



Polycyclic aromatic compounds in indoor dust, skin wipes, and urine of oilfield workers: Human exposure pathways and associations with oxidative stress

Ping Lu^{a,b,c}, Qiaoying Chen^c, Mengmeng Wang^{a,b,c}, Chang He^{a,b}, Hailing Li^{a,b}, Yujiao Zhu^{a,b}, Yumeng Shi^c, Zhiguo Cao^{c,*}, Guiying Li^{a,b}, Taicheng An^{a,b,**}

^a Guangdong-Hong Kong-Macao Joint Laboratory for Contaminants Exposure and Health, Key Laboratory of Environmental Catalysis and Health Risk Control, Institute of Environmental Health and Pollution Control, Guangdong University of Technology, Guangzhou, 510006, China

^b Guangzhou Key Laboratory of Environmental Catalysis and Pollution Control, Guangdong Basic Research Center of Excellence for Ecological Security and Green Development, School of Environmental Science and Engineering, Guangdong University of Technology, Guangzhou, 510006, China

^c School of Environment, Key Laboratory of Yellow River and Huai River Water Environment and Pollution Control, Ministry of Education, Henan Key Laboratory of Environmental Pollution Control, Henan Normal University, Xinxiang, 453007, China

ARTICLE INFO

Keywords:

Polycyclic aromatic compounds
Skin wipes
Metabolites
Dermal absorption
Lipid peroxidation

ABSTRACT

Polycyclic aromatic compounds (PACs) are common constituents of crude oil and its refined products, and they can be released into the ambient environment during oil exploitation activities, potentially adversely affecting environmental and human health. Herein, forehead (n = 76) and hand wipes (n = 76) and urine samples (n = 102) from oilfield workers as well as indoor dust samples (n = 19) (not individually paired with skin wipe and urine samples) in the oil exploitation area were collected, and 45 PACs and 15 PAC metabolites (mPACs) in these matrices were comparably determined. The median concentrations of Σ PACs in forehead and hand wipes and Σ mPACs in urine were 1.2–4.3 times higher in frontline workers than those in office administrators. Significant differences in PAC profiles were observed between different matrices, with relatively hydrophilic PACs being least in indoor dust, intermediate in hand wipes, and most abundant in forehead wipes. Furthermore, five PACs in forehead and hand wipes and their corresponding mPACs in urine exhibited significant positive correlations. Exposure assessment indicated that dermal uptake of low molecular weight (LMW) PACs contributed dominantly to internal exposure (20.2%–67.4%) compared to dust ingestion (<2%). The quantile g-computation model revealed that hydroxynaphthalene (Σ OH-Nap), 1-OH-pyrene, and 2-OH-dibenzofuran were the major contributors to the mPAC mixture's effect on lipid peroxidation, and dermal exposure may represent a potential pathway by which LMW PACs, particularly Nap, were associated with lipid peroxidation based on multiple linear regression. This study enhances understanding of less well-studied PAC exposure and supports oil exploitation contamination control.

1. Introduction

Polycyclic aromatic compounds (PACs), a group of persistent organic pollutants, include polycyclic aromatic hydrocarbons (PAHs) and their derivatives, such as methylated PAHs (MPAHs), heterocyclic PAHs (HPAHs), oxygenated PAHs (OPAHs), and halogenated PAHs (XPAHs). They are widely distributed in the ambient environment due to diverse emission sources, including pyrogenic sources (e.g., fuel combustion),

petrogenic sources (e.g., crude oil volatilization), and photochemical secondary transformation of parent PAHs (Akinrinade and Rosa, 2025; Yao et al., 2026; Zhang et al., 2026a). Toxicological and epidemiological studies have shown that some PAHs exhibit various toxic effects, such as carcinogenicity, mutagenicity, and developmental toxicity, posing a potential threat to human health (Berrigan and Freedman, 2024; Jiao et al., 2026; Liang et al., 2026). Furthermore, some PAH derivatives, such as MPAHs, HPAHs, and OPAHs, are more carcinogenic and

* Corresponding author.

** Corresponding author. Guangdong-Hong Kong-Macao Joint Laboratory for Contaminants Exposure and Health, Key Laboratory of Environmental Catalysis and Health Risk Control, Institute of Environmental Health and Pollution Control, Guangdong University of Technology, Guangzhou, 510006, China.

E-mail addresses: wq11ab@163.com (Z. Cao), antc99@gdut.edu.cn (T. An).

<https://doi.org/10.1016/j.envres.2026.125642>

Received 27 June 2026; Received in revised form 29 August 2026; Accepted 7 September 2026

Available online 8 September 2026

0013-9351/© 2026 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

mutagenic than their parent PAHs, though at lower environmental concentration (Jin and Yang, 2025; Wu et al., 2020). Therefore, growing concern has been raised regarding human exposure to PACs and their public health risks.

Among dust ingestion, inhalation, and dermal absorption, exposure investigations have reported that dust ingestion is the main exposure pathway of PAHs (Ali et al., 2016). However, an increasing number of studies highlight that dermal absorption also serves as a significant route of exposure to PAHs, especially for residents living in contaminated areas and occupational populations (Wang et al., 2024b; Zhang et al., 2023). For instance, significant correlations between PAHs in hand wipes and their metabolites in urine have been observed ($p < 0.05$) (Tang et al., 2021). Additionally, some PAH derivatives exhibit more suitable hydrophobicity than parent PAHs, therefore promoting their dermal absorption and accordingly exacerbating their exposure risk (Wu et al., 2016). Overall, most available studies concerning human exposure to PAH derivatives have generally focused on pathways of dust/soil ingestion, dietary ingestion, and inhalation, whereas personal dermal exposure and its contribution to body burden still remains poorly understood (Gao et al., 2024; Zhang et al., 2024).

Linking external exposure to PACs with internal exposure provides the possibility to assess the specific contribution of each exposure pathway to the total body burden and to identify the dominant exposure pathway, thereby developing effective strategies to minimize human exposure to PACs (Shi et al., 2024). Urine, a key biological matrix that effectively reflects short term external exposure, is generally used to indicate internal exposure to PACs (Li et al., 2023b; Lin et al., 2020). Although the associations between dermal exposure to PAHs and their urinary metabolites have been preliminary investigated in limited studies, the contributions of dermal exposure to the total body burden are still unclear (McCormick et al., 2022; Tang et al., 2021). Besides, the research about the relationship of PAH derivatives between external (e.g., dust and skin wipes) and internal exposure matrices is also rather limited. There is therefore an urgent need to understand dermal exposure to PACs and systematically assess their contribution to the total body burden.

Epidemiological and toxicological studies have reported that exposure to PACs is associated with various adverse health outcomes, potentially through an oxidative stress mediated mechanism (Liao et al., 2024; Mallah et al., 2022; Yu et al., 2024). Several studies have demonstrated significant associations between urinary hydroxy-PAHs (OH-PAHs) and oxidative stress biomarkers, such as F2-isoprostane isomers (Hua et al., 2024; Kuang et al., 2013). However, the relationship between other PACs and oxidative stress biomarkers is still limited. Furthermore, there is sparse information on the association between PACs from different exposure pathways and oxidative stress, hindering the clarification of the primary sources of health risk. Consequently, identifying the relationship between exposure pathways (e.g. dermal exposure) and oxidative damage would provide a scientific basis for the prevention of health damage elicited by exposure to PACs.

PACs are common constituents of crude oil and refined petroleum products, and they can be released into the ambient environment during oil exploration, exploitation, transportation, and storage (Han et al., 2023; Wang et al., 2024a). As expected, higher levels of PACs have also been detected in various matrices including soils, seawater, and sediments surrounding oil exploitation industry, hinting that oilfield workers may suffer more severe PAC exposure than general populations (Fu et al., 2018; Liu et al., 2024). Herein, forehead wipes, hand wipes, and urine samples were collected from oilfield workers, together with indoor dust samples in the oil exploitation area where they worked, and the concentrations of PACs in these matrices were comparably determined. The main purposes of this study are: (1) to characterize the pollution levels and profiles of PACs in multiple environmental matrices and urine samples of oilfield workers; (2) to explore and compare the contributions of dermal absorption and dust ingestion to the total body burden; (3) to unveil the associations of oxidative stress with PACs from

each exposure pathway. Overall, these findings advance our understanding of exposure pathways of PACs and provide critical insights for the pertinent prevention and health risk control measures for oilfield workers.

2. Materials and methods

2.1. Reagents and materials

All chemicals and reagents used in this study are listed in Text S1.

2.2. Sample collection

All samples were collected from May to July 2023. Total 102 participants working at oil exploitation area of an oilfield in northern China for over one year were recruited, and the basic demographics of all participants were summarized in Table S1. The participants' ages were between 28 and 70 years. Among collected paired forehead ($n = 76$) and hand wipes ($n = 76$), 60 pairs were collected from frontline workers directly engaged in frontline operations (e.g., safety inspection, technical support, gathering and transportation, gas injection operation, downhole operation, and oil exploitation), and 16 pairs from office administrators involved in material management. Both of them were collectively referred to as oilfield workers herein. Urine samples ($n = 102$) were first collected using polypropylene containers at the beginning of work in the morning (8:00 a.m.), of which 86 were from frontline workers and 16 from office administrators. To avoid interfering with the workers' routine tasks and to ensure the quality of samples, skin wipes were sampled when participants finish their work at noon (11:00 a.m.) or in the afternoon (3:00 p.m.). Participants were informed not to wash their sampling locations for at least 1 h prior to sampling. All forehead ($n = 76$) and hand wipes ($n = 76$) were paired with corresponding urine samples. Compared with urine samples, 26 fewer paired skin wipe samples were collected. This was because the corresponding participants had washed the sampled skin locations within 1 h before. Thus, they were not included in skin wipe collection. Because this missingness resulted from pre-sampling washing behaviour rather than intentional selection by the researchers, the potential selection bias was considered to be acceptable. It should be noted that there was a time interval (3–7 h) between the collection of urine and skin wipes, and morning urine samples likely reflected exposure on the previous workday other than the sampling day. Nevertheless, the workers in this study had been chronically working in the same occupational environment with relatively stable job tasks and exposure scenarios, therefore, their daily exposure levels were expected to be relatively consistent during the working period. Overall, the influence of the mismatched exposure windows on the results was limited. All participants were requested to avoid consuming barbecued foods for one week before sampling to reduce potential dietary interference. Indoor dust samples ($n = 19$) were sampled from three types of functional rooms in the oil exploitation area, including pump room (sill: $n = 4$; floor: $n = 4$), duty room (sill: $n = 5$; floor: $n = 4$), and central control room (sill: $n = 2$). Notably, indoor dust samples were not paired with skin wipe and urine samples at the individual level because oilfield workers could not be clearly linked to the specific dust sampling rooms. Each participant gave clearly informed consent prior to sample collection, and all sampling protocols were approved by the Ethical Committee of Guangdong University of Technology. The detailed sampling protocols is provided in Text S2.

2.3. Sample preparation and analysis

For skin wipe and indoor dust samples, the extraction and cleanup process of PACs were adopted from former publications with some modifications (Gao et al., 2024; Wang et al., 2024b; Zhang et al., 2024), and gas chromatography system coupled with tandem mass

spectrometry (GC-MS-TQ8040, Shimadzu, Inc.) was performed to quantify target compounds. For urine samples, the preparation procedures of PAC metabolites (mPACs) and lipid peroxidation biomarkers (8-iso-prostaglandin-F2 α (8-iso-PGF2 α), 8-iso-15(R)-prostaglandinF2 α (8-iso-15-PGF2 α), and 15(R)-prostaglandinF2 α (15-PGF2 α)) were referenced in our previous studies (Li et al., 2023a, 2023b), and liquid chromatography system coupled with triple quadrupole mass spectrometer (1260 Infinity-6470, Agilent Technologies, Inc.) was conducted to analyze these target compounds. Detailed sample preparation, instrumental conditions, and chromatograms of critical PAC isomers sharing identical or similar precursor and product ions are described in the Text S3, Table S2, and Fig. S1.

2.4. Quality assurance (QA) and quality control (QC)

A procedural blank and a spiked matrix were conducted for each batch of 10 samples. The analytes detected in blank samples were detected with amounts less than 15% of the mean levels in the skin wipes and indoor dust, and they were below 5% of the mean levels for urine analyzed. The average blank values were subtracted from the reported concentrations of all target analytes in field samples to conduct blank corrections. The method detection limits (MDLs) were defined as the three standard deviations of target analyte levels detected in the procedural blanks. In regards to analytes undetected in the blanks, the MDLs were set as the levels at signal-to-noise ratio of three in all matrices analyzed. Spiked matrix samples were prepared by fortifying known amounts of target analytes into blank skin wipes, anhydrous Na₂SO₄ as well as matrix urine. The recoveries of the target compounds in the standard spiked samples were 51.3%–132% for PACs in skin wipes, 49.8%–140% for PACs in dust, 41.9%–142% for mPACs in urine, and 99.0%–108% for lipid peroxidation biomarkers in urine, respectively. More detailed information on QA/QC is described in Text S4, Tables S3 and S4.

2.5. Exposure assessment

Estimated daily intake (EDI) (ng/kg body weight (BW)/day) of PACs through three exposure pathways were calculated in this study: whole-body dermal absorption (EDI_{derm}), dust ingestion (EDI_{ing-HW} and EDI_{ing-dust}), and total internal exposure (EDI_{total}). Specifically, EDI_{derm}, EDI_{ing-HW} and EDI_{ing-dust}, and EDI_{total} were estimated based on the concentrations of target analytes in skin wipes (forehead and hand wipes), hand wipes and indoor dust, and urine, respectively. Notably, daily intake of PACs via dust ingestion was estimated by two methods herein, one based on PAC levels in indoor dust, i.e. EDI_{ing-dust}. Given that indoor dust samples were not paired with the skin wipe and urine samples at the individual level herein, it represents a theoretical estimate based on area-wide median concentrations of PACs rather than a personal exposure metric. The other based on PAC concentrations in hand wipes, i.e. EDI_{ing-HW}, which also represents hand-to-mouth contact pathway. Detailed calculation methods and related parameters used in these models are also provided in Text S5 and Table S5, respectively.

2.6. Statistical analyses

Statistical analyses including Mann-Whitney *U* test, Spearman's correlation, and multiple linear regression were implemented using SPSS (Version 24.0). Besides, quantile g-computation (qgcomp) approach was further adopted to estimate the cumulative effects of multiple chemicals on the oxidative stress, adjusting by covariates of gender, age, body mass index (BMI), and smoking status. The qgcomp model was conducted based on the R (version 4.4.2) package “qgcomp”. Only target analytes with detection frequencies (DFs) > 50% are included in the correlation analyses, and data were log₁₀-transformed beforehand. Any values of target analytes lower than the MDLs were set as MDLs/2 for the statistical analyses. To confirm the robustness of our

results, sensitivity analyses were performed. The correlation analyses were repeated using multiple imputation for values below the MDLs to validate the results obtained from the MDL/2 substitution approach. A value of *p* less than 0.05 was considered as statistical significance level in this study. Urinary concentrations of target analytes and lipid peroxidation biomarkers were described in ng/mL without creatinine adjustment. It should be noted that uncorrected urinary dilution may introduce some uncertainty into the results of between-group comparisons and exposure-effect association analyses. Detailed information on statistical analyses is described in Text S6.

3. Results and discussion

3.1. Pollution levels and profiles of PACs in indoor dust and skin wipes

3.1.1. Indoor dust

In indoor dust, except for 1,5-dichloroanthracene (1,5-Cl₂-Ant), 9,10-Cl₂-Ant/9,10-dichlorophenanthrene (9,10-Cl₂-Phe), 4-bromopyrene (4-Br-Pyr), 2-bromofluorene (2-Br-Fle), and benzanthrone, all target PACs had the DFs of 100% (Table S6). PAHs ($\sum_{19}$ PAHs: 1170–67100 ng/g; median: 4410 ng/g) and MPAHs ($\sum_7$ MPAHs: 899–4500 ng/g; median: 1860 ng/g) were the major PACs, followed by HPAHs ($\sum_{10}$ HPAHs: 314–4210 ng/g; median: 1180 ng/g), OPAHs ($\sum_3$ OPAHs: 82.3–6840 ng/g; median: 560 ng/g), and XPAHs ($\sum_6$ XPAHs: 12.4–543 ng/g; median: 88.5 ng/g), accounting for 55.6%, 22.4%, 14.2%, 6.7%, and 1.1% of total concentrations of PACs, respectively (Fig. S2 and Table S6). Generally, PAH levels are served as indicators of pollution severity and environmental recovery in oil-contaminated sites (Allan et al., 2012), reflecting their widespread presence in such environments. Analogously, MPAHs are considered as markers for emissions from petrogenic sources (e.g., crude oil) (Lin et al., 2021). Overall, the dominance of PAHs and MPAHs in indoor dust may be due to their higher abundance in crude oil and its refined products. These contaminants can be released into the environment during oil exploitation and transportation through leakage accidents, subsequently enter indoor environments through air infiltration and dust/soil tracked indoors on shoes, and ultimately accumulate in indoor dust (Ali, 2019).

Specifically, for PAH congeners, high molecular weight (HMW) PAHs ($\geq$ four aromatic rings), especially four-ring PAHs, were the predominant PAHs in indoor dust, contributing 49.0%–93.7% to $\sum_{19}$ PAHs (Fig. S3). Notably, Phe was the most abundant PAHs detected and contributed 20.6% to $\sum_{19}$ PAHs (Fig. S4). This may be because phenanthrene represents one of the major classes of aromatic compounds in crude oil (Konan et al., 2023). Of the MPAHs congeners, 2,7-dimethylnaphthalene (2,7-DMNap) and 1,3-DMNap were the dominant MPAHs, contributing 30.5% and 28.1% to $\sum_7$ MPAHs, respectively. Similarly, 1,3-DMNap was also the major contributor of MPAHs in surface soil in petrochemical park (Zhou et al., 2024). For HPAH congeners, carbazole (CBZ) was the most abundant HPAH congener, followed by dibenzothiophene (DBT) and 4-methyldibenzofuran (4-MDBF), contributing 23.4%, 16.3%, and 15.0% to $\sum_{10}$ HPAHs, respectively. As reported, CBZ, DBF and its alkylated homologues of DBF (e.g., 4-MDBF) are common HPAHs in crude oil and source rock extracts (Li and Ellis, 2015; Oliveira et al., 2006). In the case of OPAH and XPAH congeners, 9-fluorenone (9-FLU) and 2-Br-Fle were the dominant components detected in indoor dust, contributing 56.5% and 46.0% to $\sum_6$ XPAHs and $\sum_3$ OPAHs, respectively. Collectively, our results clearly demonstrate the widespread presence of most target PACs in indoor dust, and their distribution characteristics are closely related to the oil exploitation-related activities, indicating broad occupational exposure to these contaminants through different exposure pathways (e.g., dust ingestion).

3.1.2. Skin wipes

Total 33 out of 45 PAC congeners in skin wipes were detected with the DFs > 50% (Table S6). The median concentrations of $\sum_{19}$ PAHs,

$\sum_7$ MPAHs, $\sum_{10}$ HPAHs, $\sum_3$ OPAHs, and $\sum_6$ XPAHs were 12000 (1730–37500 ng/m²), 6730 (277–17400 ng/m²), 1120 (294–6100 ng/m²), 185 (not detected (n.d.)–1550 ng/m²), and 386 ng/m² (2.1–1440 ng/m²) in forehead wipes, and 2200 (346–11100 ng/m²), 807 (61.6–5910 ng/m²), 234 (40.8–1300 ng/m²), 76.7 (10.1–539 ng/m²), and 60.8 ng/m² (n.d. –319 ng/m²) in hand wipes from all oilfield workers. Of note, PAC levels in forehead and hand wipes showed substantial inter-individual variability. The maximum values of all five PAC groups were observed in oil exploitation workers, whereas most minimum values were found in office administrators responsible for material management. Oil exploitation workers were mainly engaged in the operation and maintenance of oil production equipment, cleaning of oily residues at well sites, and others, which increased their opportunities for direct contact with oily residues and other contaminated surfaces. Differences in occupational categories may contribute to the inter-individual variability in PAC levels in skin wipes. Besides, significantly higher concentrations of the other PACs in forehead and hand wipes were found in frontline workers than those in office administrators by approximately 1.2–4.3 times, respectively ($p < 0.05$) (Fig. 1). This result indicates that oil production-related activities may contribute considerably to elevated dermal exposure levels to PACs for frontline workers. Specifically, 15 PAHs (excluding fluoranthene, indeno[1,2,3-cd]pyrene (IcdP), dibenz[a,h]anthracene (DBaH), and Benzo[ghi]perylene (BghiP)), 4 MPAHs (2-methylnaphthalene (2-MN), 1,3-DMN, 1,6,7-trimethylnaphthalene (1,6,7-TMN), 1,4,6,7-TMN), 5 HPAHs (DBF, 4-MDBF, DBT, 4-MDBT, and 3-MDBT), and 9-Cl-Flu were present in significantly higher levels ($p < 0.05$) in forehead and hand wipes of frontline workers than those of office administrators (Table S7). This highlights the need to pay greater attention to some less well-studied PACs (e.g., HPAHs) beyond parent PAHs in the oil exploitation area. Notably, HPAHs exhibit greater mobility and bioavailability (Larsson

et al., 2018; Peng et al., 2023), and some of which have been considered as suspected carcinogens (e.g., DBF and CBZ) (Ghosh and Mukherji, 2023), indicating their potential human exposure risk. Additionally, the concentrations of $\sum_{19}$ PAHs, $\sum_7$ MPAHs, $\sum_{10}$ HPAHs, $\sum_3$ OPAHs, and $\sum_6$ XPAHs in forehead wipes were significantly higher than those in hand wipes ($p < 0.05$). This may be partly explained by the greater amount of sebum secreted by the forehead than the hands, and higher sebum loads may contribute to organic contaminants' dermal adsorption (Pan et al., 2020; Ri et al., 2015). Additionally, personal behavioral factors, such as handwashing, may reduce PAC accumulation on the hands, and the use of protective gloves may also prevent the hands from being directly exposed to PACs.

Similar to the profiles of five types of PACs in indoor dust, PAHs were the most abundant PACs in both forehead and hand wipes, followed by MPAHs and HPAHs, accounting for 58.7%, 33.0%, and 5.5% of total PACs in forehead wipes and 65.1%, 23.9%, and 6.9% in hand wipes, respectively (Fig. S2). Specifically, for PAH congeners, unlike in indoor dust, low molecular weight (LMW) PAHs (2–3 aromatic rings) were the predominant PAHs in skin wipes from all oilfield workers, particularly forehead wipes, accounting for 20.9%–98.9% of $\sum_{19}$ PAHs (Fig. S3). This may be closely related to matrix composition and physicochemical properties (e.g., hydrophilicity) of these compounds. Human skin is covered with a skin-surface film lipid, consisting of a mixture of sweat and sebum in varying proportions (Wang et al., 2024c). As a result, this film contains a certain fraction of aqueous phase, contributing to dissolve and absorb compounds with relatively high hydrophilicity, such as LMW PAHs (log K_{OW} : 3.2–4.4; water solubility (WS): 0.68–142 mg/L), compared to their HMW counterparts (log K_{OW} : 5.0–6.7; WS: 0.002–0.13 mg/L).

Of the 19 PAH congeners measured, Nap and Phe were the dominant components in skin wipes. For hand wipes, Phe was the most dominant

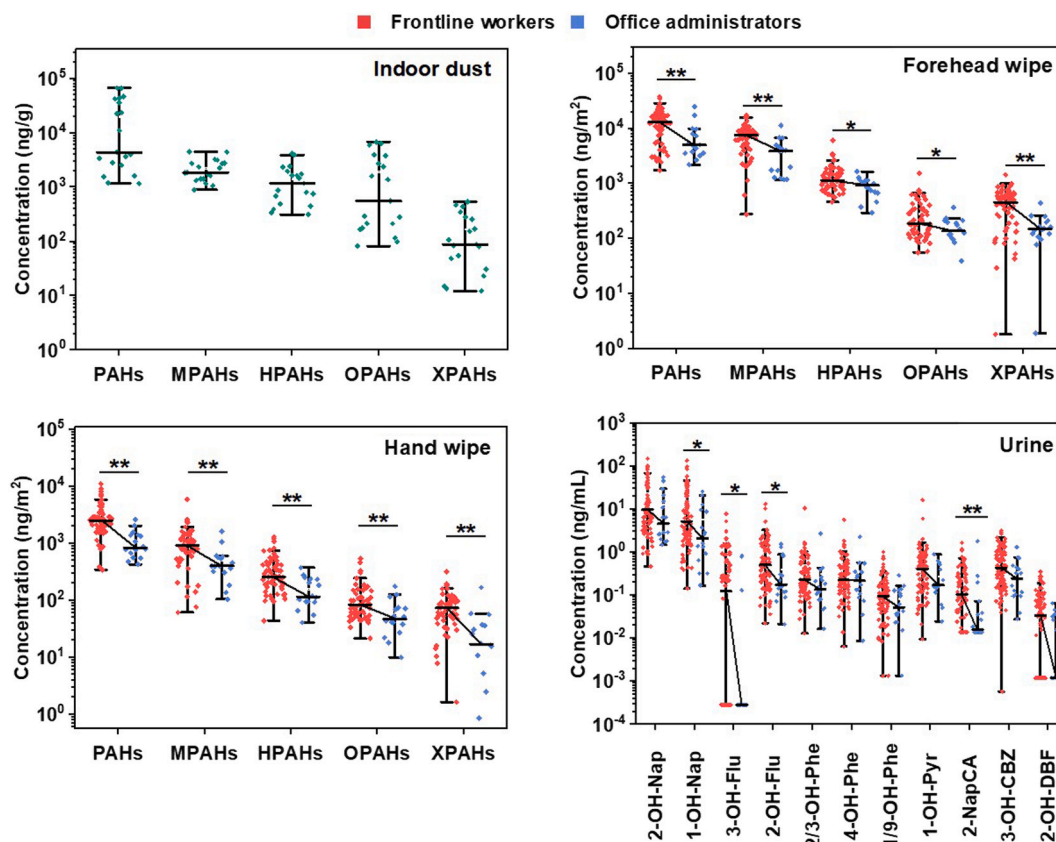


Fig. 1. Concentrations of PACs in indoor dust, forehead wipe, hand wipe, and mPACs in urine of frontline workers and office administrators. The horizontal black solid lines indicate the median (long line), as well as 5th percentile (lower short line) and 95th percentile (upper short line) levels, respectively. * $p < 0.05$ level; ** $p < 0.01$ level.

PAH congener and accounted for 29.1% of $\sum_{19}$ PAHs, consistent with the result observed in indoor dust (Fig. S4). While for forehead wipes, Nap with higher hydrophilicity ($\log K_{OW}$: 3.2; WS:142 mg/L) was the most prevalent compound, followed by Phe, accounting for 34.0% and 28.9% of $\sum_{19}$ PAHs, respectively (Fig. S4). For the MPAH congeners, 2-MNap was the most abundant in both forehead and hand wipes, followed by 1,3-DMNap, accounting for 38.2% and 21.4% of $\sum_7$ MPAHs in forehead wipes, and 42.2% and 15.4% in hand wipes, respectively. For HPAH congeners, CBZ was the most abundant in hand wipes, accounting for 22.2% of $\sum_{10}$ HPAHs, aligning with the patterns observed in indoor dust (Fig. S4). While quinoline (QL) with higher hydrophilicity ($\log K_{OW}$: 2.1 and WS:1710 mg/L) dominated the forehead wipes, accounting for 31.7% of $\sum_{10}$ HPAHs. Regarding OPAH and XPAH congeners, 9-FLU and 9-Cl-Flu were the predominant congeners detected in skin wipes, accounting for 91.4% (hand wipe) and 100% (forehead wipe) of $\sum_3$ OPAHs and 64.7% and 74.1% of $\sum_3$ XPAHs, respectively, with both compounds also dominating indoor dust but at lower proportions. Overall, the profiles of PACs in hand wipes were more similar to that in indoor dust compared to forehead wipes. This may be due to frequent hand contact with dust or item surfaces during daily activities (Cao et al., 2019a).

3.1.3. PAC profiles among indoor dust, forehead wipes, and hand wipes

The compositional profiles of PACs among indoor dust, forehead and hand wipe were further investigated in this study. As Fig. S4 reveals, the proportion of compounds with higher hydrophilicity (e.g., Nap and QL) was basically lowest in indoor dust, followed by hand wipes, and most pronounced in forehead wipes. This pattern can be attributed to the differences in the matrix composition. Dust contains a high content of organic matter, facilitating the strong sorption of lipophilic compounds (Wei et al., 2015). In contrast, the sweat on the human skin surface may contribute to the sorption of some relatively hydrophilic chemicals, as we above-mentioned Nap and QL. Furthermore, the higher proportion of relatively hydrophilic PACs observed in forehead wipes than those in hand wipes may be due to greater amount of sweat on the forehead skin.

The correlations between the concentration ratios of PACs between forehead and hand wipes and their hydrophilicity (represented by $\log K_{OW}$ and WS) and volatility (represented by $\log K_{OA}$ and vapor pressure (V_p)) further supported the above statement. The concentration ratios of PACs were significantly and negatively correlated with $\log K_{OA}$ ($r = -0.754$, $p < 0.001$) and $\log K_{OW}$ values ($r = -0.541$, $p < 0.001$), whereas positively correlated with V_p ($r = 0.823$, $p < 0.001$) and WS ($r = 0.758$, $p < 0.001$) values (Fig. 2). Taken together, the occurrence of PACs in indoor dust and forehead and hand wipes was largely determined by their physicochemical properties, and chemicals with relatively high hydrophilicity and volatility were more prone to accumulate on the forehead skin. Based on the compositional differences among the three matrices, it can be deduced that hydrophilicity may play a more important role in governing the distribution of PACs across indoor dust, forehead and hand wipes.

3.2. Pollution levels and profiles of mPACs in urine

Environmental contaminants can enter the human body through multiple exposure pathways, and then be excreted in urine following a series of metabolic transformations; therefore, analyzing urinary metabolites enables the characterization of their internal exposure levels. All individual mPACs were detected in urine with DFs ranging from 55.9% to 100%, except for 3-hydroxyfluorene (3-OH-Flu), 6-hydroxy-chrysene (6-OH-Chr), and 3-hydroxybenzo[a]pyrene (3-OH-BaP) (Table S8). 6-OH-Chr and 3-OH-BaP were not detected in all urine samples, possibly because HMW PAHs are predominantly excreted through the feces rather than urine (Guo et al., 2013). Hence, these two compounds were not included in the subsequent analyses.

The concentrations of $\sum_{13}$ mPACs in urine of oilfield workers ranged from 1.7 to 229 ng/mL, with a median value of 15.7 ng/mL (Table S8). The elevated median concentration was observed in frontline workers (19.2 ng/mL) compared with office administrators (10.9 ng/mL) ($p > 0.05$) (Table S7). Specifically, all 13 mPAC congeners investigated were also present at higher concentrations in frontline workers than

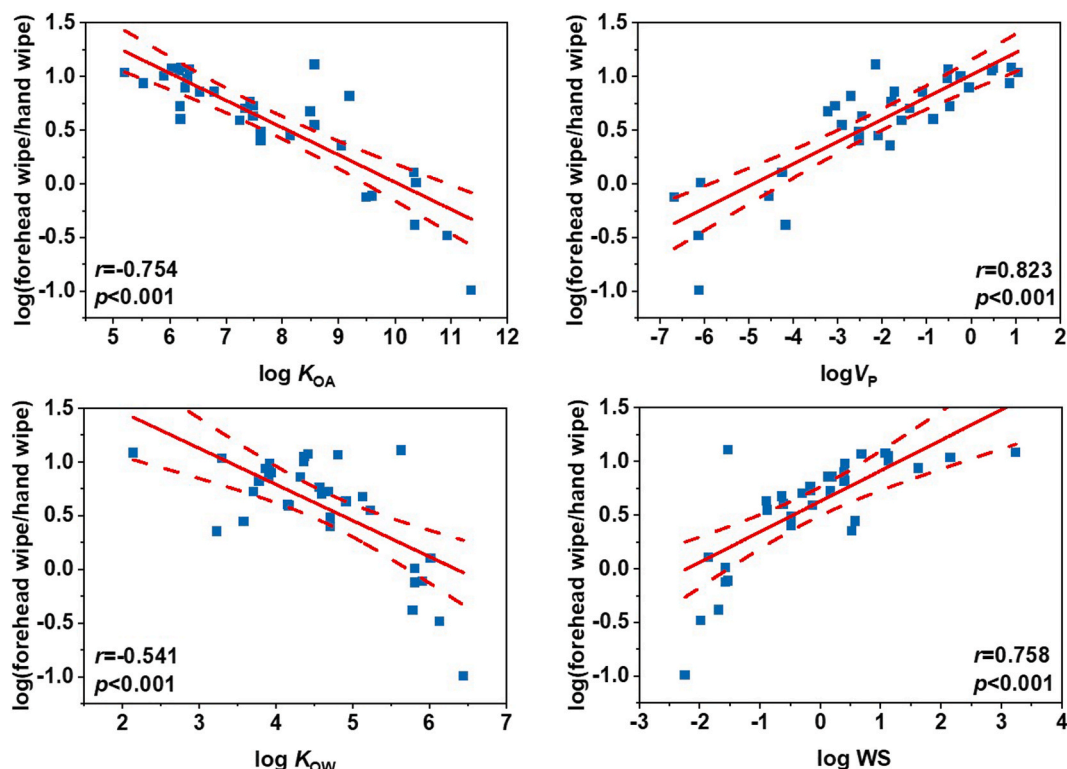


Fig. 2. Spearman's correlation analysis between PAC concentration ratios of forehead wipes and hand wipes and $\log K_{OA}$, V_p , $\log K_{OW}$, and WS.

those in office administrators. Among these, 1-OH-Nap, 2-OH-Flu, 3-OH-Flu, and 2-naphthoic acid (2-NapCA) exhibited significant differences between the two populations ($p < 0.05$) (Fig. 1). This suggests that frontline workers were subjected to more severe PAC exposure than office administrators, further confirming that oil exploitation activities are the primary emission source of PAC pollution. Notably, the DFs (=55.9%) and concentrations (<0.1 ng/mL) of 2-NapCA in urine of oilfield workers were relatively low, inconsistent with the dominance of 2-MNap in indoor dust and skin wipes. This may be due to relatively high lipophilicity of 2-MNap ($\log K_{ow} = 3.7$), potentially slowing its clearance in the human body (Golzadeh et al., 2021; Zhang et al., 2026b). Indeed, the lipophilic properties of 2-MNap have been reported to contribute to its accumulation in serum of petrochemical park workers (Zhao et al., 2024). Regarding the compositional profiles of mPACs in urine, 2-OH-Nap and 1-OH-Nap were most predominant in urine from oilfield workers, constituting 59.0% and 29.4% of $\sum_{13}$ mPACs, respectively, followed by 3-OH-CBZ, 1-OH-Pyr, and 2-OH-Flu (Fig. S4). OH-PAHs emerged as the dominant component and accounted for 56.8%–99.9% of $\sum_{13}$ mPACs, which was consistent with the prevalence of their parent compounds in indoor dust and skin wipes (Fig. S4).

3.3. Correlations among PACs in environmental matrices and mPACs in urine

To gain insight into the relationship between internal and external exposure to PACs in oilfield workers, Spearman's correlation analysis was performed herein. It is noteworthy that forehead wipe is regarded as a key proxy to assess human exposure to SVOCs via dermal exposure, whereas hand wipe is more commonly used to represent exposure via hand-to-mouth contact (Cao et al., 2019a, 2019b). Moreover, hand-to-mouth contact is considered as a predominant pathway of dust ingestion (Li et al., 2023c; Özkaynak et al., 2010; Yun et al., 2025). Therefore, hand wipes were used as an indicator of dust ingestion in this study. Since the collection of indoor dust from the oil exploitation area was not strictly paired with skin wipes and urine samples from the oilfield workers, indoor dust samples were not included in the following Spearman's correlation analysis. Table S9 presents the Spearman's correlation coefficients between the parent compounds in skin wipes and their respective urinary metabolites. Overall, five PACs in forehead and hand wipes showed significant positive correlations with their corresponding mPACs in urine of all oilfield workers ($p < 0.05$). Specifically, Phe in forehead wipes ($r = 0.325$, $p < 0.01$) and hand wipes ($r = 0.351$, $p < 0.01$) were both positively correlated with $\sum$ OH-Phe in urine, as well as individual OH-Phe isomers (i.e., 2-/3-OH-Phe, 4-OH-Phe, and 1-/9-OH-Phe) for oilfield workers ($r = 0.268$ – 0.394 , $p < 0.05$). Besides, Flu, 2-MNap, DBF, and CBZ in forehead and hand wipes also showed positive correlations with $\sum$ OH-Flu, 2-NapCA, 2-OH-DBF, and 3-OH-CBZ in urine of oilfield workers ($r = 0.267$ – 0.444 , $p < 0.05$), respectively. These results suggest that oilfield workers' exposure to Phe, Flu, 2-MNap, DBF, and CBZ via both dermal absorption and dust ingestion were closely related to their internal exposure. In terms of the rest compounds, Nap in forehead wipes was positively correlated with $\sum$ OH-Nap and individual isomers (i.e., 2-OH-Nap and 1-OH-Nap) in urine ($r = 0.243$ – 0.275 , $p < 0.05$), while Pyr in hand wipes showed positive correlations with 1-OH-Pyr ($r = 0.255$, $p < 0.05$) for oilfield workers. This suggests that dermal exposure to Nap may be more closely associated with internal exposure, whereas dust ingestion may contribute to internal exposure of Pyr. This may be due to their physicochemical properties, compared to Pyr, Nap with lower molecular weight, lower $\log K_{ow}$ value, and higher WS, may achieve faster dermal penetration and metabolism thereafter. Conversely, Pyr, being of higher molecular weight and more lipophilic, may exhibit limited transdermal uptake, thereby weakening the association between dermal absorption and internal exposure (Weschler and Nazaroff, 2012; Wu et al., 2016).

Notably, potential difference in Phe metabolism was observed

between frontline workers and office administrators (Table S9). Specifically, of the five OH-Phe isomers, 2-/3-OH-Phe exhibited the strongest positive correlations with Phe in skin wipes for frontline workers (forehead wipe: $r = 0.393$ and hand wipe: $r = 0.394$, $p < 0.01$). Whereas for office administrators, 1-/9-OH-Phe showed the strongest positive correlations with Phe in hand wipes ($r = 0.632$, $p < 0.01$), followed by 2-/3-OH-Phe ($r = 0.594$, $p < 0.05$). This result might be attributed to the variances in environmental factors (e.g., activity pattern, lifestyles, and smoking) and enzyme expressions among individuals (Hou et al., 2021; Peng et al., 2023). Besides, significant positive correlations were observed between other PACs (except for CBZ) in skin wipes and the corresponding metabolites in frontline workers, while no such associations were found in office administrators.

3.4. External and internal exposure assessment of PACs

External and internal exposure assessments were further conducted to evaluate the contributions of different external exposure pathways to internal exposure. The median EDI values of individual PACs (excluding 2,8-dimethyldibenzothiophene due to its unavailability of the permeability coefficient (K_{p-1})) via dermal absorption (EDI_{derm}) and dust ingestion (EDI_{ing-HW} and $EDI_{ing-dust}$) are presented in Fig. S5 and Table S10. The EDI values of total PACs calculated from hand wipes (EDI_{ing-HW} : 2.7 ng/kg BW/day) was comparable to that from indoor dust ($EDI_{ing-dust}$: 3.4 ng/kg BW/day). Notably, because indoor dust and skin wipe samples were not individually paired, daily intake based on indoor dust may not accurately reflect personal exposure levels and should therefore be interpreted cautiously. Nevertheless, this still provides support for the notion that dust ingestion occurs predominantly through hand-to-mouth contact to a certain extent. Moreover, given that EDI_{ing-HW} was calculated based on individual hand wipe sample, which facilitated comparison with EDI values of other exposure pathways, it was used to represent daily intake via dust ingestion in the subsequent analyses. The EDI value of total PACs via dermal absorption (227 ng/kg BW/day) was two orders of magnitude higher than that via dust ingestion (2.7 ng/kg BW/day) among oilfield workers. This result indicates that dermal absorption is a far more predominant pathway outweighing dust ingestion for oilfield workers, consistent with our findings on the residents around a nonferrous metal smelting plant (Wang et al., 2024b). Therefore, reducing dermal PAC exposure should be prioritized in occupational risk management for oilfield workers. Practical measures may include proper use and replacement of protective gloves and work clothing, enhancement of workplace cleaning, and timely skin cleaning after work tasks.

The metabolites of PACs in urine were generally used to assess human total internal exposure dose (EDI_{total}) from all pathways. In this study, the EDI_{total} values of seven PACs (i.e., Nap, Flu, Phe, Pyr, 2-MNap, DBF, and CBZ) were calculated by their respective metabolites in urine. Of them, EDI_{total} (202, 8.1, 86.8, 90.4 and 11.3 ng/kg BW/day) of Nap, Flu, Phe, Pyr, and CBZ were substantially higher than those of EDI_{ing-HW} (0.35, 0.10, 0.47, 0.21, and 0.04 ng/kg BW/day), while basically comparable in magnitude to the corresponding EDI_{derm} values (92, 5.5, 18.1, 3.2, and 2.3 ng/kg BW/day) (Fig. 3). Specifically, the contributions of dermal absorption to the total body burden of Nap, Flu, Phe, Pyr, and CBZ were 45.4%, 67.4%, 20.8%, 3.5%, and 20.2%, respectively, which were much higher than the contributions from dust ingestion ($<2\%$). Together with significant positive correlations observed in these compounds in forehead wipes and their metabolites in urine, it can be deduced that dermal absorption may serve as a non-negligible contributor to the total body burden of PACs, especially for LMW PACs (e.g., Nap, Flu, Phe, and CBZ). Notably, compared to LMW PACs, Pyr has a higher molecular weight, higher $\log K_{ow}$, and lower WS, which may result in a lower dermal penetration rate and consequently a lower daily intake via dermal absorption (Wu et al., 2016). Pyr might be more likely to enter the body via other pathways, such as dietary ingestion (Wang et al., 2024b). Besides, the EDI_{total} (1.4 and 0.75 ng/kg BW/day) of

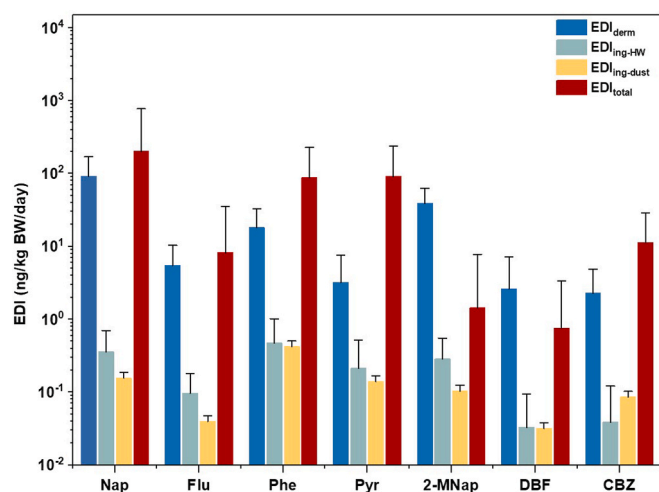


Fig. 3. The EDI values of seven PACs via external and internal pathways.

2-MNap and DBF were much lower than those of EDI_{derm} (39.0 and 2.6 ng/kg BW/day). This may be due to an underestimation of their true internal exposure levels. Although 2-NapCA and 2-OH-DBF are the most commonly monitored urinary metabolites for characterizing 2-MNap and DBF exposure, other biotransformation products may also be present in the body (Hammer et al., 2001; Peng et al., 2023). Additionally, 2-MNap and DBF are relatively lipophilic, while their distribution in serum was not further considered in the present study.

3.5. Dose-response associations between mPACs/PACs in urine, forehead wipes, hand wipes and oxidative stress

Oxidative damage is considered to act as a vital role in the pathogenesis of diseases associated with PAC exposure (Martinez and Kannan, 2018). Therefore, the associations between PACs and oxidative stress were examined. Three isomers of F2-isoprostanes (i.e., 8-iso-15-PGF2 α , 8-iso-PGF2 α , and 15-PGF2 α) which are commonly detected lipid peroxidation products in urine, are widely recognized as reliable biomarkers for assessing lipid oxidative levels in the human body (Basu, 2010). The median concentrations of 8-iso-15-PGF2 α , 8-iso-PGF2 α , and 15-PGF2 α among oilfield workers were 1.4, 0.50, and 1.6 ng/mL, respectively, with the DFs ranging from 84% to 100% (Table S8). Spearman's correlation analysis was used to preliminarily investigate the relationship between lipid peroxidation biomarkers and mPACs/PACs in urine and skin wipes of oilfield workers (Table S11). In urine, all individual mPACs (except for 2-NapCA) showed significant positive correlations with three lipid peroxidation biomarkers ($r = 0.239$ – 0.595 , $p < 0.05$). This indicates that oxidative damage in oilfield workers might be related to PAC exposure in the environment. Furthermore, positive correlations were also observed between lipid peroxidation biomarkers and some individual PACs in forehead ($r = 0.226$ – 0.352 , $p < 0.05$) and hand wipes ($r = 0.226$ – 0.339 , $p < 0.05$) (Fig. S6 and Table S11). Of these correlations, 8-iso-15-PGF2 α exhibited the strongest correlations with 2-MNap in forehead wipes ($r = 0.352$, $p < 0.01$), followed by Phe ($r = 0.307$, $p < 0.01$). Similarly, 8-iso-PGF2 α also exhibited the strongest correlations with 2-MNap in forehead wipes ($r = 0.343$, $p < 0.01$), followed by Nap (8-iso-PGF2 α : $r = 0.286$, $p < 0.05$). While for hand wipes, 8-iso-15-PGF2 α showed the strongest correlations with 4-MDBF ($r = 0.321$, $p < 0.01$), followed by Ant ($r = 0.292$, $p < 0.05$), and 8-iso-PGF2 α showed the strongest correlations with BbF ($r = 0.339$, $p < 0.01$), followed by Ant ($r = 0.324$, $p < 0.01$). These correlations suggest that LMW PACs were more closely related to lipid peroxidation biomarkers through dermal exposure pathway.

Multiple linear regression analysis was further conducted to evaluate the influence of mPACs/PACs on lipid peroxidation, adjusting by

potential confounders including age, gender, BMI, and smoking status. For simplicity, the OH-PAHs with common parent compounds were combined (i.e., Σ OH-Nap, Σ OH-Flu and Σ OH-Phe) herein. Similarly, the sum concentrations of each PAC class (i.e., Σ PAHs, Σ MPAHs, Σ HPAHs, Σ OPAHs, and Σ XPAHs) were also included as variables in the model. In urine, Σ OH-Nap was significantly and positively correlated with 15-PGF2 α ($\beta = 0.242$, $p < 0.05$) (Fig. 4a and Table S12). This suggests a potential link between urinary Σ OH-Nap and lipid peroxidation, as reflected by 15-PGF2 α . Additionally, Σ PAHs in hand wipes was notably and positively correlated with 8-iso-PGF2 α ($\beta = 3.317$, $p < 0.01$), and Σ PACs in forehead wipes was marginally significantly and positively correlated with 8-iso-PGF2 α ($\beta = 1.372$, $p = 0.055$) (Table S12), indicating increased levels of 8-iso-15-PGF2 α may be correlated with Σ PACs through both dermal exposure and dust ingestion pathways. Furthermore, as the urinary metabolites detected herein corresponded to seven parent PACs, the associations of these seven compounds in forehead and hand wipes with oxidative stress were further evaluated. The results showed that Nap in forehead wipes was significantly and positively associated with 15-PGF2 α ($\beta = 0.253$, $p < 0.05$), whereas no such significant positive association was found in hand wipes. This finding suggests a potential link between dermal exposure to Nap and increased 15-PGF2 α levels, which is generally consistent with the associations observed in urine (Fig. 4a and Table S12). This further confirms that the dermal exposure to LMW PACs, particularly Nap, were more closely associated with increased levels of lipid peroxidation biomarkers. To date, limited studies on external exposure to PACs and oxidative stress, especially for dermal absorption. Only one study reported an association between dermal exposure to bisphenol A and oxidative DNA damage, but this study has not yet established a direct link between dermal absorption and oxidative stress due to the lack of concentration data on dermal exposure (Lv et al., 2017). Our study provided data supporting the potential link between dermal exposure to PACs and oxidative stress.

Considering the integrated exposure of multiple PACs, a qgcomp model was applied to evaluate the joint effects of exposure to the PAC mixture on lipid peroxidation for all oilfield workers, adjusting by potential confounders including age, gender, BMI, and smoking status. Table S13 displays the estimated regression coefficients of the established qgcomp model among different matrices. Consistent with the patterns observed in single mPACs, both 8-iso-15-PGF2 α and 15-PGF2 α showed significant and positive associations with the mPAC mixture in urine ($p < 0.05$). In detail, a quartile increases in mixed PAC concentrations resulted in 8-iso-15-PGF2 α and 15-PGF2 α levels being elevated by 0.35 ($\beta = 0.35$, 95% CI: 0.12, 0.58) and 0.19 ($\beta = 0.19$, 95% CI: 0.073, 0.30), respectively. Furthermore, the positive and negative estimated weights of each mPAC were showed in Fig. 4b. The weights represented the relative contributions to the combined effect on 8-iso-15-PGF2 α and 15-PGF2 α , respectively. Notably, Σ OH-Nap emerged as the dominant contributors to the positive impact on 8-iso-15-PGF2 α and 15-PGF2 α , followed by 1-OH-Pyr and 2-OH-DBF, basically consistent with the results obtained from multiple linear regression analysis above. In contrast to the overall trend, 3-OH-CBZ appeared to exhibit antagonistic effects on the elevation of both 8-iso-15-PGF2 α and 15-PGF2 α . This indicate that focusing on a single group of PACs might not accurately capture the complexity of real-world human exposure. Overall, particular attention should be paid to compounds including Σ OH-Nap, 1-OH-Pyr and 2-OH-DBF, which contributed predominantly to the overall mixture effect for elevated lipid peroxidation. There was no significant association between PAC mixture in forehead and hand wipes and any lipid peroxidation biomarkers ($p > 0.05$), which was inconsistent with the significant and positive associations observed for individual PACs (e.g., Nap) in the single-pollutant model. This may be attributed to the high correlations and complex interactions among co-exposure of multiple PACs, which affect their combined impact on health outcomes (Wen et al., 2024). Therefore, the associations observed in single-pollutant and mixture exposure models still need to be further

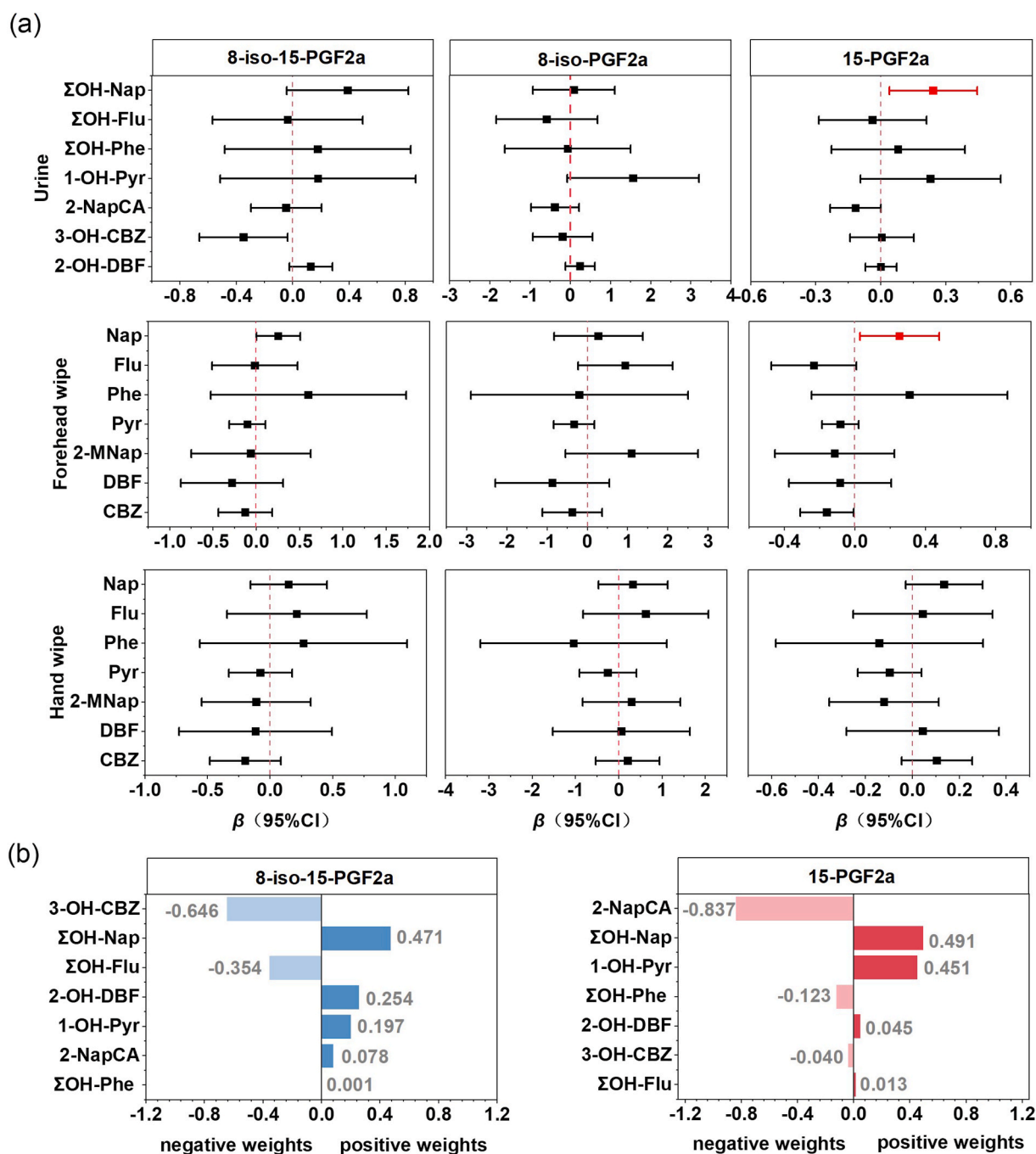


Fig. 4. Results of correlation analyses between mPACs/PACs in urine/skin wipes and lipid peroxidation biomarkers in urine for all oilfield workers (adjusting for age, gender, BMI, and smoking status). (a) Multiple linear regression (regression coefficient β and 95% CI (confidence interval)). (b) The relative contributions of each mPAC in urine to lipid peroxidation estimated from qgcomp model.

verified by *in vitro* or *in vivo* experiments.

There are several possible explanations for the associations of co-exposure to PACs with oxidative stress. PAHs are metabolized by cytochrome P450 to generate free radical intermediates, such as diol-epoxides and radical cations, and further produce reactive oxygen species (ROS), which can attack and modify cellular lipids and cause oxidative damage to lipids eventually (Kuang et al., 2013). Additionally, aryl hydrocarbon receptor (AhR) may play a vital role in mediating the oxidative stress induced by PAH exposure through regulating gene transcription and protein expression (Peng et al., 2023; Stockinger et al., 2014). AhR activation can strongly trigger cytochrome P450 1A1 to increase ROS formation and further cause oxidative stress (Vogel et al.,

2020). Notably, PAH derivatives may be more toxic than their parent PAHs. For instance, some reactive OPAHs exhibit a heightened likelihood of ROS generation without metabolic activation (Wang et al., 2011). PAC exposure typically occurs as mixtures in the ambient environment, co-exposure to these pollutants generally shows a more complex and profound impact on living organisms than single pollutant exposure. The mixture effects observed in this study should be further investigated through cellular and animal models to clarify the underlying biological mechanisms.

3.6. Results of sensitivity analysis

For the sensitivity analysis, we re-evaluated the main correlation results using multiple-imputation datasets to assess the influence of values below the MDLs. Specifically, we reanalyzed the correlations between parent compounds in skin wipes and their corresponding urinary metabolites, and further assessed the exposure-response relationships between mPACs/PACs in urine and skin wipes and oxidative stress biomarkers. Overall, the results were generally consistent with those obtained using the MDL/2 substitution approach. Most significant associations remained, and the directions and magnitudes of the correlation or regression coefficients were largely unchanged (Tables S14–S16). Notably, for compounds with relatively low DFs, such as 2-NapCA, the correlations remained statistically significant, although the correlation coefficients were slightly attenuated. These findings further support the robustness of our main results.

4. Conclusions

In short, this study evaluated and compared the exposure characteristics of PACs in indoor dust, forehead and hand wipes, as well as urine of oilfield workers, and further explored their associations with oxidative stress. Frontline workers suffered higher PAC exposure than those in office administrators, indicating that oil exploitation activities are major emission sources of PACs, especially for PAHs and MPAHs. The distribution of PACs in different matrices is governed by their physicochemical properties, and compounds with relatively hydrophilicity may be more prone to accumulate on forehead surface. Moreover, dermal absorption played a significant role in the total body burden of LMW PACs. The PAC mixture in oilfield workers demonstrated positive effects on lipid peroxidation with $\sum$ OH-Nap being the most contributor. Our results highlighted that dermal exposure to LMW PACs, especially Nap, may be associated with lipid peroxidation. The results provide scientific evidence for the tailored exposure prevention and risk control measures associated with PACs in the oil exploitation industry. Furthermore, the air inhalation also represents an important exposure pathway. Due to limitations in sampling conditions, collecting these paired environmental samples remains highly challenging. This factor will be taken into account in our future research to better elucidate human external exposure. Additionally, the mechanisms underlying PAC-induced oxidative stress should be further elucidated based on omics-based technologies, providing a more comprehensive understanding of their interference with important biological pathways.

CRediT authorship contribution statement

Ping Lu: Writing – original draft, Methodology, Formal analysis. **Qiaoying Chen:** Methodology, Data curation. **Mengmeng Wang:** Methodology, Formal analysis. **Chang He:** Methodology, Investigation. **Hailing Li:** Methodology, Investigation. **Yujiao Zhu:** Formal analysis. **Yumeng Shi:** Formal analysis. **Zhiguo Cao:** Writing – review & editing, Supervision, Conceptualization. **Guiying Li:** Writing – review & editing. **Taicheng An:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study includes human biological material and consent was obtained by donors, or their next of kin or legal representatives, for use in this study and for publication of the article. The samples used in this research were not sourced from executed prisoners or prisoners of conscience.

This study was performed in compliance with relevant laws,

regulatory frameworks and guidelines where the research took place. This study was approved by the Ethics Committee of the Guangdong University of Technology. (Approval No. GDUTXS20260214)

Declaration of competing interest

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.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (42530702, 42477473, U25A20825), Introduction Innovative and Research Teams Project of Guangdong Pearl River Talents Program (2023ZT10L102), the Central Plain Talent Program of Henan Province (5201219430020), the National Natural Science Foundation of Henan Province (252300421080), and the Huanghuai Lab Sci-Tech Innovation Project (240700008).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2026.125642>.

Data availability

No data was used for the research described in the article.

References

- Akinrinade, O.E., Rosa, A.H., 2025. Current levels, sources, and risks of human exposure to PAHs, PBDEs and PCBs in South American outdoor air: a critical review. *Environ. Res.* 270, 120941.
- Ali, N., 2019. Polycyclic aromatic hydrocarbons (PAHs) in indoor air and dust samples of different Saudi microenvironments; health and carcinogenic risk assessment for the general population. *Sci. Total Environ.* 696, 133995.
- Ali, N., Ismail, I.M.I., Khoder, M., Shamy, M., Alghamdi, M., Costa, M., Ali, L.N., Wang, W., Eqani, S.A.M.A.S., 2016. Polycyclic aromatic hydrocarbons (PAHs) in indoor dust samples from cities of Jeddah and Kuwait: levels, sources and non-dietary human exposure. *Sci. Total Environ.* 573, 1607–1614.
- Allan, S.E., Smith, B.W., Anderson, K.A., 2012. Impact of the deepwater horizon oil spill on bioavailable polycyclic aromatic hydrocarbons in Gulf of Mexico coastal waters. *Environ. Sci. Technol.* 46 (4), 2033–2039.
- Basu, S., 2010. Bioactive eicosanoids: role of prostaglandin F_{2α} and F₂-isoprostanes in inflammation and oxidative stress related pathology. *Mol. Cells* 30 (5), 383–392.
- Berrigan, D., Freedman, N.D., 2024. Polyaromatic hydrocarbons in alcohol-an unappreciated carcinogenic mechanism? *Environ. Health Perspect.* 132 (1), 11302.
- Cao, Z., Chen, Q., Zhu, C., Chen, X., Wang, N., Zou, W., Zhang, X., Zhu, G., Li, J., Mai, B., Luo, X., 2019a. Halogenated organic pollutant residuals in human bared and clothing-covered skin areas: source differentiation and comprehensive health risk assessment. *Environ. Sci. Technol.* 53 (24), 14700–14708.
- Cao, Z., Zhao, L., Zhang, Y., Ren, M., Zhang, Y., Liu, X., Jie, J., Wang, Z., Li, C., Shen, M., Bu, Q., 2019b. Influence of air pollution on inhalation and dermal exposure of human to organophosphate flame retardants: a case study during a prolonged haze episode. *Environ. Sci. Technol.* 53 (7), 3880–3887.
- Fu, X.-W., Li, T.-Y., Ji, L., Wang, L.-L., Zheng, L.-W., Wang, J.-N., Zhang, Q., 2018. Occurrence, sources and health risk of polycyclic aromatic hydrocarbons in soils around oil wells in the border regions between oil fields and suburbs. *Ecotoxicol. Environ. Saf.* 157, 276–284.
- Gao, Y., Geng, M., Wang, G., Yu, H., Ji, Y., Jordan, R.W., Jiang, S.-J., Gu, Y.-G., An, T., 2024. Environmental and dietary exposure to 24 polycyclic aromatic hydrocarbons in a typical Chinese coking plant. *Environ. Pollut.* 346, 123684.
- Ghosh, P., Mukherji, S., 2023. Fate, detection technologies and toxicity of heterocyclic PAHs in the aquatic and soil environments. *Sci. Total Environ.* 892, 164499.
- Golzadeh, N., Barst, B.D., Baker, J.M., Auger, J.C., McKinney, M.A., 2021. Alkylated polycyclic aromatic hydrocarbons are the largest contributor to polycyclic aromatic compound concentrations in traditional foods of the bigstone Cree nation in Alberta, Canada. *Environ. Pollut.* 275, 116625.
- Guo, Y., Senthilkumar, K., Alomirah, H., Moon, H.B., Minh, T.B., Mohd, M.A., Nakata, H., Kannan, K., 2013. Concentrations and profiles of urinary polycyclic aromatic hydrocarbon metabolites (OH-PAHs) in several Asian countries. *Environ. Sci. Technol.* 47 (6), 2932–2938.
- Hammer, E., Schoefer, L., Schafer, A., Hundt, K., Schauer, F., 2001. Formation of glucoside conjugates during biotransformation of dibenzofuran by *Penicillium canescens* SBUG-M 1139. *Appl. Microbiol. Biotechnol.* 57 (3), 390–394.

- Han, M., Yu, K., Zhang, R., Chen, B., Li, H., Zhang, Z.-e., Li, J., Zhang, G., 2023. Sources of the elevating polycyclic aromatic hydrocarbon pollution in the Western South China sea and its environmental implications. *Environ. Sci. Technol.* 57 (49), 20750–20760.
- Hou, M., Shi, Y., Na, G., Cai, Y., 2021. A review of organophosphate esters in indoor dust, air, hand wipes and silicone wristbands: implications for human exposure. *Environ. Int.* 146, 106261.
- Hua, L., Gao, Y., Guo, S., Zhu, H., Yao, Y., Wang, B., Fang, J., Sun, H., Xu, F., Zhao, H., 2024. Urinary metabolites of polycyclic aromatic hydrocarbons of rural population in northwestern China: oxidative stress and health risk assessment. *Environ. Sci. Technol.* 58 (18), 7758–7769.
- Jiao, A., Zhu, S., Chen, X., He, Q., Benmarhnia, T., Wu, J., 2026. Associations of PM_{2.5} and PAHs from wildland fires with pregnancy outcomes: evidence based on high-resolution exposure assessment. *Environ. Res.* 298, 124195.
- Jin, R., Yang, Y.Y., 2025. Global hotspots of industrial chlorinated and brominated polycyclic aromatic hydrocarbon emissions. *Nat. Sustain.* 8 (12), 1443–1444.
- Konan, N.G.F.D.S., Li, M., Shi, S., Toyin, A., Tine, A.H.L., Amoako, K., Appau, P.O., 2023. Distribution and isotopic compositions of phenanthrene and methylphenanthrenes in crude oils: implications for source input delineation and grouping oil families. *Appl. Geochem.* 158, 13, 000.
- Kuang, D., Zhang, W., Deng, Q., Zhang, X., Huang, K., Guan, L., Hu, D., Wu, T., Guo, H., 2013. Dose-response relationships of polycyclic aromatic hydrocarbons exposure and oxidative damage to DNA and lipid in coke oven workers. *Environ. Sci. Technol.* 47 (13), 7446–7456.
- Larsson, M., Lam, M.M., van Hees, P., Giesy, J.P., Engwall, M., 2018. Occurrence and leachability of polycyclic aromatic compounds in contaminated soils: Chemical and bioanalytical characterization. *Sci. Total Environ.* 622–623, 1476–1484.
- Li, H., Yao, C., He, C., Yu, H., Yue, C., Zhang, S., Li, G., Ma, S., Zhang, X., Cao, Z., An, T., 2023a. Coking-produced aromatic compounds in urine of exposed and nonexposed populations: exposure levels, source identification, and model-based health implications. *Environ. Sci. Technol.* 57 (41), 15379–15391.
- Li, H., Zhang, S., Yao, C., He, R., Lu, P., Li, G., Liu, R., Ma, S., Zhang, X., Cao, Z., An, T., 2023b. Nontarget screening of novel urinary biomarkers for occupational exposure to toxic chemicals from coking industry using HPLC-QTOF-MS. *Environ. Sci. Technol.* 57 (35), 13004–13014.
- Li, M., Ellis, G.S., 2015. Qualitative and quantitative analysis of dibenzofuran, alkyldibenzofurans, and Benzo[b]naphthofurans in crude oils and source rock extracts. *Energy Fuels* 29 (3), 1421–1430.
- Li, N., Zhang, J., Yu, H., Xu, M., Feng, Q., Zhang, J., Wang, X., Wei, P., Fan, Y., Yan, G., Zou, W., Cao, Z., Li, L., 2023c. A systematic characterization of soil/dust ingestion for typical subpopulations in China. *Environ. Geochem. Health* 45 (8), 6199–6214.
- Liang, W., Li, X., Ding, J., Mao, H., Wang, T., 2026. PM_{2.5}-bound nitrated and oxygenated PAHs induced lipid metabolism disorder through different target organs. *Environ. Res.* 294, 123875.
- Liao, Q., Huang, L., Cai, F., Luo, W., Li, M., Yang, J., Tang, B., Xiao, X., Yan, X., Zheng, J., 2024. Metabolomics perspectives into the co-exposure effect of polycyclic aromatic hydrocarbons and metals on renal function: a meet-in-the-middle approach. *Sci. Total Environ.* 921, 170975.
- Lin, M., Tang, J., Ma, S., Yu, Y., Li, G., Fan, R., Mai, B., An, T., 2020. Insights into biomonitoring of human exposure to polycyclic aromatic hydrocarbons with hair analysis: a case study in e-waste recycling area. *Environ. Int.* 136, 105432.
- Lin, Y., Gao, X., Qiu, X., Liu, J., Tseng, C.-H., Zhang, J.J., Araujo, J.A., Zhu, Y., 2021. Urinary carboxylic acid metabolites as possible novel biomarkers of exposures to alkylated polycyclic aromatic hydrocarbons. *Environ. Int.* 147, 106325.
- Liu, X., Hong, X., Song, H., Zhang, T., Chen, K., Chu, J., 2024. Exploring source-specific ecological risks of PAHs near oil platforms in the yellow river Estuary, Bohai sea. *Mar. Pollut. Bull.* 207, 116870.
- Lv, Y., Lu, S., Dai, Y., Rui, C., Wang, Y., Zhou, Y., Li, Y., Pang, Q., Fan, R., 2017. Higher dermal exposure of cashiers to BPA and its association with DNA oxidative damage. *Environ. Int.* 98, 69–74.
- Mallah, M.A., Changxing, L., Mallah, M.A., Noreen, S., Liu, Y., Saeed, M., Xi, H., Ahmed, B., Feng, F., Mirjat, A.A., Wang, W., Jabar, A., Naveed, M., Li, J.-H., Zhang, Q., 2022. Polycyclic aromatic hydrocarbon and its effects on human health: an overview. *Chemosphere* 296, 133948.
- Martinez, M.P., Kannan, K., 2018. Simultaneous analysis of seven biomarkers of oxidative damage to lipids, proteins, and DNA in urine. *Environ. Sci. Technol.* 52 (11), 6647–6655.
- McCormick, S., Snawder, J.E., Chen, I.C., Slone, J., Calafat, A.M., Wang, Y., Meng, L., Alexander-Scott, M., Breitenstein, M., Johnson, B., Meadows, J., Fairfield Estill, C., 2022. Exposure assessment of polycyclic aromatic hydrocarbons in refined coal tar sealant applications. *Int. J. Hyg Environ. Health* 242, 113971.
- Oliveira, E.C., Vaz de Campos, M.C., Rodrigues, M.R., Perez, V.F., Melechi, M.I., Vale, M.G., Zini, C.A., Caramao, E.B., 2006. Identification of alkyl carbazoles and alkyl benzocarbazoles in Brazilian petroleum derivatives. *J. Chromatogr. A* 1105 (1–2), 186–190.
- Özkaynak, H., Xue, J., Zartarian, V.G., Glen, G., Smith, L., 2010. Modeled estimates of soil and dust ingestion rates for children. *Risk Anal.* 31 (4), 592–608.
- Pan, W., Zeng, D., Ding, N., Luo, K., Man, Y.B., Zeng, L., Zhang, Q., Luo, J., Kang, Y., 2020. Percutaneous penetration and metabolism of plasticizers by skin cells and its implication in dermal exposure to plasticizers by skin wipes. *Environ. Sci. Technol.* 54 (16), 10181–10190.
- Peng, B., Dong, Q., Li, F., Wang, T., Qiu, X., Zhu, T., 2023. A systematic review of polycyclic aromatic hydrocarbon derivatives: occurrences, levels, biotransformation, exposure biomarkers, and toxicity. *Environ. Sci. Technol.* 57 (41), 15314–15335.
- Ri, B., Kim, Young, M., S, Chun Ae, Youn, Woong S., 2015. Sebum secretion of the trunk and the development of truncal acne in women: do truncal acne and sebum affect each other? *Dermatology* 231 (1), 87–93.
- Shi, S., Feng, Q., Zhang, J., Wang, X., Zhao, L., Fan, Y., Hu, P., Wei, P., Bu, Q., Cao, Z., 2024. Global patterns of human exposure to flame retardants indoors. *Sci. Total Environ.* 912, 169393.
- Stockinger, B., Meglio, P.D., Gialitakis, M., Duarte, J.H., 2014. The aryl hydrocarbon receptor: multitasking in the immune system. *Annu. Rev. Immunol.* 32 (1), 403–432.
- Tang, J., Lin, M., Ma, S., Yang, Y., Li, G., Yu, Y., Fan, R., An, T., 2021. Identifying dermal uptake as a significant pathway for human exposure to typical semivolatile organic compounds in an e-waste dismantling site: the relationship of contaminant levels in handwipes and urine metabolites. *Environ. Sci. Technol.* 55 (20), 14026–14036.
- Vogel, C.F.A., Van Winkle, L.S., Esser, C., Haarmann-Stemmann, T., 2020. The aryl hydrocarbon receptor as a target of environmental stressors-implications for pollution mediated stress and inflammatory responses. *Redox Biol.* 34, 101530.
- Wang, C., Wang, W., Liu, X., Tang, Y., Wang, F., Li, H., Wen, M., Li, G., An, T., 2024a. Aqueous VOCs in complex water environment of oil exploitation sites: spatial distribution, migration flux, and risk assessment. *J. Hazard. Mater.* 476, 135121.
- Wang, M., Li, Y., Lv, Y., Tang, J., Wei, P., Lu, P., Zhao, L., Li, G., Cao, Z., An, T., 2024b. Quantitative characterization of resident' exposure to typical semi-volatile organic compounds (SVOCs) around a non-ferrous metal smelting plant. *J. Hazard. Mater.* 465, 133353.
- Wang, W., Jariyapit, N., Schrlau, J., Jia, Y., Tao, S., Yu, T.-W., Dashwood, R.H., Zhang, W., Wang, X., Simonich, S.L.M., 2011. Concentration and photochemistry of PAHs, NPAHs, and OPAHs and toxicity of PM_{2.5} during the Beijing olympic games. *Environ. Sci. Technol.* 45 (16), 6887–6895.
- Wang, Z., Geng, S., Zhang, J., Yang, H., Shi, S., Zhao, L., Luo, X., Cao, Z., 2024c. Methods for the characterisation of dermal uptake: progress and perspectives for organophosphate esters. *Environ. Int.* 183, 108400.
- Wei, C., Bandowe, B.A.M., Han, Y., Cao, J., Zhan, C., Wilcke, W., 2015. Polycyclic aromatic hydrocarbons (PAHs) and their derivatives (alkyl-PAHs, oxygenated-PAHs, nitrated-PAHs and azaarenes) in urban road dusts from Xi'an, central China. *Chemosphere* 134, 512–520.
- Wen, Y., Wang, Y., Chen, R., Guo, Y., Pu, J., Li, J., Jia, H., Wu, Z., 2024. Association between exposure to a mixture of organochlorine pesticides and hyperuricemia in U. S. adults: a comparison of four statistical models. *Eco-Environ. Health* 3 (2), 192–201.
- Weschler, C.J., Nazaroff, W.W., 2012. SVOC exposure indoors: fresh look at dermal pathways. *Indoor Air* 22 (5), 356–377.
- Wu, C., Bao, L., Tao, S., Zeng, E.Y., 2016. Dermal uptake from airborne organics as an important route of human exposure to e-waste combustion fumes. *Environ. Sci. Technol.* 50 (13), 6599–6605.
- Wu, H., Lu, L., Chen, J., Zhang, C., Liu, W., Zhuang, S., 2020. Inhibited nitric oxide production of human endothelial nitric oxide synthase by nitrated and oxygenated polycyclic aromatic hydrocarbons. *Environ. Sci. Technol.* 54 (5), 2922–2930.
- Yao, J., Yang, X.P., Wu, T.T., Zhang, X.J., Chen, H.F., Song, W.Q., Tong, X.H., Wang, Y.J., Li, X., Ding, Y., 2026. From emission to toxicity: unraveling the overlooked challenge of polycyclic aromatic hydrocarbons from vehicle exhaust. *Environ. Pollut.* 397, 128016.
- Yu, H., Ma, J., Chen, D., Gao, Y., Li, G., An, T., 2024. Associations between inhalation of typical volatile and semi-volatile organic compounds in e-waste dismantling workers with liver function damage. *J. Hazard. Mater.* 464, 133004.
- Yun, P., Han, X., Liu, H., Jia, Y., Cao, Z., 2025. Soil and dust ingestion rate: concept, methodology, available data and knowledge gaps. *Glob. Environ. Sci.* 1 (1), 56–58.
- Zhang, Q., Zhang, H., Chen, L., 2026a. Overlooked polycyclic aromatic compounds from aviation emissions beyond regulated pollutants. *ACS ES&T Air* 3 (4), 910–912.
- Zhang, X., Wang, X., Liang, W., Liu, M., Wang, X., Zhao, X., 2024. The occurrence, sources, and health risks of substituted polycyclic aromatic hydrocarbons (SPAHs) cannot be ignored. *Environ. Int.* 183, 108390.
- Zhang, X., Wang, X., Wang, S., Zhou, L., Liang, W., Liang, J., Wu, F., Zhao, X., 2026b. Substituted polycyclic aromatic hydrocarbons (SPAHs) in petrochemical park workers: external and internal exposure assessment and half-lives. *Environ. Sci. Technol.* 60 (2), 1713–1722.
- Zhang, Y., Hu, Q., Fu, J., Li, X., Mao, H., Wang, T., 2023. Influence of exposure pathways on tissue distribution and health impact of polycyclic aromatic hydrocarbon derivatives. *Environ. Health* 1 (3), 150–167.
- Zhao, K., Jiang, C., Han, Y., Li, W., Li, Y., Liu, L., Ma, W., Hu, Y., Zhang, Z., 2024. Differential occupational health risks between methylated PAHs and PAHs: monitoring 126 PAHs and 6 oxidative stress markers in paired serum-urine samples. *Environ. Health* 2 (3), 150–160.
- Zhou, Y., Xiao, K., Zhang, Y., Fu, D., Jiang, K., Luo, J., Li, Y., Shen, G., Liu, W., Tao, S., Lu, S., 2024. Polycyclic aromatic compounds (PACs) in industrial soils from northwestern of China: occurrence, distribution, exposure risk, and implications on risk-based controls. *Environ. Geochem. Health* 46 (4), 135.