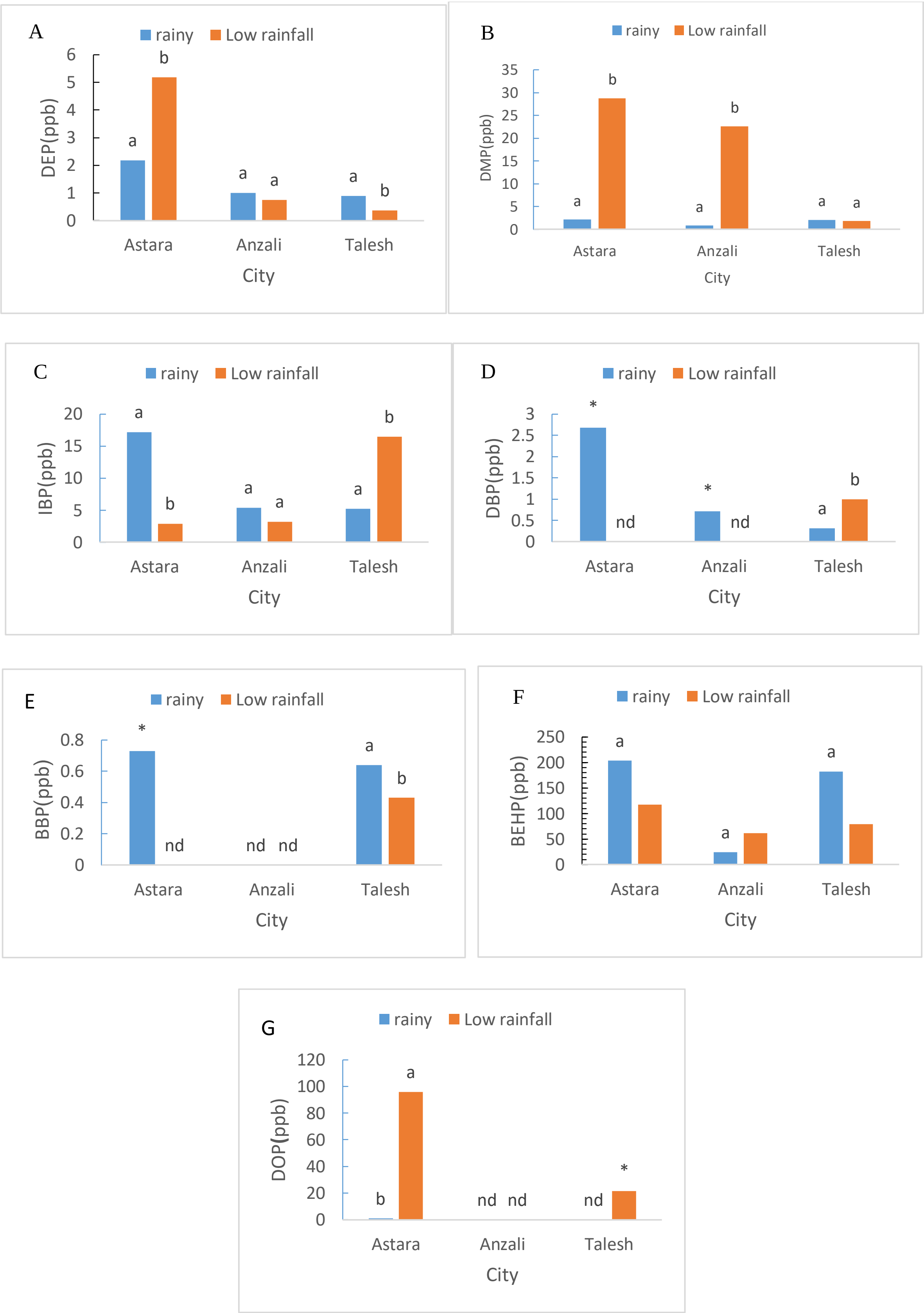

Figure 2. Mean concentrations of PAEs in landfill leachate collected from the rainy and dry seasons in western Guilan province (Different letters indicate significant differences $P < 0.05$). A: DEP, diethyl phthalate; B: DMP, dimethyl phthalate; C: IBP, Diisobuthyl Phthalate; D: DBP,dibutyl phthalate; E: BBP, butylbenzyl phthalate; F: BEHP, bis(2-ethylhexyl) phthalate; G: DOP, di-N-octyl-phthalate

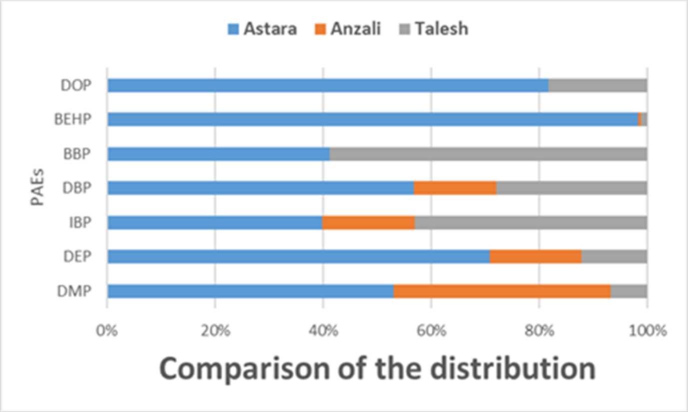

Figure 3. Comparison of the frequency distribution of phthalates in landfill cities in western Guilan province

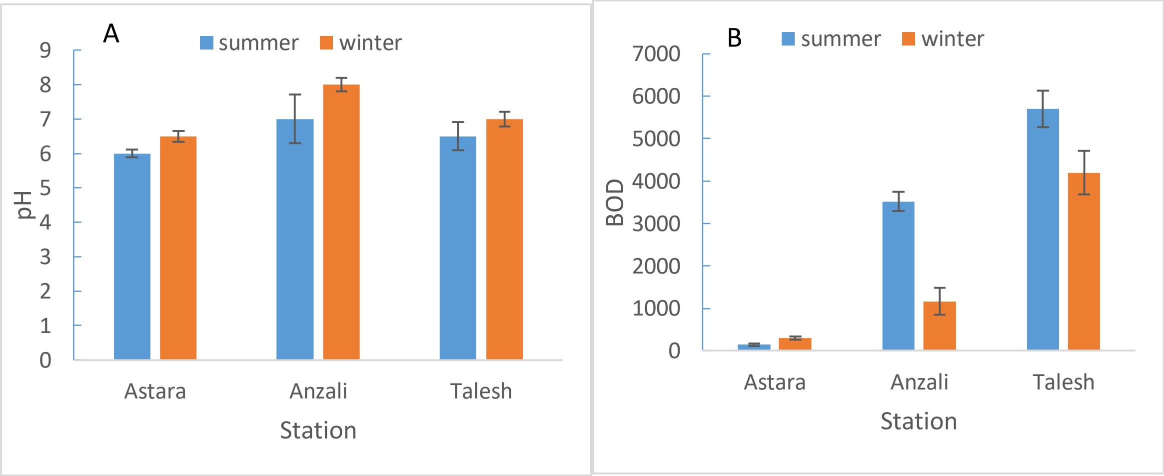

Figure 4. Comparison of pH and BOD of leachate in landfills in western Guilan Province

Table 4. Health Risk Assessment

Station	CFi	PLI
Astara	10.69222	20.24
Anzali	45.52439	11.32
Talesh	80.30469	32.32

4. Discussion

Phthalate degradation in landfill environments typically involves the microbial breakdown of diesters into monoesters. Consequently, elevated concentrations of monoesters are expected in leachate from landfills in the methanogenic phase, where microbial activity actively degrades diesters. Thus, the landfill phase—characterized by factors such as water infiltration into waste or contaminated soil—significantly influences the types and concentrations of phthalates released into leachate (Matike and Ngole-Jeme, 2024).

Among the phthalates analyzed, DEP, DBP, and BEHP are generally the most abundant in landfill leachate, whereas DMP is detected less frequently. Consistent with this trend, the present study identified BEHP as the dominant compound, accounting for 73.2% of total phthalates. This aligns with findings by Kotowska et al. (2020), who reported BEHP as the most prevalent phthalate in Polish municipal solid waste leachate, detected in 97% of samples. Similarly, Bauer and Herrmann (1998) observed that BEHP comprised up to 91% of total phthalates leached from household waste, with DBP, DMP, DEP, and BBP collectively accounting for only 8%. A comprehensive review by Wowkonowicz et al. (2021) further confirmed that BEHP is not only frequently detected but also present at the highest concentrations in municipal solid waste leachate worldwide.

The predominance of DEP, DBP, and BEHP in landfill leachates is likely attributable to their widespread use in manufacturing everyday products. Typically, waste containing these compounds is solid, whereas DMP-containing materials are often liquid and disposed of with

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wastewater, resulting in lower detection frequencies in landfill leachate studies (Matike and Ngole-Jeme, 2024).

The concentration pattern observed in this study follows the order: BEHP > DOP > DMP > IBP > DEP > DBP > BBP. This differs from the pattern reported by Gholaminijad et al. (2024) in a coastal city near the Persian Gulf, which found BEHP > DnBP > DnOP > DEP > DMP. Regional variations were also noted within this study: Anzali exhibited BEHP > DMP > IBP > DEP > DBP; Astara showed BEHP > DOP > DMP > IBP > DEP > DBP > BBP; and Talesh displayed BEHP > IBP > DOP > DMP > DBP > DEP > BBP. These discrepancies likely reflect differences in waste composition, local environmental conditions, and waste management practices.

Jonsson et al. (2003) documented a 99.5% reduction in DMP, DEP, and DBP concentrations during the first nine months of landfill deposition, with initial concentrations of 245, 5, and 1 µg/L, respectively. In contrast, BEHP concentration increased by 91.6% from an initial 1 µg/L over the same period. These findings corroborate Liu et al. (2010), who reported that hydrophilic phthalates degrade more readily during the aerobic phase of landfill operation than under anaerobic conditions, highlighting landfill age as a critical factor influencing phthalate diversity in leachate. Consequently, specific phthalates detected in landfill leachate can serve as indicators of landfill degradation stage.

Phthalates with shorter carbon chains (e.g., DMP, DEP, DBP) are generally more susceptible to degradation and extraction than those with longer chains such as BEHP, which are more resistant (Huang et al., 2013). Both the hydrolysis and biodegradation of phthalates in landfills are influenced by several factors, including the landfill's decomposition stage, the chemical characteristics of the phthalates, pH, redox conditions, and the organic matter content of the leachate. Due to their low electrophilic nature, phthalate esters are relatively unreactive at neutral pH; however, hydrolysis rates increase significantly under acidic or basic conditions (Xu et al., 2008).

The present study observed that leachate pH tends to become more acidic during low-rainfall periods, a change that can directly impact phthalate degradation and concentration. Acidic conditions accelerate phthalate hydrolysis, potentially increasing the concentration of certain phthalates in leachate. Additionally, low pH can alter microbial activity, thereby influencing biodegradation processes. These findings suggest that pH management in landfill leachate could be a critical strategy for controlling phthalate levels and mitigating environmental pollution.

Leachate composition is affected by multiple factors including waste composition, waste density, landfill age, and ambient temperature and rainfall (Abdel-Shafy et al., 2024). Consistent with this, the current study found higher average phthalate concentrations during low-rainfall seasons compared to high-rainfall seasons. Shukur et al. (2024) similarly reported elevated phthalate percentages during dry seasons in the Tigris River, attributing the variations to biological oxygen demand (BOD) and turbidity in dry seasons, and to phthalates and pH in wet seasons.

Landfill waste decomposition initially occurs under aerobic conditions but rapidly transitions to anaerobic as oxygen is depleted Slack (Sahnsarayi et al., 2025). Under anaerobic conditions, hydrolysis and fermentation degrade organic matter into metabolites such as carboxylic acids and alcohols, depending on compound properties. Phthalate biodegradation predominantly occurs in the upper landfill layers, where microbial populations are more active, whereas hydrolysis dominates in the lower layers (Huang et al., 2013).

Phthalate degradation proceeds more slowly under anaerobic conditions, as only the side chains (e.g., –CH3 groups) of the phthalate molecules are cleaved, while the aromatic ring remains intact (Ren et al., 2025). At the base of landfills, hydrolysis occurs via a two-step process: initially, phthalate diesters are converted into monoesters and corresponding alcohol moieties, followed by further hydrolysis to phthalic acid and a second alcohol (Huang et al., 2013). This hydrolysis is strongly associated with methanogenic zones within the landfill, where microbial enzymes cleave phthalate side chains (Bauer and Herrmann, 1998; Jonsson et al., 2003). However, Bauer and Herrmann (1998) also noted that abiotic hydrolysis is more prevalent in dryland environments compared to biological hydrolysis. The primary drivers of abiotic hydrolysis in terrestrial settings are environmental pH and the length of the phthalate side chain (Alao et al., 2025). Detailed decomposition pathways of phthalates under dryland conditions have been extensively reviewed by Huang et al. (2013).

Both biodegradation and hydrolysis of phthalates in landfills are influenced by multiple factors, including landfill degradation phase, phthalate chemical properties, pH, redox conditions, and organic matter content of the leachate. Due to the low electrophilicity of phthalate esters, they exhibit minimal reactivity at neutral pH; however, hydrolysis rates increase significantly under acidic or alkaline conditions (Shen et al., 2025; Xu et al., 2008).

Ecological risk assessments in urban aquatic environments in China have demonstrated that certain phthalates, such as diethyl phthalate (DEP) and dibutyl phthalate (DBP), occur at elevated concentrations and pose significant ecological risks (Zhang et al., 2015). According to this study, the ecological risk values for DEP and DBP were 2.37 and 2.16, respectively, indicating a high risk to aquatic environments. Similarly, Gao et al. (2020) reported high levels of dimethyl phthalate (DMP) and DEP in the Taihu Lake basin, with ecological risk values of 2.54 and 2.39, respectively. Xu et al. (2008) assessed phthalate contamination in sediments of the Yangtze River, reporting elevated ecological risks for DBP (1.92) and di(2-ethylhexyl) phthalate (DEHP) (2.11). Beyond ecological concerns, Liu et al. (2019) evaluated human health risks from phthalate contamination in China, revealing carcinogenic and non-carcinogenic risk values exceeding permissible limits in certain regions. Consistent with these findings, the present study in coastal areas of the southern Caspian Sea identified significant public health risks associated with phthalate contamination. Astara station exhibited the highest Pollution Load Index (PLI) of 20.24, indicating substantial health risks, while Talesh station recorded the highest Contamination Factor index (CFi) of 80.30, suggesting the greatest exposure to phthalate pollution. These results align with Shan et al. (2016), who demonstrated that elevated CFi values correspond to increased environmental risk. Compared with other global studies, the coastal Caspian Sea regions, particularly Astara and Talesh, are notably vulnerable to phthalate-associated environmental and health hazards. This concurs with Gao et al. (2020) whose ecological risk assessment in the Taihu Lake basin highlighted similar concerns.

Overall, the PLI and CFi indices applied in this study underscore the significant risk posed by phthalate pollution in Caspian coastal areas. These findings provide valuable insights for the development and implementation of targeted management and remediation strategies.

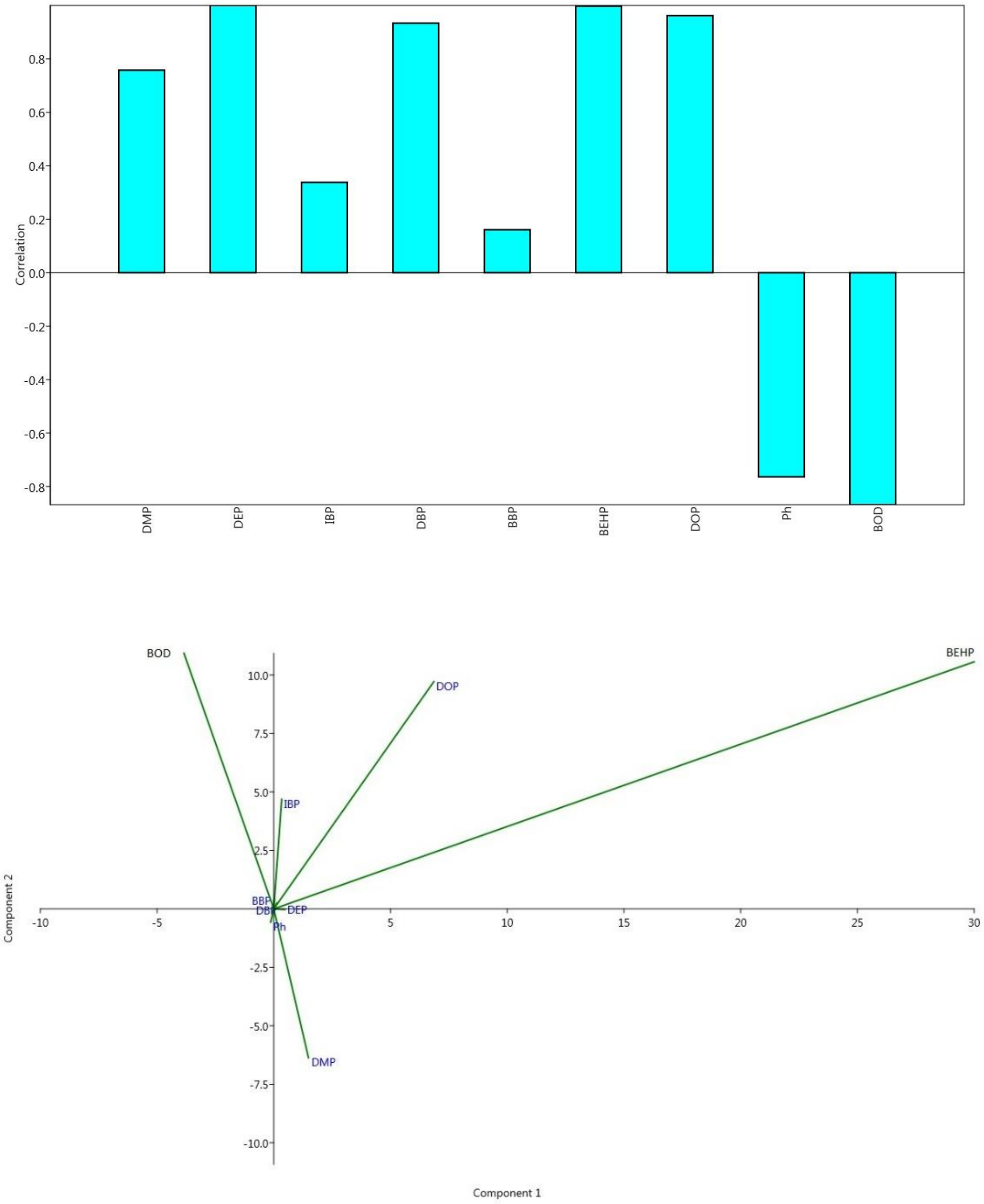

Figure 5. Principal Component Analysis (PCA) for the relationship between pH and BOD and phthalates in leachate

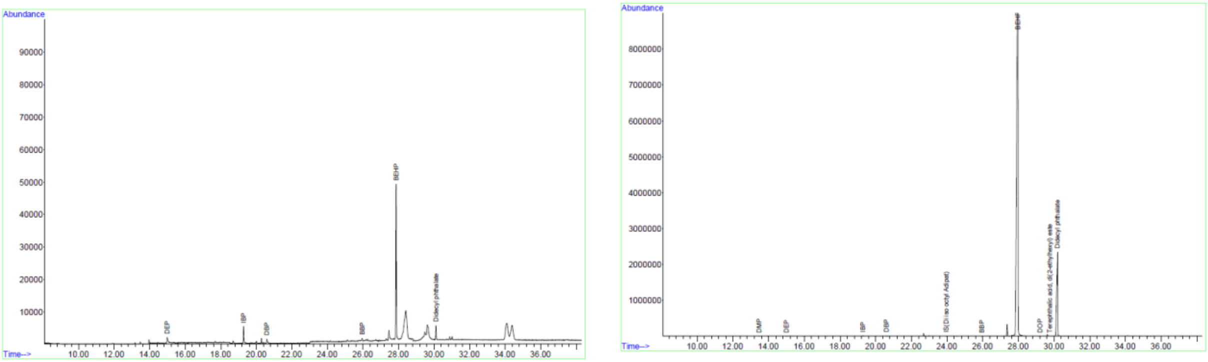

Figure 6. Separation and identification of various phthalate esters in two samples using GC-MS

Landfill waste decomposition is governed by both aerobic and anaerobic processes. Under anaerobic conditions, the degradation of compounds such as phthalates is slower and heavily influenced by environmental parameters including pH and chemical characteristics of the compounds. These factors critically affect hydrolysis and biodegradation rates, emphasizing the importance of optimizing landfill management and environmental conditions to mitigate phthalate pollution effectively.

5. Conclusion

This study demonstrated significant variations in phthalate concentrations in landfill leachate across the cities of Astara, Talesh, and Anzali. These variations are influenced by environmental factors including precipitation, waste composition, and the uncontrolled, unsegregated disposal of different waste types. The highest phthalate concentrations, particularly BEHP, were detected in Astara, with a positive correlation observed between phthalate levels and the biochemical oxygen demand (BOD) of the leachate. Health risk assessments revealed elevated contamination at the Talesh station and considerable public health risks at the Astara station. These findings highlight the critical need for enhanced monitoring and management of landfill leachates and underscore the necessity for further research into the health and environmental impacts of phthalate contamination. The results obtained demonstrate the need for continuous monitoring of the quality of landfill leachate and management measures to reduce the impacts of these compounds. To improve the management of landfill leachate, it is recommended that comprehensive and continuous monitoring programs be established to monitor the concentrations of phthalates and other pollutants in leachate. It is also necessary to improve waste management methods, including waste separation at source and the use of modern technologies to reduce leachate generation. Increasing public awareness of the dangers of phthalates and encouraging the use of phthalate-free products can also help reduce pollution. In addition, further research is needed to investigate the long-term effects of phthalates on the ecosystem and human health and to identify the sources of pollution. Among the limitations of this study, we can mention the lack of a more detailed examination of seasonal and geographical effects on phthalate concentrations. Also, the lack of a more comprehensive assessment of different sources of pollution and their effects on the results obtained may lead to the neglect of some local and regional variations. In addition, due to the limited number of samples and sampling stations, some fluctuations in phthalate concentrations at different locations may have been overlooked. Therefore, it is suggested that future studies include more extensive sampling and investigation of environmental factors affecting phthalate concentrations to gain a better understanding of the pollution dynamics in these areas.

Acknowledgments: The authors are grateful to all supporting organizations for providing facilities to conduct and complete this study.

Disclosure statement

The authors declare that they have no conflict of interest

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Funding

This research did not receive any grant from public, commercial, or non-profit agencies.

Ethical Approval and Consent to Participate

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Consent for publication

The authors declare that this manuscript does not contain any person’s data and material in any form.

Authors Contribution

Somayeh Nemati Gaskaminjan:Conceptualization, Research, Methodology, Illustration, Writing - main draft - preparation, creation
Fatemeh Shariati: Supervision, Conceptualization, Methodology, Writing - review and editing
Mohsen Mohammadi Galangash: Writing - review and editing
Leila Ooshaksaraei: Writing - review and editing

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

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

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