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Polycyclic Aromatic Hydrocarbons in the GCC Region: Exposure and Health Risk Assessment

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Abstract: Polycyclic aromatic hydrocarbons (PAHs) are persistent toxic pollutants of increasing concern in Gulf Cooperation Council (GCC) region due to rapid urbanization, industrialization and the dominance of oil and gas extraction activities. This review synthesizes evidence from eligible studies published between 2020 and 2025 that assessed PAH contamination in environmental dust from households, cars, mosques, and sporting walkways. Across these environments, total PAH concentrations ranged from several hundred to over 37,000 ng/g, frequently exceeding international safety benchmarks. While health risk assessments revealed benzo[a]pyrene-equivalent toxicity (BaP-TEQ) values reaching critical threshold of 700 ng/g in some scenarios, incremental lifetime cancer risks (ILCRs) in all the assessed studies spanned 10^{-5} to 10^{-3}, exceeding the U.S. Environmental Protection Agency's acceptable limit of 10^{-6}. Dermal contact and ingestion were consistently the dominant exposure pathways, particularly for children and occupationally exposed groups such as taxi drivers. Smoking, incense burning, and proximity to high-traffic areas intensified PAH burdens. While non-carcinogenic risks were less frequently assessed, hazard index values(HI) occasionally exceeded the safety threshold of 1.0. These findings highlight substantial deficiency of research on chemical exposure-based health risk assessment across GCC countries beyond Kuwait and Kingdom of Saudi Arabia (KSA) and underscore the need for coordinated region-specific health risk frameworks to mitigate PAH exposure risks.

I. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs), defined as organic compounds consisting of multiple aromatic rings formed during combustion processes, represent a significant category of environmental contaminants globally (Alghamdi et al., 2024; Al-Harbi et al., 2020). These semi-volatile organic compounds (SVOCs) are associated with severe adverse health outcomes, including endocrine disruption, neurological disorders, reduced lung function, hormonal imbalance, and elevated cancer risk for children and adults (Alamri et al., 2021; Al-Harbi et al., 2020). In the Gulf Cooperation Council (GCC) region, polycyclic aromatic hydrocarbons (PAHs) are widespread, largely due to extensive fossil fuel use and combustion linked to oil production. The impact of PAHs is further exacerbated by the region arid climate where dust storms mediate PAHs transportation and accumulation (Al-Harbi et al., 2020, 2021).

Wide scope reviews, covering a broad range of geographic regions, allows investigating the linkage between environmental exposures and potential health outcomes and detect underlying patterns and risk correlations that may be overlooked in smaller-scale studies. At the regional level, (Ouda et al., 2021) have primarily focused on the occurrence and spatial distribution of emerging contaminants in the MENA region including GCC, without extending their analysis to the associated health risks. At GCC level, (Khaled et al., 2023) et al. have provided a synthesis of biomonitoring findings, but their work has been limited to human biological samples such as urine, blood, and breast milk. However, to the best of the author's knowledge, no comprehensive review to date has assessed health exposure risks based on environmental data across the GCC region.

Focusing on PAHs, this review addresses a critical gap by evaluating health risks stemming from dust exposure across the GCC. The affinity of PAHs for accumulating in dust and its prevalence in the arid GCC environment make dust an ideal medium for PAHs monitoring (Alghamdi et al., 2024; Al-Harbi et al., 2020). This review considers multiple exposure pathways, namely inhalation, ingestion, and dermal contact. The aim is to deliver a comprehensive regional assessment of human health risks associated with PAHs contamination, supporting evidence-based mitigation and policy interventions tailored to the unique environmental and demographic context of the GCC.

Figure 1: Map of the Gulf Cooperation Council (GCC) region showing the study areas covered by the reviewed articles.

II. SEARCH METHODOLOGY

A systematic literature search was conducted in Scopus to identify peer-reviewed studies assessing human health risks associated with exposure to PAHs in the (GCC) region. The following query was applied: TITLE-ABS-KEY (health AND risk AND (Bahrain OR Saudi Arabia OR Kuwait OR Oman OR Qatar OR UAE)) AND TITLE-ABS-KEY (pollutants OR contaminants OR microcontaminants OR micropollutants) AND TITLE-ABS-KEY (Polycyclic Aromatic Hydrocarbons OR PAHs). Studies were considered eligible if they met all the following criteria:

1) Publication timeframe: 2020-2025
2) Contact medium: dust
3) Geographical Scope: Conducted in at least one GCC country (Saudi Arabia, Kuwait, Oman, Qatar, United Arab Emirates, or Bahrain).
4) Exposure Assessment: Reported measurement of micropollutants, emerging contaminants, or related chemical stressors in environmental media (e.g., water, wastewater, food, air, sediments, or human biomonitoring).
5) Health Risk Outcomes: Provided quantitative human health risk assessment metrics.

The search retrieved a total of 15 records. Only six studies met the eligibility criteria and were included in the review. Notably, the studies retrieved were exclusively from Kuwait (n=2) and Saudi Arabia (n=4), highlighting the limited research from other parts of the GCC region in the field of human exposure and health risk assessment (Figure 1).

III. HEALTH RISK INDICATORS

Health risk assessment methodologies employ several key indicators, mainly categorized into measures for carcinogenic risk and non-carcinogenic risk. These indicators are calculated based on contaminant concentrations and exposure parameters, often following models developed by the United States Environmental Protection Agency (U.S. EPA) ((Al-Harbi et al., 2021); (Alghamdi et al., 2024). In addition, specific metrics dedicated to quantifying risk associated with PAH exposure, such as benzo[a]pyrene (BaP) Toxicity equivalent (BaP-TEQ) and benzo[a]pyrene mutagenic equivalent concentration (BaP-MEQ) are also applied (Alghamdi et al., 2024).

A. *Benzo[a]pyrene (BaP) Toxicity equivalent (BaP-TEQ)*

Benzo[a]pyrene Toxicity equivalent concentration BaP-TEQ is an indicator used in health risk assessment to evaluate the carcinogenic potential of a complex mixture of polycyclic aromatic hydrocarbons (PAHs) relative to the potency of benzo[a]pyrene (BaP) which is considered the most potent carcinogenic and mutagenic PAH indicator (Alamri et al., 2021; Alghamdi et al., 2021, 2024; Al-Harbi et al., 2020).

The BaP-TEQ is calculated using one of two primary methods mentioned in the reviewed articles: 1) The toxic equivalency factor (TEF) method (Alghamdi et al., 2021, 2024; Al-Harbi et al., 2020) or 2) a method based on key highly potent carcinogenic PAHs (Alamri et al., 2021; Ali et al., 2021). The resulting total BaP-TEQ *concentration* is used in subsequent risk calculations, such as the Incremental Lifetime Cancer Risk (ILCR) to assess carcinogenic risk (Alghamdi et al., 2024; Al-Harbi et al., 2020, 2021).

1) *Calculation Using Toxic Equivalency Factors (TEF)*

BaP-TEQ concentration for the PAHs mixture is calculated by multiplying the concentration of individual carcinogenic PAH compounds by their corresponding Toxic Equivalency Factors (TEF) and then summing these results. The formula is expressed as (Alghamdi et al., 2021, 2024; Al-Harbi et al., 2020):

$$\text{BaP-TEQ (mixture)} = \Sigma\,(C_i \times \text{TEF}) \qquad \text{eq (1)}$$

Where:

- BaP-TEQ : The BaP equivalent concentration of the PAH mixture
- C_i : The concentration (e.g., ng/g) of a specific PAH in the sample
- TEF: The Toxic Equivalency Factor, which is the relative cancer potency of the individual PAH compound compared to BaP . The TEFs used are often adapted from those proposed by (Nisbet & LaGoy, 1992). Table1 contains TEF values for various PAHs

2) *Calculation based on the most toxic set of PAHs compounds*

Another specific equation is suggested in a few of the reviewed articles as an alternative way to understand the carcinogenic potential using only the most toxic PAHs (Alamri et al., 2021; Ali et al., 2021):

$$\text{BaP-TEQ} = 0.06 \text{ x BaA} + 0.07 \text{ x B(b + k)F} + \text{BaP} + 0.6 \text{ x DahA} + 0.08 \text{ x IcdP} \qquad \text{eq (2)}$$

Where:

- BaA is Benz[a]anthracene.
- B(b + k)F is the sum of Benzo[b]fluoranthene and Benzo[b]fluoranthene.
- BaP is Benzo[a]pyrene.
- DahA is Dibenz[a,h]anthracene.
- IcdP is Indeno[1,2,3-cd]pyrene.

3) *Interpretation*

BaP-TEQ <70 ng/g: no risk;
BaP-TEQ in the range of 70–700 ng/g: low potential risk;
BaP-TEQ in the range of 700-7000 ng/g: critical value;
BaP-TEQ > 7000 ng/g :high potential risk ((Alghamdi et al., 2024)

B. *The Benzo[a] pyrene mutagenic potency (BaP-MEQ)*

The Benzo[a] pyrene mutagenic potency (BaP-MEQ) is an indicator utilized in health risk assessment to evaluate the mutagenic potential of PAHs mixtures The (BaP-MEQ) value is calculated using a method analogous to the carcinogenic potency BaP-TEQ, but the toxic equivalency factors (TEF) are substituted with Mutagenic Equivalency Factors (MEF) (Alghamdi et al., 2024).

The formula used to calculate BaP-MEQ is (Alghamdi et al., 2024):

$$\text{BaP-MEQ (mixture)} = \Sigma\,(C_i \times \text{MEF}) \qquad \text{eq (3)}$$

Where:

- BaP-MEQ is the Benzo(a)pyrene mutagenic equivalent concentration
- C_i : The concentration (e.g., ng/g) of a specific PAH in the sample
- MEF is the Mutagenic Equivalency Factor, representing the relative mutagenic potential of the individual PAH compound compared to BaP. MEF Values for various PAHs are given in Table 1 . The PAH compounds typically used for calculating

BaP-MEQ are those highly potent compounds considered carcinogenic (Alghamdi et al., 2024): Benz[a]anthracene (BaA), Chrysene (CRY), Benzo[b]fluoranthene (BbF), Benzo[k]fluoranthene (BkF), Benzo[a]pyrene (BaP), Dibenz[a,h]anthracene (DBA), and Indeno[1,2,3-cd]pyrene (IND).

III.1.1. Interpretation**:**

Elevated BaP-MEQ values signal a greater overall mutagenic potential of the PAH mixture.

Table 1: Toxic Equivalency Factors (TEFs) and Mutagenic Equivalency Factors (MEFs) for PAHs

Compound	NA	ACY	ACE	FLU	PHE	ANT	FLT	PYR	BaA	CRY	BbF	BkF	BaP	IND	DBA	BGP
TEF	0.001	0.001	0.001	0.001	0.001	0.01	0.001	0.001	0.1	0.01	0.1	0.1	1	0.1	1	0.01
MEF									0.082	0.017	0.25	0.11	1	0.31	0.29	

C. Indicators for Carcinogenic Risk: Incremental Lifetime Cancer Risk (ILCR) and the Total Cancer Risk (CR)

Incremental Lifetime Cancer Risk (ILCR) Estimates the probability of an individual developing cancer over a lifetime due to exposure to carcinogenic substances. ILCR values are calculated for specific exposure pathways (ingestion, inhalation, and dermal contact), using the Daily Intake (DI) (e.g., ng/(g-day)) for carcinogenic effects eq (4), multiplied by the appropriate Cancer Slope Factor (SF) for that pathway (eq (5)). The total cancer risk (CR) is the summation of ILCR values(eq (6)) (Alamri et al., 2021; Al-Harbi et al., 2021; Ali et al., 2021).

A generic mathematical expression for the DI is (US EPA, 1989) :

$$\mathrm{DI} = \frac{\left(\begin{array}{c}\text{Measured}\\ \text{concentration}\end{array}\right) \text{x} \left(\begin{array}{c}\text{Amount of}\\ \text{contaminated media}\\ \text{contacted}\end{array}\right) \text{x} \left(\begin{array}{c}\text{Exposure}\\ \text{frequency and}\\ \text{duration}\end{array}\right)}{(\text{Body weight}) \text{ x} \left(\begin{array}{c}\text{averaging time: period over which}\\ \text{exposure is averaged}\end{array}\right)} \quad \text{eq (4)}$$

This equation has several variations, depending on the type of contacted medium (e.g., dust, water, etc.) and the route of exposure (e.g., ingestion, inhalation, or dermal contact) (Alamri et al., 2021; Al-Harbi et al., 2021; Ali et al., 2021; US EPA, 1989). For carcinogenic risks, the measured concentration is often substituted by the BaP-TEQ concentration (eq(1)) (Alghamdi et al., 2024; Al-Harbi et al., 2021). Exposure frequency and duration are used to compute the total time of exposure by multiplying the exposure frequency (e.g., days/year) by the exposure duration (e.g., years). In carcinogenic risk assessments, the averaging time is the standard human life expectancy, i.e., 70 years (US EPA, 1989). Conversion factors are sometimes used to maintain consistency of units (Alamri et al., 2021). Additionally, a body-weight scaling factor can be used to adjust the exposure estimate when the assessed population's weight deviates from the standard human weight of 70 kg (Alghamdi et al., 2024; Al-Harbi et al., 2020, 2021). Table 2 shows the commonly used parameters in daily intake (DI) and carcinogenic risk (CR) calculations. Case-specific parameters such as exposure time and exposure frequency are determined based on the research question and are therefore excluded.

For a specific exposure route (Alamri et al., 2021; Al-Harbi et al., 2021; Ali et al., 2021) :

$$\mathrm{ILCR} = \mathrm{DI} \times SF \quad \text{eq (5)}$$

Table 3 contains SF values for the three contact routes (Alamri et al., 2021; Alghamdi et al., 2024; Al-Harbi et al., 2020, 2021).

Total cancer risk (CR) is expressed as:

$$\mathrm{CR} = \mathrm{ILCR}_{\text{Ingestion}} + \mathrm{ILCR}_{\text{inhal.}} + \mathrm{ILCR}_{\text{Dermal}} \quad \text{eq (6)}$$

1) Interpretation

Based on US EPA rules (Alghamdi et al., 2024):

ILCR or CR $\leq 10^{-6}$: Considered virtually safe or insignificant risk.

ILCR or CR between 10^{-6} and 10^{-4}: Denotes a potential cancer risk

ILCR or CR between $\geq 10^{-4}$ likelihood of great risk.

Table 2: Parameters Used in the Health Risk Assessment Models.

Parameters	(Alghamdi et al., 2021; Al-Harbi et al., 2020, 2021)		(Alamri et al., 2021)		(Ali et al., 2021)
Description	Adult	Child	Adult	Child	Driver
Ingestion rate (mg/day)	100	200	100	200	200
Exposed skin area (cm^2/day)	5700	2800	6700	1600	890 (hands)
Skin adherence factor (mg/cm^2)	0.07	0.2	0.5	0.5	0.1
Exposure duration (year)	24	6	30	2	25
Lifetime	70	70	70	70	75
Body weight (kg)	70 61.5 (Al-Harbi et al., 2020, 2021)	15	70	15	70
Dermal adsorption fraction (unitless)	0.13	0.13	0.001	0.03	0.2
Inhalation rate (m^3/day)	20	10	20	7.6	15.8
Particle emission factor (PEF) (m^3/kg)	1.36×10^9	1.36×10^9	1.36×10^9	1.36×10^9	Expressed as Particle concentration in air: 0.76 µg/m³

Table 3: Table Carcinogenic slope factor (SF) for various contact pathways (Alghamdi et al., 2024; Al-Harbi et al., 2020)

Carcinogenic slope factor (SF)	Value
$SF_{ingestion}$ (mg/kg/day)	7.3
$SF_{inhalation}$ (mg/kg/day)	3.85
SF_{dermal} (mg/kg/day)	25

D. Indicators for Non-Carcinogenic Risk: Hazard Quotient (HQ) and the Hazard Index (HI)

The non-carcinogenic risk is quantified using the Hazard Index (HI), which is derived from the calculated Daily Intake (DI) and the Hazard Quotient (HQ) for various exposure pathways (Alamri et al., 2021; Al-Harbi et al., 2021). The initial step involves calculating the DI as described in section 3.3 (eq (4)). Unlike carcinogenic risk which apply BaP-TEQ concentrations, the non-carcinogenic risk calculations rely on using the actual concentration of the pollutant (Al-Harbi et al., 2021), and the averaging time is often the exposure duration instead of life time (US EPA, 1989). The Hazard Quotient (HQ) is calculated for each exposure route by dividing DI for that route by the corresponding Reference Dose (RFD) (eq (7)) (Alamri et al., 2021; Al-Harbi et al., 2021). Table 4 shows reference values of sellected PAHs. The hazard index HI is the summation of HQ values calculated for all simultaneous exposure routes (eq (8)) (Alamri et al., 2021; Al-Harbi et al., 2021).

$$HQ = DI/RFD \qquad \text{eq (7)}$$

$$HI = \Sigma\ HQ \qquad \text{eq (8)}$$

1) Interpretation

- HQ or HI ≤ 1: no potential non-carcinogenic risk.
- HQ or HI > 1: a potential for adverse non-carcinogenic health effects (Al-Harbi et al., 2021).

Table 4: Reference Doses (RfDs) for Selected Polycyclic Aromatic Hydrocarbons (PAHs)

Compound	Nap	Pyr	(B[a]P)	Reference
Reference value mg/(kg/day)	0.02	0.03	0.0000667	(*Federal Contaminated Site Risk Assessment in Canada*, 2021)

IV. POLYCYCLIC AROMATIC HYDROCARBONS OCCURRENCE AND HEALTH IMPLICATIONS

The reviewed studies fell into two groups. The first group comprised closed environments, including samples collected from houses, cars, and mosques, and contained five studies. The second group addressed an open environment, represented by a single study that examined the occurrence of PAHs in walkway dust. The review focused on the main characteristics of each study, namely, (i) occurrence and concentrations, (ii) PAH profiles, (iii) predominant exposure pathways, and (iv) health risk assessment finding. These characteristics are summarized in Table 5 for the reviewed studies.

A. Closed Environment

In Kuwait, (Al-Harbi et al., 2020) conducted a comprehensive survey across 90 residential areas in Kuwait and reported that indoor dust was heavily polluted, with total PAH (Σ16 PAHs) concentrations ranging from 450 to 2242 µg/kg, and an average of 1112 µg/kg. Among the PAHs detected, phenanthrene (179 µg/kg), chrysene (123 µg/kg), and benzo[g,h,i]perylene (BghiP) (88 µg/kg) were the most abundant, indicating strong contributions from petroleum combustion and vehicular emissions. High molecular weight PAHs (HMPAH) (4-6 ring PAHs) made up 61% of the total PAH concentration. The benzo[a]pyrene (BaP) Toxicity equivalent (BaP-TEQ) concentration was 126 mg/kg on average. The study applied the US EPA's incremental lifetime cancer risk (ILCR) model to assess health risks based on BaP-TEQ concentrations. The ILCR values for children (2.23×10^{-3}) and adults (2.15×10^{-3}), mainly via ingestion and dermal contact, exceeded the US EPA's threshold of 1×10^{-6} and even surpassed the critical value of 1×10^{-4}, suggesting a significant carcinogenic hazard from exposure to PAHs. The findings underscore the elevated cancer risk posed by indoor dust-borne PAHs in Kuwait, particularly for children, who are more likely to come into contact with contaminated surfaces.

In Jeddah, Saudi Arabia, (Alamri et al., 2021) found that indoor environments in Saudi households during the COVID-19 lockdown exhibited significantly elevated concentrations of polycyclic aromatic hydrocarbons (PAHs) in settled dust, with total PAHs (Σ 13 PAHs) ranged from 2310 to 37,665 ng/g, with a median concentration of 3980 ng/g and a mean of 6570 ng/g. This level of PAHs was approximately two times higher than those reported in pre-pandemic studies from the same region (e.g., Jeddah and Kuwait). Despite the reduction in outdoor vehicular traffic and industrial activity during the lockdown, indoor PAH levels rose due to these intensified indoor activities such as cooking and incense use. The PAH profile was dominated by low molecular weight compounds, with phenanthrene (Phe) being the most abundant (mean: 1590 ng/g, median: 950 ng/g), followed by pyrene (Pyr) (mean: 910 ng/g, median: 600 ng/g), and fluorene (Flu) (mean: 520 ng/g, median: 255 ng/g). The BaP-TEQ concentrations in indoor dust ranged from 5 to 2710 ng/g, with a mean value of 385 ng/g and a median of 100 ng/g. The health risk assessment revealed that while the non-carcinogenic risk (Hazard Index, HI) remained below the threshold of concern (HI < 1) for PAHs with available derived Reference Doses (RfDs) , the incremental lifetime cancer risk (ILCR) values for total PAHs exceeded the USEPA's acceptable limit of 1×10^{-4} for both adults and children, with ingestion identified as the primary exposure pathway, followed by inhalation and dermal route. For instance, the ILCR for children was calculated at 1.9×10^{-4}, compared to 1.5×10^{-4} for adults. High molecular weight (HMW, 5-6 ring) PAHs contributed 32% of the total PAH . Despite their lower abundance, high molecular weight compounds contributed >90% in the carcinogenic index of PAHs. These results highlight that indoor dust serves as a critical reservoir for PAHs, and prolonged exposure—particularly among vulnerable populations such as children—poses significant long-term health risks.

In Kuwait, (Al-Harbi et al., 2021) studied polycyclic aromatic hydrocarbons (PAHs) in indoor dust from houses and cars in Kuwait. The total PAH concentrations (∑16-PAHs) were similar in houses and cars, with median values under smoking conditions nearly double those in non-smoking environments. In smoking houses, the total PAH concentration (Σ16PAHs) ranged from 1140 to 3402 µg/kg, with a median of 1972 µg/kg and a mean of 2067 ± 653 µg/kg. Similarly, smoking cars had ΣPAH levels ranging from 1082 to 3086 µg/kg, with a median of 1799 µg/kg and a mean of 1908 ± 610 µg/kg. In contrast, non-smoking houses exhibited lower levels, with concentrations ranging from 507 to 1857 µg/kg, a median of 993 µg/kg, and a mean of 1046 ± 347 µg/kg; non-smoking cars had levels ranging from 516 to 1554 µg/kg, with a median of 900 µg/kg and a mean of 945 ± 299 µg/kg. Across all indoor environments, the top three most abundant PAHs were consistently phenanthrene (Phe) , chrysene (Chr) and Benzo[ghi]perylene (BghiP). Interestingly, smoking significantly altered the PAH profile in both settings. In smoking environments, the levels of 3-ring PAHs such as acenaphthene (Ace), acenaphthylene (Acy), and anthracene (Ant) were notably elevated. Across both houses and cars, HMW PAHs (4–6 rings) made up 59–61% of total PAHs. Among exposure pathways, dermal contact accounted for over 65% of the total daily intake, followed by ingestion, while inhalation contributed less than 2%. Health risk assessment based on U.S. EPA models showed that non-carcinogenic risks, expressed as hazard index (HI), were notably high averaging 5.2 ± 1.8 in non-smoking environments and increasing to 11 ± 2.1 in smoking settings, far exceeding the safe threshold of 1.0.

Carcinogenic risk showed ILCR values of 2.78×10^{-3} for children and 2.35×10^{-3} for adults in non-smoking homes, increasing by 1.2–1.5 times in smoking environments. These values far exceed the U.S. EPA's acceptable risk threshold (10^{-6}), indicating a significant cancer risk, particularly for children, due to their skin frequent contact with indoor dust and hand-to-mouth behaviors.

Car Dust (Jeddah): In car dust samples studied in Jeddah by (Ali et al., 2021) , Saudi Arabia, the total PAH concentration (Σ16PAHs) was 2762 ng/g on mean basis. The mean concentrations of the three most abundant PAHs were 410 ng/g for pyrene (Pyr), 340 ng/g for benzo[b]fluoranthene (BbF), and 280 ng/g for phenanthrene (Phe). (BaP), a high molecular weight PAH (HMPAH) with strong carcinogenic potential, was 145 ng/g. Notably, (4–6 ring) HMPAHs—approximately 60% of the total PAH burden in car dust. The most significant exposure route for PAHs in car dust was identified as dermal contact followed by dust ingestion,, and then inhalation, based on estimated dose calculations and ILCR modeling. The BaP-TEQ for the Saudi car dust samples ranged between 5 and 630 ng/g, with a median value of 180 ng/g. Exposure to polycyclic aromatic hydrocarbons (PAHs) via car dust was assessed separately for taxi drivers and regular drivers. Due to their prolonged daily exposure, estimated at 10 hours per day, and likely less car cleaning frequency than regular drivers, taxi drivers exhibited significantly higher PAH intake levels compared to regular drivers. The median ILCR for ΣPAHs reached $8.2 \times 10^{-6}$and the maximum ILCR value, reached 2.2×10^{-5}. Whereas regular drivers experienced a median ILCR of $1.7 \times 10^{-6}$and a maximum ILCR of 4.3×10^{-6}. All these ILCR values exceeded the U.S. EPA safety threshold of 1×10^{-6}

Dust from mosques in Jeddah: (Alghamdi et al., 2024) studied the occurrence of polycyclic aromatic hydrocarbons (PAHs) in indoor dust collected from air conditioning filters of mosques across different functional areas in Jeddah, Saudi Arabia. The highest total concentration of the 16 priority PAHs (Σ16 PAHs) concentration detected in mosques located near car repair workshops(CRWM) (5208 ng/g), followed by urban mosques (UM) (2284 ng/g), suburban mosques (SM) (1527 ng/g), and residential areas mosques (RM) (1039 ng/g). These concentrations significantly exceed the 1000 ng/g threshold commonly used to indicate high pollution. The three most abundant components were benzo[b]fluoranthene (BbF), Chrysene (CRY) , and benzo[ghi]perylene (BGP), with relative contributions of 12.7%, 11.9%, and 9.4%, respectively. The average concentration of BbF, the most prevalent congener, was 306.4 ng/g. The (4-6 ring) HMW-PAHs in mosque represented on average 84.4 % of the total PAHs concentrations. The dermal exposure contributed the highest risk, followed by ingestion and inhalation. Health risk assessment revealed that the incremental lifetime cancer risks (ILCRs) for both children and adults via ingestion and dermal contact exceeded the acceptable threshold of 1×10^{-4}, particularly in mosques near car repair workshops and urban mosques. Notably, children exhibited higher average total cancer risk values (CR = 5.74×10^{-3}) compared to adults (CR = 5.07×10^{-3}), primarily due to behavioral factors such as increased dermal contact with dust and hand-to-mouth activity. Additionally, benzo[a]pyrene equivalent indices were applied, namely the (BaP-TEQ) for *carcinogenic potency* and the benzo[a]pyrene mutagenic equivalent concentration (BaP-MEQ) for *Mutagenic potency*. The values of BaP-TEQ followed the order: CRWM (1124.5 ng/g) > UM (493.2 ng/g) > SM (313.9 ng/g) > RM (196 ng/g) with average value of 510 ng/g. According to established thresholds (<70 ng/g: no risk; 70–700 ng/g: low potential risk; 700-7000 ng/g: critical value; > 7000 ng/g: high potential risk), dust samples from mosques situated near car repair workshops and high-traffic areas surpassed the 700 ng/g critical threshold, reflecting a high carcinogenic burden. The sequence of the BaP-MEQ values was similar to those BaP-TEQ values, and followed the order: CRWM (926.1 ng/g) > UM (406.2 ng/g) > SM (289.3 ng/g) > RM (181.8 ng/g), with average value of 432.92 ng/g. The study concluded that PAH contamination in mosque dust poses a potentially high cancer risk, especially to children, and emphasized the urgent need for routine monitoring and source mitigation strategies in indoor religious environments.

B. Open Environment

In Jeddah, Saudi Arabia, (Alghamdi et al., 2021) investigated the 16 different polycyclic aromatic hydrocarbons (∑16 PAHs) in deposited dust from nine sporting walkways across Jeddah, Saudi Arabia, categorized into urban (USW), suburban (SUBSW), and residential (RSW) zones. The mean concentrations of total PAHs (ΣPAHs) followed a clear spatial gradient—3764 ng/g in USW, 2136 ng/g in SUBSW, and 1357 ng/g in RSW , with an average value of 2420 ng/g across all sites—highlighting the influence of local traffic density. Among the individual PAHs, the three most abundant compounds were benzo[ghi]perylene (BGP), indeno[1,2,3-cd]pyrene (IND) and Dibenz(a,h)anthracene, all of which are high molecular weight. The three compounds were detected in Jeddah sporting walkway dust in a ratio of 17:12:11, respectively, with BGP having the highest average concentration at 406.91 ng/g. (4-6 ring) HMPAHs represented about 87.65% – 89.34% of the total PAHs in the deposited dust across all sites. While respiratory and dermal exposures were considered minimal due to the stationary nature of surface dust, ingestion—especially among children and frequent users—was identified as the primary route of exposure.

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To assess health risks, the study calculated benzo[a]pyrene-equivalent concentrations (BaP-TEQ) using toxic equivalency factors, resulting in values of 780 ng/g (USW), 471 ng/g (SUBSW), and 283 ng/g (RSW). These values were similar to household dust observed in Jeddah in a previous study (mean BaP-TEQ = 663 ng/g) and lower than the global average for indoor and road dust. The authors viewed that the carcinogenic risk posed by the detected PAHs in deposited dust on sporting walkways is relatively low. While not alarming, the risk is still present, especially considering the regular use of these walkways by the public, including children and elderly.

Table 5: Characteristics of the Reviewed Studies on PAH Contamination in GCC

Reference	Matrix	Country	Environment	Total PAHs	BaP-TEQ	Top PAHs	HMW %	population	CR
Al-Harbi et al. (2020), Kuwait - Residential Indoor Dust	Indoor (house Dust)	Kuwait	Closed	1112 µg/kg	126 µgg/kg	Phe, Chr, BghiP	61% (4–6 rings)	Adults	2.15E-03
								Children	2.23E-03
Alamri et al. (2021), Saudi Arabia - Indoor Dust (COVID)	Indoor (house Dust)	Saudi Arabia	Closed	6570 ng/g	385 ng/g	Phe, Pyr, Flu	32% (5–6 rings)	Adults	1.50E-04
								Children	1.90E-04
Al-Harbi et al. (2021), Kuwait - Homes/Cars Smoking	Indoor (House & Car Dust)	Kuwait	Closed	1046 µg/kg (houses /non-smoking)	-------	Phe, Chr, BghiP	59-61% (4–6 rings)	Adults (non - smoking env.)	2.35E-03
				2067 µg/kg (houses/ smoking)				Adults (smoking env.)	3.17E-03
				945 µg/kg (cars /non-smoking)				Children (non-smoking env.)	2.78E-03
				1908 µg/kg (cars /smoking)				Children (smoking env.)	3.75E-03
Ali et al. (2021), Saudi Arabia - Car Dust	Indoor(Car dust)	Saudi Arabia	Closed	2762 ng/g (avg)	180 ng/g	Pyr, BbF, Phe	60% (4–6 rings)	Taxi driver	2.20E-05
								Regular	4.30E-06
Alghamdi et al. (2024), Saudi Arabia - Mosque Dust	Mosque dust	Saudi Arabia	Closed	5208 ng/g (near car repair workshop) 2284 ng/g (Urban) 1527 ng/g (Suburb.) 1039 ng/g (Resid.)	1124 ng/g (near car repair workshop), 493 ng/g (Urban), 313 ng/g (Suburb.), 196 ng/g (Resid.), 510 ng/g (avg)	BbF, Chr, BghiP	84.4% (4–6 rings)	Adults	5.07E-03
								Children	5.74E-03
Alghamdi et al. (2021), Saudi Arabia - Walkway Dust	Outdoor (sporting walkway dust)	Saudi Arabia	Open	3764 ng/g (Urban), 2136 ng/g (Suburb.), 1357 ng/g (Resid.), 2420 ng/g (avg.)	780 ng/g (Urban), 471 ng/g (Suburb.), 283 ng/g (Resid.),	BghiP, IND, DBA	87.65 - 89.34% (4–6 rings)	General population	------

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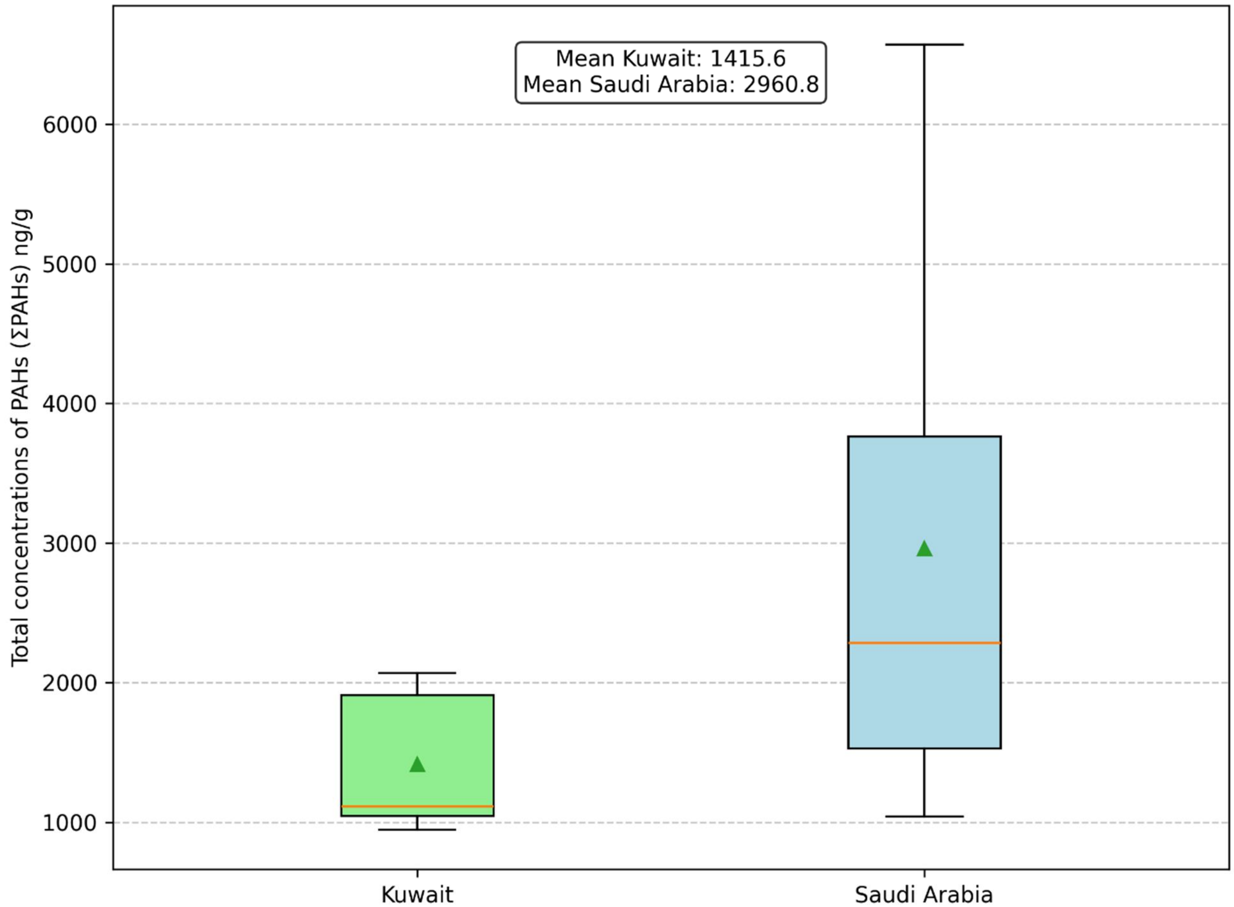

Figure 2: Comparison of total PAHs concentrations (ΣPAHs) in environmental samples from Kuwait and Saudi Arabia.

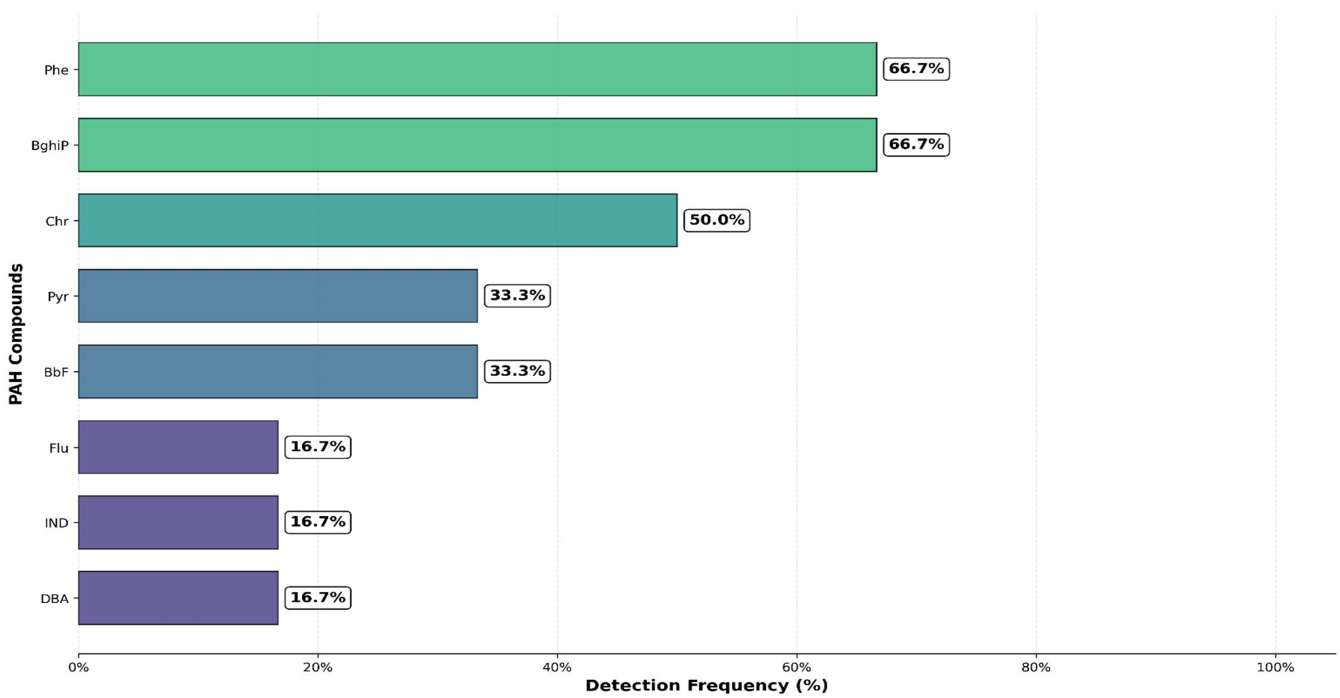

Figure 3: Detection frequency of the most abundant PAHs across reviewed studies in the GCC region

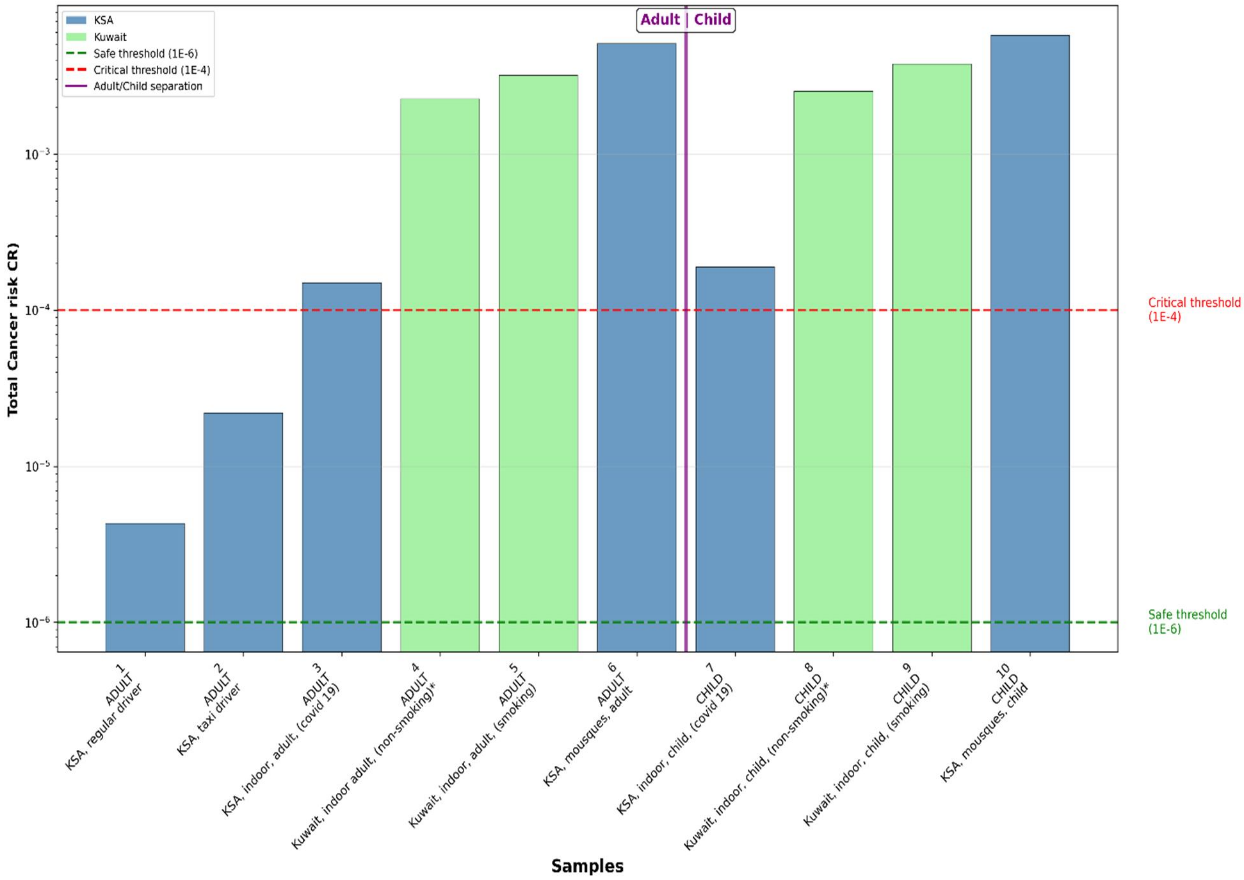

Figure 4: Total cancer risk (CR) from PAH exposure in Kuwait and Saudi Arabia across different environments and population groups (adults vs. children). *: average results of (Al-Harbi et al., 2020) and non-smoking results of (Al-Harbi et al., 2021)

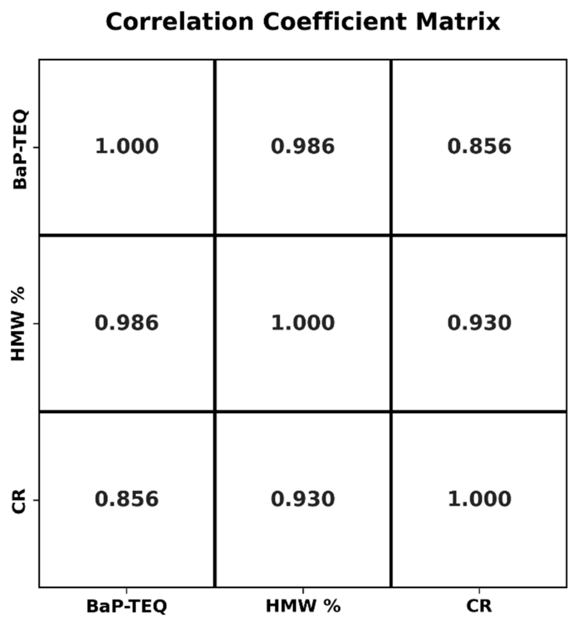

Figure 5: Pearson correlation coefficient matrix for Benzo[a]pyrene Toxic Equivalency concentration (BaP-TEQ), High Molecular Weight Percentage (HMW), and Carcinogenic Risk (CR)

V. KEY INSIGHTS ON PAHS OCCURRENCE AND HEALTH RISK IMPLICATIONS IN GCC COUNTRIES

A thorough examination of the results of the reviewed studies as summarized in Table 5 highlight the following insights.

1) PAHs levels in house and car dust were similar (Al-Harbi et al., 2021)
2) Smoking doubled PAHs levels in closed environments compared to non-smoking conditions (Al-Harbi et al., 2021)
3) Incense use and cooking activities can significantly increase PAH levels in indoor environment (Alamri et al., 2021).
4) Despite the average PAHs contamination level in dust samples from Saudi Arabia (2961 ng/kg), including the various settings (houses, cars, mosques and walkways), was higher than the average value of Kuwait (1416 ng/kg), no statistically significant difference was detected between the two locations using Mann-Whitney U Test ($p = 0.05$) (Figure 2)
5) Focusing on the three most abundant PAHs in each study, phenanthrene (Phe) and benzo[ghi]perylene (BghiP) were the most frequently detected (66.7%), followed by chrysene (Chr) (50%). Other compounds, including pyrene (Pyr), benzo[b]fluoranthene (BbF), fluoranthene (Flu), indeno[1,2,3-cd]pyrene (IND), and dibenz[a,h]anthracene (DBA), showed lower detection frequencies. Phe dominated dust samples from closed environments, whereas IND and DBA occupied a high ranking in open environments (Figure 3, Table 5). This distribution pattern can be attributed to the ability of confined spaces to retain volatile compounds such as Phe, whereas IND and DBA tend to dominate in outdoor environments because they are heavier, and more likely to be associated with traffic-related emissions.
6) Across all assessed closed environments – including houses, cars and mosques – dermal contact followed by ingestion was the dominant exposure route for all populations (children, adults and taxi drivers) (Alghamdi et al., 2024; Al-Harbi et al., 2020, 2021; Ali et al., 2021). An exception was found in a study assessing indoor PAH risks during COVID-19, where the primary exposure scenario was ingestion, followed by inhalation and dermal contact (Alamri et al., 2021). For outdoor exposure, ingestion was the predominant route. The limited volatility of dust-bound PAHs and reduced dermal contact due to skin covering rendered other exposure routes less significant in this case (Alghamdi et al., 2021).
7) Proximity to dense traffic areas is associated with high BaP-TEQ concentrations. Examples include walkways in urban areas (Alghamdi et al., 2021) and mosques near car repair workshops (Alghamdi et al., 2024) (see Table 5).
8) In all the studies that assessed cancer risks based on ILCRs, values were in the order of 10^{-5} to 10^{-3}, exceeding US EPA safe threshold of 10^{-6} and flagging the potential risk posed by PAHs exposure in the studied region (Figure 4).
9) A strong positive correlation was observed between BaP-TEQ concentrations, the percentage of high molecular weight (HMW) PAHs, and the level of carcinogenic risk (CR), indicating the significant contribution of these compounds to the health risk level (Figure 5).
10) The relatively lower risk experienced by regular drivers, who spend less time in cars than taxi drivers, demonstrates how reducing exposure frequency can mitigate an existing risk (Ali et al., 2021) (see Table 5)..
11) Overall, the health risks from environmental exposure to PAHs in the GCC region are alarming, based on the results.

VI. CONCLUSION AND RECOMMENDATIONS

This review confirms that GCC populations are exposed to PAHs at levels exceeding international safety thresholds, particularly for carcinogenic risks. Children and workers with high exposure frequency are especially vulnerable. Based on the findings of this review , the following are recommended:

1) Establishing GCC-wide monitoring programs covering air, water, soil, food, and indoor environments.
2) Developing region-specific health risk guidelines that reflect unique environmental and cultural conditions.
3) Integrating environmental monitoring with biomonitoring and epidemiological studies.
4) Implementing stricter emission and waste management regulations while promoting public awareness of exposure risks.

By adopting coordinated monitoring and policy frameworks, GCC states can mitigate risks, protect public health, and enhance environmental resilience in the face of chemical exposure.

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