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ORIGINAL RESEARCH ARTICLE

Analysis of benzene, toluene, and xylene contaminants in the groundwater of Tripoli, Lebanon

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Abstract: Globally, groundwater is a critical source of freshwater that supports drinking water, agriculture, and industry. Its protection is vital for long-term water safety and public health. In Lebanon, groundwater provides nearly half of the nation's water supply; however, it faces significant challenges from unregulated extraction, poor infrastructure, and widespread contamination. The city of Tripoli is particularly vulnerable, where defective underground fuel storage tanks, unmanaged waste, and unrestricted well usage have led to alarming levels of toxins such as benzene, toluene, and xylene (BTX). Such conditions pose serious risks to both water sustainability and human health, emphasizing the critical need for regular monitoring and effective regulation. This study aims to investigate the presence of BTX in the groundwater of Tripoli, Lebanon, and to quantify their compound concentrations using gas chromatography–mass spectrometry. A total of 24 water samples were collected on multiple occasions from private wells during the winter, spring, and summer seasons and subsequently analyzed. Results indicated that BTX concentrations in many of the sampled wells, across most seasons, exceeded the maximum contaminant levels established by the United States Environmental Protection Agency for safe drinking water (0.005 ppm for benzene, 1 ppm for toluene, and 10 ppm for xylene), rendering the water unsuitable for drinking. The study revealed seasonal variations in BTX concentrations, with higher levels detected in spring and summer, and lower levels in winter, likely due to seasonal dilution effects from rainfall and infiltration. Among the BTX compounds, xylene exhibited the highest concentrations, followed by toluene, with benzene present at the lowest levels. The detection of BTX in the sampled groundwater clearly indicates pollution. Consequently, remediation measures are necessary to mitigate long-term health risks associated with these pollutants, and continuous monitoring of BTX levels is strongly recommended to effectively assess and manage groundwater pollution.

Keywords: Groundwater; Pollution; Benzene; Toluene; Xylene; Gas chromatography–mass spectrometry; Tripoli, Lebanon

1. Introduction

Globally, groundwater contamination by petroleum hydrocarbons is a pressing public-health and water-security issue.[1,2] Exposure to benzene, toluene, and xylene (BTX) can cause serious health effects, including carcinogenic risks and neurotoxicity.[3] Short-term exposure may lead to temporary disruptions of the nervous and immune systems, with symptoms such as fatigue, nausea, and confusion,[4] while long-term exposure has been associated with chromosomal aberrations, various cancers, liver and kidney damage, and significant neurological disorders, including tremors and impaired cognitive function.[5-7] Accordingly, continuous monitoring and risk assessment of BTX exposure, particularly in occupational settings, are essential for protecting public health.[8,9] These concerns overlap with broader water security challenges, where improving wastewater treatment,[10] enforcing stricter groundwater extraction regulations,[11] and implementing climate-resilient water management strategies are widely recommended to safeguard future water resources.[12] More broadly, contamination and depletion, intensified by unregulated extraction, pollution, and inadequate infrastructure, elevate the risks to effective groundwater protection.[13]

Pathways that introduce petroleum-related pollutants into aquifers are well recognized.[14] Faulty or poorly maintained underground storage tanks can leak gasoline into surrounding groundwater, and the decomposition of organic waste released into the environment due to poor waste management increases pollutant loads through infiltration—processes that introduce harmful compounds such as BTX into aquifers.[15,16] These mechanisms highlight why sustained regulatory oversight and technical monitoring are critically needed to prevent contamination events before they translate into public health impacts.[5,17]

At the regional scale, groundwater serves as a primary source of water for Lebanon, supplying nearly 50% of the national needs.[18] The nation's karstic aquifers, particularly the Jurassic (J4) and Cretaceous (C4–C5) formations, are essential to this supply but are highly susceptible to overexploitation and contamination.[19] An estimated 55,000 to 60,000 unregulated wells place substantial pressure on groundwater reserves, complicating efforts to manage water quality and ensure long-term sustainability.[20] Although public wells are subject to regulation, monitoring and oversight remain insufficient to prevent misuse and maintain water integrity.[21] Studies conducted by institutions in Lebanon underscore the pressing demand for sustainable groundwater management, recommending policies that regulate well usage and enhance monitoring systems.[22,23] In parallel, organizations such as the United Nations Children's Fund and the United Nations Development Program have consistently reported on the country's water quality challenges and emphasized the importance of stronger controls and climate-resilient approaches.[12]

Locally, Tripoli is the second-largest city in Lebanon. It is situated at approximately 34°26'12''N latitude and 35°50'04''E longitude, with altitudes varying from 6 to about 90 meters above sea level.[24] The city is bordered by the Mediterranean Sea to the west and by neighboring towns such as El-Mina, El-Baddawi, Zgharta, and El-Koura. The geography of Tripoli features two main hills to the northwest—Abou Samra and El-Kobbeh—which rise to about 75 and 85 m, respectively, with lower-lying lands stretching southeast. The Abou Ali River runs between these elevated regions, highlighting the city's diverse topographical layout.[23,25,26] The main drinking-water sources for Tripoli are the Rachiine and Hab springs, located outside the city.[27] Following the end of the Lebanese Civil War in 1990, damage to the water infrastructure, particularly the channels supplying these springs, led water authorities to increasingly depend on local groundwater wells.[28] This shift resulted in the establishment of around 250 licensed private wells; however, the number of unlicensed and unmetered wells is estimated to be three to four times greater due to weak regulatory oversight. Many of these wells were drilled to address shortages, yet remain untreated, making the water unsuitable for direct consumption without further purification.[28,29]

The region's heavy reliance on groundwater has led to high levels of contamination from various pollutants, particularly in unregulated wells, and research highlights the need for more robust monitoring and regulations to manage these resources sustainably.[30] This contamination depends on several key factors, such as the timing of sampling and monitoring, fluctuating risk levels, the effectiveness of remediation strategies, pollutant transport behavior, and other environmental variables. Within Tripoli's approximately 20.17 km^2, there are around 71 fuel stations—a notably high density—with many reported to have faulty underground storage tanks that leak gasoline into the groundwater.[31] In addition, poor waste management and the decomposition of organic waste contribute to elevated pollutant levels.[15,16] Through infiltration, such leakage is a significant driver of BTX contamination in groundwater.[5,17] In this study, we investigate the presence of BTX in the groundwater of Tripoli, Lebanon, and quantify their concentrations using gas chromatography–mass spectrometry.

2. Materials and methods

2.1. Studied area and hydrogeological conditions

Background research on the study area was conducted to review existing data and to identify community-perceived problems or issues of concern. This was followed by a field-based assessment of land use patterns and their implications for water quality, supplemented where possible with additional data. A 1-year sampling process was then carried out to identify pollution hotspots and potential point and non-point sources of contamination. Based on the city's topography, Tripoli was divided into four geographical districts, as represented in Figure 1.

Figure 1. Satellite view of Tripoli[32]

Hydrogeologically, Tripoli lies above a coastal aquifer system from the Miocene to Quaternary periods. The system consists mostly of permeable materials like marly sands and conglomerates, which rest on a less permeable marl-limestone layer, located around 200 m below sea level (Figure 2). Groundwater in the area is mainly replenished by rainfall and snowmelt flowing from the eastern mountains, although the short wet season limits the volume of recharge. The aquifer is highly karstified and fractured, allowing rapid water movement toward the Mediterranean Sea.[33,34] However, decades of intensive groundwater extraction have led to overuse, resulting in a significant deficit and the intrusion of seawater into freshwater zones. Water quality has further deteriorated due to increasing concentrations of salts and pollutants, likely stemming from seawater intrusion, wastewater discharge, and agricultural runoff.[35]

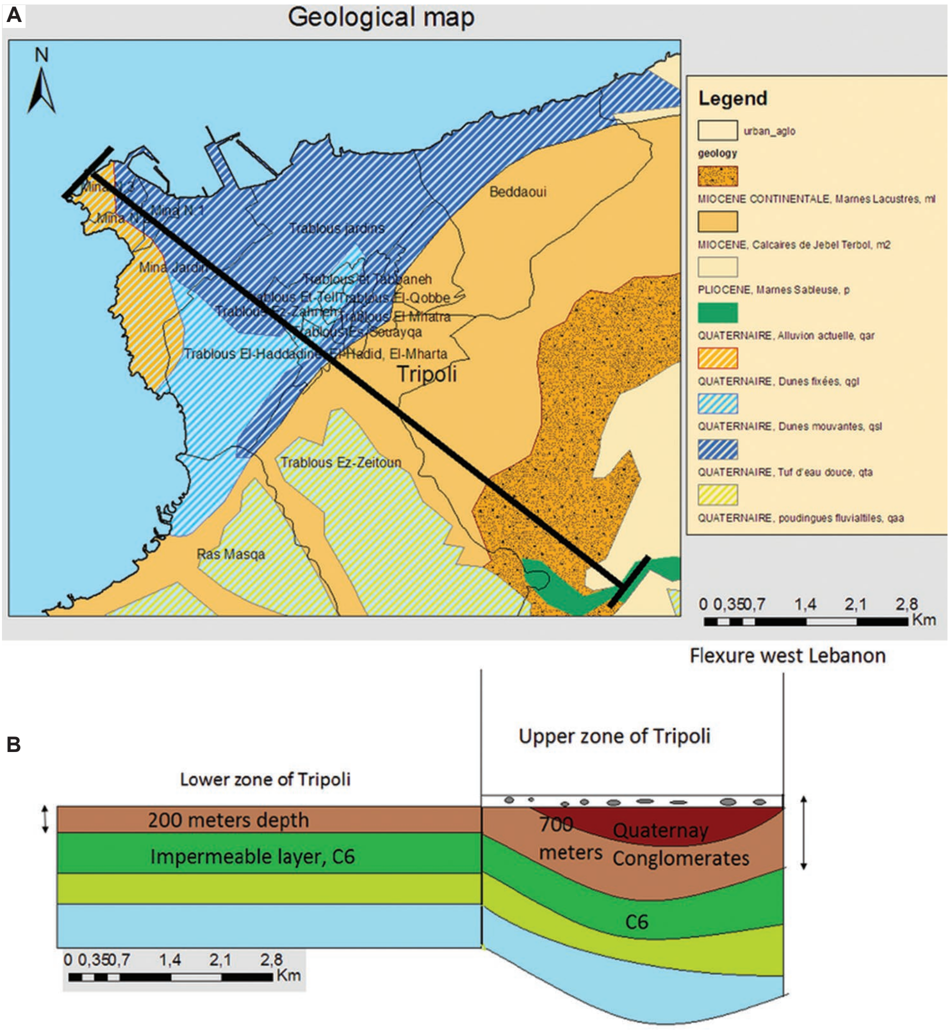

Figure 2. Elevation and geological maps of the study area. (A) Elevation map of Tripoli watershed; (B) Geological map and stratigraphy of Tripoli. Adopted from Kalaoun *et al.*[36]

2.2. Methodology

2.2.1. Collection of samples

Samples were collected and monitored for over a period of 9 months, from January to September 2013. Figure 3 shows the sampling locations and the locations of fuel stations in Tripoli.

Proper sampling procedures are an important part of any water quality survey and are essential for evaluating compliance with water quality standards. Improper collection, preservation, transportation, or identification of samples can lead to misleading test results. Given that water quality test outcomes form the basis for decisions that affect public health, scientifically rigorous sampling procedures were followed. A 500 mL polyethylene bottle was used for sample collection. After sampling, the bottles were placed in a cooler packed with ice and transported to the Water Quality Engineering Laboratory at the University of Balamand. The time between collection and analysis was kept under 24 h.

A total of 24 samples were collected from various private wells distributed across the city, selected based on a 500-meter radius between wells and the availability of wells in each area. A Global Positioning System device, model eXplorist 100 Magellan (Magellan, USA, was used to record the geographical coordinates of the sampling points. The distribution of sampling locations across the four districts is as follows:

(i) Old Tripoli district: Eight samples, referenced OT1 to OT8.

(ii) New Tripoli district: Three samples, referenced NT1 to NT3.

(iii) Abou Samra district: Six samples, referenced AS1 to AS6.

(iv) Kobbeh district: Seven samples, referenced K1 to K7.

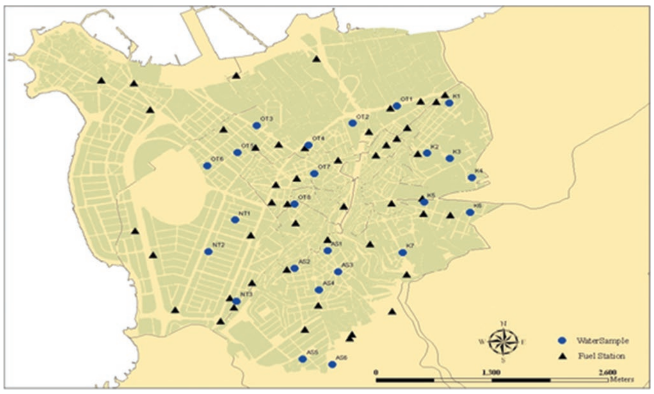

Figure 3. Sampling and fuel station locations (Water Establishment of North Lebanon)

Notes: Dots in blue represent the water sampling; Triangles in black represent the fuel station (as per 2013)

Abbreviations: AS: Samples from Abou Samra; K: Samples from Kobbeh; NT: Samples from New Tripoli; OT: Samples from Old Tripoli.

2.2.2. Equipment used

The gas chromatography used in this study was Varian CP-3800 (Agilent Technologies, USA), coupled with a Saturn 2200 mass spectrometer (Agilent Technologies, USA), and equipped with a Varian PAL auto-sampler. Equilibrium headspace analysis was employed to extract BTX compounds from the water samples.[37]

2.3. Analysis procedure

Each sample was introduced into a 20 mL standard headspace vial and sealed. The vial was then heated and stirred, allowing the BTX compounds to volatilize into the headspace until equilibrium between the headspace and the sample matrix was reached. The volatile fraction containing the BTX under study was then directly introduced into the gas chromatography column via the injector by the headspace syringe (auto sampler).[38]

After passing through the gas chromatography, the BTX molecules entered the mass spectrometer, where they were ionized by electron impact, causing them to break into fragments and become positively charged particles. As the ions passed through the MS, they traveled through an electromagnetic field that filtered them based on their mass-to-charge ratio (m/z). In this study, the MS scanned from m/z = 50 to m/z = 300. The filter continuously scanned this mass range as the ion stream was emitted from the source. A detector counted the number of ions at each specific mass, and this information was sent to a computer to generate a mass spectrum (Figure 4). The mass spectrum is a graph

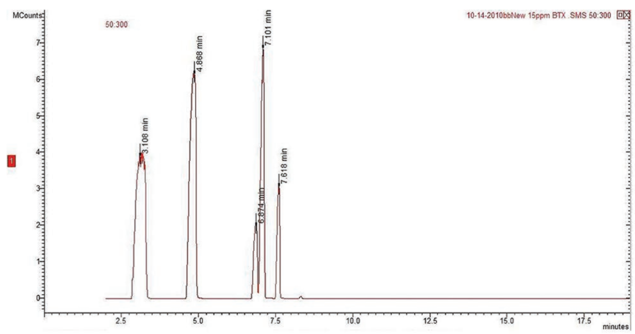

Figure 4. Chromatogram of benzene, toluene, and xylene standard solutions obtained by gas chromatography–mass spectrometry

displaying the number of ions with different masses that traveled through the filter.[39]

The gas chromatography–mass spectrometer conditions are as follows:

- Gas chromatography parameters: Syringe temperature: 35°C; agitator temperature: 35ºC; incubation time: 20 min; incubation revolutions per min: 5,000 rpm; injector type: 1177; injector temperature: 200ºC; column: VF-5ms, 30 m × 0.25 mm ID × 0.25µm df; oven temperature: 35ºC to 200ºC at 7ºC/min; total run time: 25.57 min; column flow: 1.2 mL/min (He).
- Mass spectrometer parameters: Full scan mode with mass range between 50 and 300 m/z.

2.4. Calculation method

An external standard reference material for BTX was prepared with 10,000 ppm of each compound dissolved in methanol (solution A). Various standard solutions with different concentrations were prepared from solution A by serial dilution. These solutions were injected into the gas chromatography–mass spectrometry system to generate calibration curves. Figure 4 shows the chromatogram of a standard solution, and Table 1 provides the retention time of benzene, toluene, p-xylene, o-xylene, and m-xylene, which are the target compounds in this study.

3. Results

To evaluate seasonal variations in groundwater contamination, the 9-month sampling period was divided into three distinct seasons: winter (January, February, and March), spring (April, May, and June), and summer (July, August, and September). As previously described, BTX concentrations in all collected samples were quantified using gas chromatography–mass spectrometry and compared against the maximum contaminant levels (MCLs) established by the United States Environmental Protection Agency (EPA) (0.005 ppm for benzene, 1 ppm for toluene, and 10 ppm for xylene).[37] The analytical results revealed that BTX concentrations in all groundwater samples exceeded the MCL throughout the study period, indicating widespread contamination. Table 2 presents the average concentrations of each BTX compound across all sampling sites during each season. Notably, seasonal variations in BTX levels were observed, with generally higher concentrations detected during the summer months. This may be attributed to increased volatilization, reduced greater microbial activity under warmer conditions, all of which can influence contaminant mobility and persistence. These findings underscore the need for continuous groundwater monitoring and the implementation of potential remediation strategies, particularly during periods of increased environmental vulnerability.

Moreover, seasonal variations in the concentrations of BTX were analyzed across all sampling locations. A consistent pattern was observed, wherein the concentrations of these three compounds were lowest during the winter season and comparatively higher in spring and summer. This trend was evident across all districts, suggesting that seasonal climatic factors, such as temperature, evaporation rates, and possibly anthropogenic activities, may influence BTX concentration levels in groundwater. Figure 5 illustrates the seasonal distribution of BTX in the New Tripoli district, used here as a representative example. The data show that BTX percentages in New Tripoli follow the same seasonal trend observed in other districts. While specific concentration values may vary by location, the overall seasonal behavior of BTX compounds remains consistent across the study area. These findings highlight the importance of considering seasonal dynamics when assessing groundwater contamination and planning mitigation efforts.

The observed seasonal variations in BTX concentrations cannot be explained solely by rainfall quantity throughout the year. Winter typically experiences higher precipitation compared to spring and summer, which are considered dry seasons. Therefore, the infiltration process is more significant in winter, and the groundwater table is generally higher, potentially contributing to some dilution of contaminants during the wet season. However, this dilution effect would likely impact all BTX compounds similarly, which is not reflected in the observed data (Figure 5). The differing trends among BTX concentrations suggest that additional factors beyond hydrological dilution, such as source variability, physicochemical properties, and potential biodegradability, may be influencing the

Table 1. Retention time of benzene, toluene, and p-, m-, o-xylene by gas chromatography–mass *spectrometry*

Parameters	Retention time (min)
Benzene	3.108
Toluene	4.868
p-xylene	6.874
m-xylene	7.101
o-xylene	7.618

Table 2. Average concentration of benzene, toluene, and xylene across the sampled seasons for all locations in Tripoli, Lebanon

Locations	Benzene concentration (ppm) (MCL=0.005 ppm)			Toluene concentration (ppm) (MCL=1 ppm)			Xylene concentration (ppm) (MCL=10 ppm)		
	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer
Old Tripoli									
OT1	0.309	0.076	0.076	98	82	82	1,175	1,033	1,034
OT2	0.075	0.039	0.03	64	13	10	399	171	150
OT3	0.201	0.667	0.03	205	462	1	726	15,243	14,108
OT4	0.157	0.679	0.84	60	737	734	1,428	4,422	4,281
OT5	0.096	0.423	0.423	203	230	230	1,317	5,490	5,489
OT6	0.329	0.267	0.168	144	0.16	335	311	6,345	6,281
OT7	0.18	0.384	0.382	117	336	1	866	4,941	4,925
OT8	0.468	0.304	0.306	142	435	431	754	5,800	5,731
New Tripoli									
NT1	0.171	0.19	0.256	69	65	66	1,062	3,004	2,945
NT2	0.132	0.6	0.733	75	735	735	558	11,364	11,120
NT3	0.164	0.005	0.004	110	15	14	932	102	83
Al-Kobbeh									
K1	0.124	0.328	0.295	128	611	574	1,195	7,145	7,202
K2	0.175	0.277	0.275	102	792	760	602	9,261	8,936
K3	0.223	0.058	0.057	83	76	75	996	736	706
K4	0.11	0.169	0.023	37	198	197	432	2,518	2,489
K5	0.115	0.002	0.026	109	10	1	709	340	343
K6	0.221	0.308	0.31	95	512	511	641	6,678	6,685
K7	0.255	0.101	0.104	79	105	103	600	1,650	1,571
Abou Samra									
AS1	0.156	0.957	1.082	117	335	347	1,028	7,368	7,262
AS2	0.161	0.021	0.021	117	32	32	993	233	239
AS3	0.035	0.004	0.004	39	13	13	512	207	196
AS4	0.56	0.005	0.005	105	14	14	422	107	106
AS5	0.08	0.006	0.0037	38	14	11	264	255	225
AS6	0.222	0.033	0.03	149	371	362	1,078	7,364	7,286

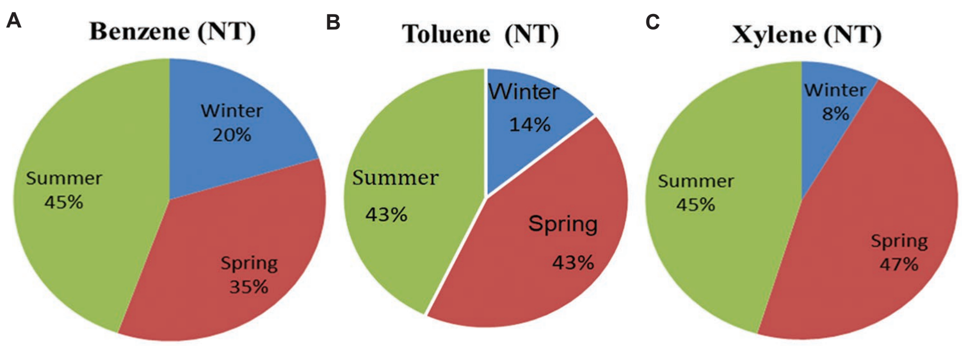

Figure 5. Percentage of benzene, toluene, and xylene in the New Tripoli district in each season. (A) Benzene, (B) Toluene, (C) Xylene (NT).

seasonal behavior, notably the high temperatures in spring and summer.

Figure 6 shows the variation of BTX concentration relative to rainfall quantity; however, further analysis is needed to assess whether other environmental or site-specific conditions are contributing to the observed distribution. Regarding the differences in concentration among the individual BTX compounds, it was observed that xylene exhibits the highest concentration across all sampling sites and seasons, followed by toluene, and then benzene. This pattern may be attributed to differences in chemical properties, environmental persistence, and potential sources. Xylene, being less volatile and more hydrophobic than benzene, may tend to accumulate more in groundwater, particularly under conditions of limited degradation. Comparing across seasons, the reduced precipitation in spring and summer may lead to higher concentrations due to limited dilution. However, this alone does not fully explain why xylene concentrations remain the highest across all seasons. This observation aligns with findings where benzene is typically known to be a persistent pollutant and more soluble under anoxic conditions.[40-42]

Figure 7 presents the average concentrations of BTX in all sampling sites during the studied seasons. As previously noted, xylene consistently exhibits the highest concentration, followed by toluene and then benzene. This distribution likely reflects differences in the compounds' chemical characteristics, including volatility, hydrophobicity, and degradation potential.

4. Discussion

The differences in concentrations among the parameters studied can be attributed to three main factors:

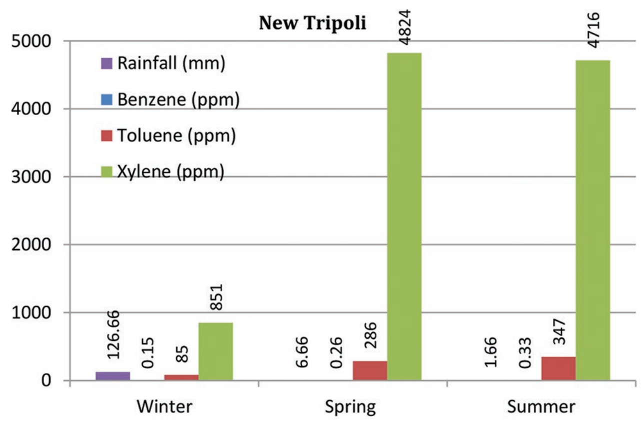

Figure 6. Variation in rainfall and concentrations of benzene, toluene, and xylene in the New Tripoli district

(i) Volatility
Xylene is less volatile than toluene and benzene. This lower volatility may explain why xylene concentrations were higher than those of toluene, which in turn were higher than those of benzene.

(ii) Biodegradation rate of BTX in groundwater
BTX compounds degrade under strictly anaerobic conditions, although xylene degradation is characterized by a prolonged lag phase. Certain bacteria, such as *Dechloromonas* spp. (e.g., strains JJ and RCB), can mineralize benzene and toluene through the benzoyl-coenzyme A pathway. However, only a limited number of microorganisms

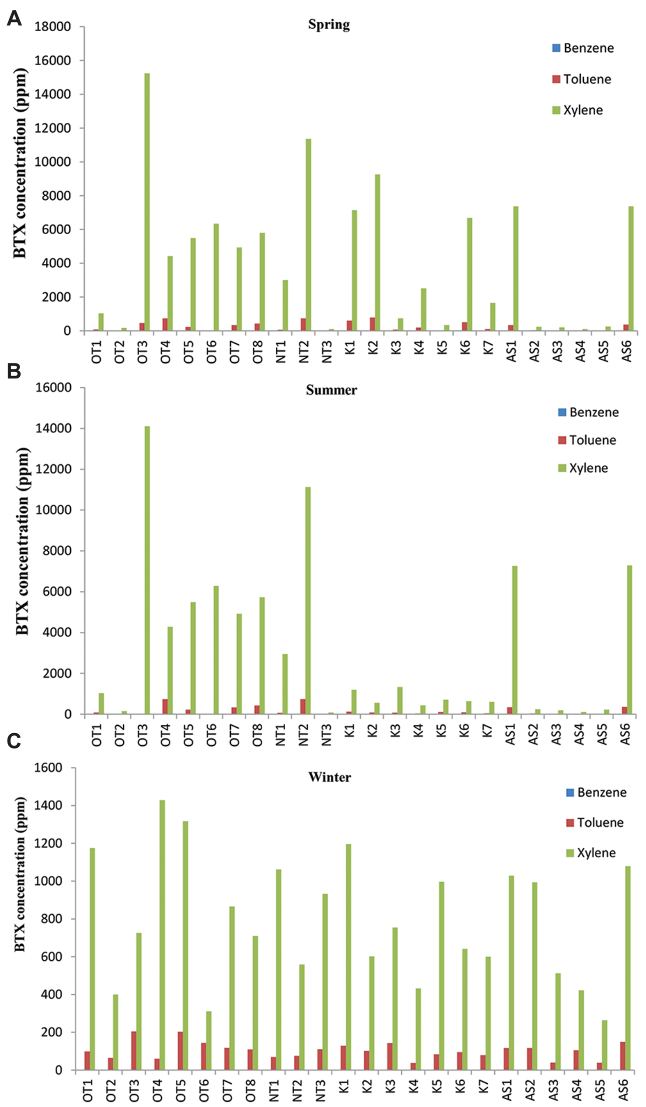

Figure 7. Concentration of benzene, toluene, and xylene (BTX) across all locations during spring, summer, and winter in Tripoli, Lebanon. (A) Spring. (B) Summer. (C) Winter.

are capable of anaerobically metabolizing xylene.[43] Therefore, the slow degradation of xylene, combined with the scarcity of bacteria capable of degrading it, contributes to its consistently higher concentration compared to benzene and toluene.

(iii) Percentage of BTX in gasoline
Gasoline typically consists of various hydrocarbons, with BTX compounds constituting approximately 10–15 % of the total blend. Among these, xylene generally accounts for 50–55%, toluene for 30–35%, and benzene for 10–15% of the BTX fraction. The exact proportions vary depending on the formulation and refining process.[44] Based on these values, xylene is expected to show the highest concentration and benzene the lowest.

The results show that groundwater in the study area is contaminated with BTX compounds. This finding conflicts with the United Nations Sustainable Development Goal (SDG 6: Clean Water and Sanitation), which includes targets such as improving water quality, reducing pollution, and increasing water-use efficiency.

The method used in this study was the Student's *t*-test, applied to compare the mean concentrations of BTX in our samples with the MCL as the reference mean. For each compound, *p*-values and 95% confidence intervals were calculated. Averages and descriptive statistics were obtained for BTX in four regions of Tripoli and for Tripoli as a whole, across three seasons (winter, spring, and summer). The results are presented in Tables 3-5.

For the whole of Tripoli (all regions combined), the *p*-values for all substances and all seasons were ≤0.001, indicating highly significant differences from the MCL. This suggests >99.9% certainty that the water is contaminated with BTX.

For Old Tripoli and Al-Kobbeh, the water is very likely contaminated with one or more BTX compounds across all seasons. In contrast, in New Tripoli and Abou Samra during spring and summer, the *p*-values

Table 3. Benzene concentrations (maximum contaminant level=0.005 ppm)

Region	Winter		Spring		Summer	
	p-value	95% confidence interval	*p*-value	95% confidence interval	*p*-value	95% confidence interval
Old Tripoli	0.002	0.116–0.338	0.004	0.156–0.554	0.024	0.053–0.511
New Tripoli	0.006	0.104–0.207	0.277	–0.491–1.021	0.267	–0.589–1.251
Kobbeh	<0.001	0.119–0.229	0.012	0.058–0.297	0.023	0.034–0.278
Abou Samra	0.049	0.0059–0.399	0.339	–0.233–0.575	0.345	–0.267–0.649
All regions	<0.001	0.146–0.248	<0.001	0.135–0.357	0.001	0.105–0.352

Table 4. Toluene concentrations (maximum contaminant level=1 ppm)

Region	Winter		Spring		Summer	
	p-value	95% confidence interval	*p*-value	95% confidence interval	*p*-value	95% confidence interval
Old Tripoli	<0.001	82.54–175.7	0.016	72.56–501.2	0.044	8.94–4467.1
New Tripoli	0.023	29.66–139.7	0.364	–727.1–1,270	0.364	–727.2–1271
Kobbeh	<0.001	63.86–117.0	0.030	46.47–611.8	0.029	45.40–589.2
Abou Samra	0.004	46.39–141.9	0.128	–52.12–311.8	0.130	–53.04–312.7
All regions	<0.001	84.64–122.4	<0.001	145.5–370.6	<0.001	123.9–346.1

Table 5. Xylene concentrations (maximum contaminant level=10 ppm)

Region	Winter		Spring		Summer	
	p-value	95% confidence interval	*p*-value	95% confidence interval	*p*-value	95% confidence interval
Old Tripoli	0.001	529.8–1,214	0.012	1,619–9,242	0.01	1,722–8,778
New Tripoli	0.031	200.7–1,501	0.29	–9,702–19,350	0.291	–9,512–18,940
Kobbeh	<0.001	495.5–983.1	0.024	744.6–7,349	0.024	737.2–7,243
Abou Samra	0.005	341.5–1,091	0.149	–1,295–6,473	0.149	–1,286–6,391
All regions	<0.001	653.0–930.3	<0.001	2,507–5,975	<0.001	2,477–5,806

exceeded 0.05, indicating no statistically significant difference from the MCL; thus, contamination in these regions during these seasons is unlikely.

5. Recommendations

The observed results highlight a serious public health concern, as the population relies on groundwater for drinking, rinsing, and many other daily activities. The observed BTX concentrations exceed acceptable limits, underscoring the urgent need for intervention.

It is recommended to implement a continuous groundwater monitoring program, including regular sampling of water wells and systematic analysis of pollutants, with a focus not only on BTX compounds but also on other contaminants. Monitoring should be performed across different regions of Tripoli and throughout the seasons. Further investigations are needed to identify the exact sources of BTX contamination (e.g., fuel leaks, industrial activities). Once identified, targeted mitigation strategies should be implemented.

From a technical perspective, there is a strong need for the development of low-cost, rapid monitoring tools that allow on-site, real-time detection of BTX. Promising options include optical and electrochemical sensors designed for environmental applications.[45-47] In parallel, stricter regulations should be enforced for fuel storage tanks and petroleum product handling to minimize the risk of leaks and spills. Public awareness campaigns should be promoted to educate communities about the environmental and health risks associated with BTX contamination and to encourage participation in pollution-prevention efforts. Finally, it is likely that actual levels of contamination are higher than the values reported in this study, especially in the aftermath of the economic crisis and the solid waste crisis in the country. This situation calls for urgent and coordinated action to protect public health and water resources.

6. Conclusion

The presence of BTX in groundwater in Tripoli, Lebanon, is of critical concern. BTX concentrations in the city were consistently high. This pollution likely results from underground leakage of gasoline products or from surface contamination infiltrating the groundwater through rainfall.

Laboratory analyses support the following conclusions: BTX contamination in Tripoli groundwater appears to be seasonally related. Concentrations are higher when the water table is low and lower when the water table is high. Across all seasons, however, BTX concentrations exceeded the MCLs for drinking water set by the EPA, the threshold above which remediation is required.

Gas chromatography–mass spectrometry proved to be a reliable method for quantifying BTX in groundwater, enabling accurate determinations in the low ppm range. The use of a headspace autosampler further improved reproducibility and time efficiency in this study.

It is therefore recommended that BTX contamination in Tripoli groundwater be cautiously monitored to provide a more detailed assessment of its distribution and severity, and to guide appropriate remediation strategies.

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Conflict of interest

The authors declare no competing interests in this study.

Author contributions

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Writing–review & editing: Ayman Chmayssem

Availability of data

The data supporting the conclusion of this work are already presented in the article.

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