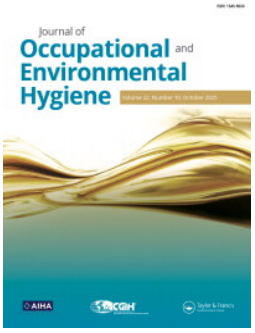

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Evaluation of the decontamination methods for turnout gear

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ABSTRACT

Firefighters are exposed to various carcinogenic substances during firefighting tasks, but also in the maintenance of firefighting personal protective equipment (PPE). Due to multiple exposures to chemical agents via different exposure routes, the International Agency for Research on Cancer (IARC) categorized the firefighting occupation as Group 1 - carcinogenic to humans. Decontamination methods have been found to play an important role in reducing firefighter chemical exposures. Unfortunately, decontamination techniques are insufficient in removing carcinogenic substances from PPE. This study aimed to evaluate decontamination methods for firefighter turnout gear. Using various techniques, the cleaning efficiency of 18 polycyclic aromatic hydrocarbons (PAHs) from turnout gear coats contaminated during firefighting exercises was measured. For turnout gear coats ($n = 40$), decontamination methods used were conventional aqueous laundering (AL) and its combination with advanced hydrogen peroxide treatment (H_2O_2) or ozone treatment in a chamber (O_3). In addition, the cleaning efficiencies of advanced liquid carbon dioxide (LCO_2) and the ozone laundry system (LO_3) were measured. Results show that when the conventional AL water wash temperature increased from 40 to 60 °C, cleaning efficiencies did not significantly increase. Cleaning efficiencies in outer layers of coats were 63% and 60%, respectively. The results in outer layers of AL combined with O_3 and H_2O_2 techniques showed cleaning efficiencies 84% and 42%, respectively. Cleaning efficiency with LO_3 and with the fully advanced LCO_2 technique demonstrated cleaning efficiency 71% and 74%, respectively. LCO_2 was the most advanced, especially in the middle layers, yielding a cleaning efficiency of 84% while other techniques in the middle layers reached a maximum efficiency 24%. The cleaning efficiency of all methods indicated approximately 20–30% lower cleaning efficiency for high molecular weight (HMW) PAHs than for low molecular weight (LMW) PAHs. The results of this study emphasized the importance of improving conventional AL and the advantage of the LCO_2 method in enhancing cleaning efficiency.

KEYWORDS
Aqueous laundering; cleaning efficiency; hydrogen peroxide treatment; liquid carbon dioxide; ozonation; ozone laundry system

Introduction

During the firefighting operations, firefighters face exposure to a wide range of carcinogenic, genotoxic, and endocrine-disrupting chemicals through multiple exposure routes. Notable groups of hazardous substances include polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), per- and poly-fluoroalkyl substances (PFAS), and asbestos fibers (Fent et al. 2014, 2015; Fent, LaGuardia, et al. 2020; Fent, Toennis, et al. 2020; Laitinen et al. 2010; Levasseur et al. 2022; Stec et al. 2018; Taeger et al. 2023). Unfortunately, the complexity of this toxic mixture of chemicals has even increased in recent decades, especially in structural fires driven by the growing use of synthetic materials in construction and household products. Extra challenges for chemical risk evaluators are posed by additive and synergistic effects of chemicals (Laitinen et al. 2012; Martin 2023).

The working environment of firefighters also significantly amplifies their exposure to harmful substances. The physical demands of firefighting operations increase their breathing rate, which in turn can increase the volume of contaminants inhaled when they are not using respiratory equipment. Additionally, the combination of intense physical stress and external heat causes

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firefighters to sweat and raises their skin temperature, further intensifying the facilitation of absorption of toxic chemicals through the skin (Demers et al. 2022; Everaert et al. 2023; Holmgaard and Nielsen 2009; Jones et al. 2003; Trabaris et al. 2012; Van den Eijnde et al. 2020).

The International Agency for Research on Cancer (IARC) recently increased the occupational carcinogenic categorization for firefighters to the highest classification, Group 1 – carcinogenic to humans. This elevation reflects that there exists sufficient evidence linking firefighter exposures to carcinogens with an increased incidence of cancer (Demers et al. 2022). As such, firefighters should follow ALARA principles and keep exposures "as low as reasonably achievable."

Due to the use of highly effective self-contained breathing apparatus (SCBA), dermal absorption is now considered to be the major route in firefighter exposures (Fent, LaGuardia, et al. 2020; Fent, Toennis, et al. 2020; Fent et al. 2014, 2015; Probert et al. 2024; Stec et al. 2018; Therkorn et al. 2024). Therefore, adequate decontamination of turnout gear must be considered in minimizing firefighters' dermal exposures to ALARA. Without proper decontamination techniques, practices, and user diligence, the extended life cycle of turnout gear makes it susceptible to accumulations of chemical contaminants, compromising breathability (Instituut Fysieke Veiligheid 2018; Magnusson and Hultman 2015; Stec et al. 2020; Wolffe et al. 2023).

Previous studies have indicated that aqueous laundering (AL) is insufficient in removing hydrophobic organic compounds like PAHs from turnout gear (Abrard et al. 2019; Banks et al. 2021; Keir et al. 2020; Mayer et al. 2019). On the other hand, promising results have been obtained from new technologies, for example liquid carbon dioxide technique (LCO_2) (Fijan et al. 2012; Madsen et al. 2014; Szmytke et al. 2022). The LCO_2 has demonstrated effectiveness in removing semi-volatile organic compounds, the lack of mechanical action in the process has been claimed to limit its effectiveness in removing particulate contaminants (Girase et al. 2023). The effectiveness of hydrogen peroxide (H_2O_2) and ozone treatments (Ozone chamber (O_3) or ozone laundering (LO_3)) has been evaluated, especially in the destruction of biological factors (Barbut et al. 2009; ECDC Technical Report 2020). In the decontamination of PAHs, chamber O_3 cleaning has been reported to generate new oxygenated PAH compounds that could be more harmful than the original PAHs (Lucena et al. 2021).

This study aimed to test and identify recommendations for optimal efficiency of removing carcinogenic substances from turnout gear exposed to realistic exposure and decontamination conditions. This project assessed cleaning efficiencies of traditionally used AL at 40 °C and 60 °C temperatures with a drying cabinet and tumble drying. Also, the enhanced efficiency of H_2O_2- and O_3-treatments combined with AL, as well as the functionality of LCO_2 and LO_3 techniques, were analyzed.

Methods

Contamination protocol

Turnout gear coats ($n = 40$) were contaminated during hot firefighting exercises in the training area at Emergency Service Academy Finland (ESAF). The exercises consisted of firefighting activities conducted in a conventional firefighting simulator (mock-up block apartment). Heat and smoke were generated by burning wood. The activities simulated real-life firefighting scenarios and fire suppression tasks performed in an upright position using a fire hose nozzle. The starting fluid used to initiate the fire was low-aromatic Nessol Liav 200 (Neste Oy, Finland), and each turnout gear coat was exposed to 20 min of high temperatures and combustion products produced by the fire. Lion VCF141101_FS (LHD Group, Germany) and Viking Model 8066088 J (Viking, Norway), EN 469-compliant turnout gear coats were used in the decontamination tests. The Lion fabric consisted of an outer layer: 93% m-aramid/5% p-aramid/2% antistatic; moisture barrier: 50% aramid/50% viscose; and an inner layer: 50% aramid/50% viscose. The Viking fabric consisted of an outer layer: 75% m-aramid/23% p-aramid/2% antistatic (fabric weight $195\,g/m^2 + 15\%$ and $195\,g/m^2 - 5\%$); moisture barrier: 100% aramid ($140 \pm 15\,g/m^2$); inner layer 93% m-aramid/5% p-aramid/2% antistatic ($200\,g/m^2 \pm 5\%$). Turnout goats did not have removable inner liners. Coats that had reached 5 years of age or undergone 50 washes were decommissioned (in accordance with ESAF guidelines) and used in this study. After exposure, the coats were packed into plastic bags to await the first sample collection and decontamination procedure. Following decontamination, coats were packed in clean plastic bags to wait for a second round of sample collection or combined advanced treatment and the third sample taking.

Sample collection and analyses

Cleaning efficiencies were evaluated by removing patch samples with a 22 mm round drive punch (3.8 cm^2) of the inner layer of the neck, chest, and back from all three turnout coat layers (outer, middle, and inner layer), resulting in a total of seven samples per turnout gear. Sampling sites were chosen to ensure they were not located beneath the location where the SCBA rests on the turnout gear. Samples were taken after exposure and after decontamination treatments ($n = 686$). Samples were stored in an air-tight container protected from sunlight.

PAH samples were prepared by dichloromethane (DCM) extraction and analyzed with gas chromatography mass-spectrometry technology (GC-MS) at the work environment laboratory of the Finnish Institute of Occupational Health (FIOH). DCM was used because it offers the best performance compared to other extraction solvents, with recoveries between 70–120% for almost all compounds (Marín-Sáez et al. 2024). Laboratory extraction experiments for LMW PAHs support these results. For comparison to EU threshold values, patch samples were weighed using a PG503-S DeltaRange scale (Toledo Metler, Columbus, USA). The work environment laboratory of the Finnish Institute of Occupational Health is an accredited testing laboratory T013 (FINAS accreditation services, EN ISO/IEC 17025).

Decontamination protocol

Test 1

In the first series of tests, 15 contaminated turnout gear coats were decontaminated by AL. Five of them were decontaminated in 14 kg capacity industrial washing machines W5130H (Electrolux, Sweden), one at a time at 60 °C, and dried for 1 hr in tumble drying T5190LE (Electrolux, Sweden). AL washing steps, washing times, used water levels during washing steps, washing temperatures, detergents used, and their automated dosages of the AL used in all tests are presented in Table 1.

Four of the turnout gear coats were processed one at a time in the O_3 chamber (Hygio a40 Medi) with a 2-hour power decontamination program at the Hygio Oy Salo production facility in Finland. The variation of ozone concentration in the ozone chamber was monitored with two ozone analyzers (O_3 41 M Environnement S. A., France, and Model 465 L Teledyne API, USA). The treatment included an ozone concentration build-up phase (30 min) until the ozone concentration reached 12 ppm. The concentration was kept constant for 1 hour, after which the ozone concentration in the cabinet was neutralized to the indoor air level in 30 min.

In addition, five turnout gear coats were decontaminated by AL at 40 °C and five at 60 °C. These were dried in drying cabinets Nascator CS360 (Electrolux, Sweden) and Passeli 401 Classic (Rosenlev, Finland). All details of the washing steps are presented in Table 1. All ALs were carried out at Kangasala fire station facilities in Finland.

Test 2

In the second series of tests, five contaminated turnout gear coats were decontaminated by the LCO_2 technique at Decontex NV in Belgium. The decontamination was done with the DECO$_2$FIRE process using an industrial LCO_2 machine DCX MF-DECO$_2$N 450 L (Electrolux, Sweden). The decontamination process took 27 min at 43 bar with a drum revolution speed of 12 revolutions per minute. Detergent used in the process was Sultrex CO_2 (Chemco Chemistry, UK).

The next five turnout gear coats were decontaminated by AL at 60 °C, and laundry was tumble-dried. All details of the washing steps are presented in Table 1. Four of five coats underwent H_2O_2 treatment

Table 1. Used washing steps in decontamination tests with aqueous laundering at 40 °C and 60 °C temperatures.

Washing step	Time, min	Water level	Temperature °C	Detergent	Dosage, g detergent/kg laundry
Prewash	4	Low	30–35	Clax 100 booster Clax Plus detergent	3 12
Prewash	4	Medium	30–35		
Drain	1				
Mainwash	10	Low	40/60	Clax 100 booster Clax Plus detergent	4 10
Mainwash	5	Medium	40/60		
Drain	1				
Rinse 1	3	High	Cold		
Drain	1				
Rinse 2	3	High	Cold		
Drain	1				
Rinse 3	4	High	40		
Final extraction	6				
Total process time:	43				

using the Cleamix VCS-100M system (Cleamix Ltd, Finland) at the Xhome decontamination facility in Ylämylly, Finland. Vaporized H_2O_2 was produced from a 50% hydrogen peroxide solution. During treatment, H_2O_2 concentrations in the exposure chamber were measured in real time with a hydrogen peroxide meter Vaisala HPP 270 series (Vaisala Oy, Finland). The treatment included an H_2O_2 concentration build-up phase of 60 min to a level of 200 ppm. The concentration was kept constant for 1 hour, and after which the hydrogen peroxide in the cabinet was neutralized. The duration of the whole treatment was 2 h.

Test 3

In the third series of tests, 10 turnout gear coats were decontaminated. Half of the coats were decontaminated by AL at 40 °C and the other half at 60 °C. All were dried in a drying cabinet. This test was provided to evaluate the effect of temperature on the washing efficiency results.

Test 4

The fourth series of turnout gear coats was exposed and washed with the LO_3 technique. In ozone laundering, the washing machine HS-6040 IC-V TILT (GIRBAU, Spain) was equipped with the ozonator unit OT0313001 (Ozone Technologies, New Zealand), which produced ozone during the aqueous laundering phase throughout the washing process. The washing process took 35 min, including wash, rinse, and spin times. The washing program was “very dirty work clothes,” “60/60.” The program includes two 8-min washes at 60 °C with three rinses (1 + 3 + 3 min) and intermediate spins. The total time of the washing process does not include intervals when, for example, the machine prepares to spin or fills water for washing and rinsing. Ozonation works throughout the washing phases of the process, producing 0.20 ppm ozone into the air of the drum, meaning the device supplies ozone regardless of the different washing or waiting phases. Ozone laundering was carried out by the Itä-Suomen Tekstiilihuolto Oy in their decontamination facility in Kitee, Finland.

Calculation of cleaning efficiency

Cleaning efficiency indicated what percentages of contaminants were removed during decontamination. Cleaning efficiency was calculated for three different layers: outer layers (outer layer of the back and chest and the inner layer of the neck), middle layers (middle layer of the back and chest), and inner layers (inner layer of the back and chest) using the following formula:

$$\text{Cleaning efficiency} = 1\text{–}(C_d/C_c) \times 100 \qquad (1)$$

where C_d = Concentration of contaminant on the sample after decontamination, and C_c = Concentration of contaminant on the sample after contamination.

Data analysis

The least squares method was used to find the best-fit line for the total amounts of PAHs after exposure and decontamination for each decontamination technique. Linear regression was applied, and the distance of an ordered pair of numbers from the regression line was calculated. If the distance of the ordered pairs from the regression line was higher than three times the standard deviation of the number set, then the ordered pair was interpreted as an outlier. Distances less than that were included in the decontamination efficiency calculations. Also, if the PAH concentrations of the individual samples varied more than three times the standard deviation of the number set, the ordered pair was excluded. Distance (d) from the regression line was calculated by the following formula:

$$d = \frac{|ax_0 + by_0 + c|}{\sqrt{a^2 + b^2}} \qquad (2)$$

where the equation ($ax_0 + by_0 + c = 0$) for the best fitting of the least squares methods is $-0{,}3994 * 1500 + 1 * 1800 - 758{,}11 = 0$ for the point (1500, 1800) in Figure 1. The correlation coefficient was calculated by Pearson’s method.

Statistical analysis was performed by IBM SPSS Statistics 29.0 2.0 (20) using one-way ANOVA followed by Bonferroni’s post-hoc test to investigate the significance between the different cleaning efficiencies. Tests of homogeneity of variances for the testing groups were done by the Levene test. If the homogeneity of variance were not equal, Tamhane’s T2 method was used. A $p < 0.05$ was considered significant.

Results

Contamination levels

The average concentrations of total PAHs and the variation range between the mean values of different layers of the turnout gear with different techniques are shown in Table 2. The middle layers were the most contaminated after exposure, followed by the outer and inner layers. Most of the contamination

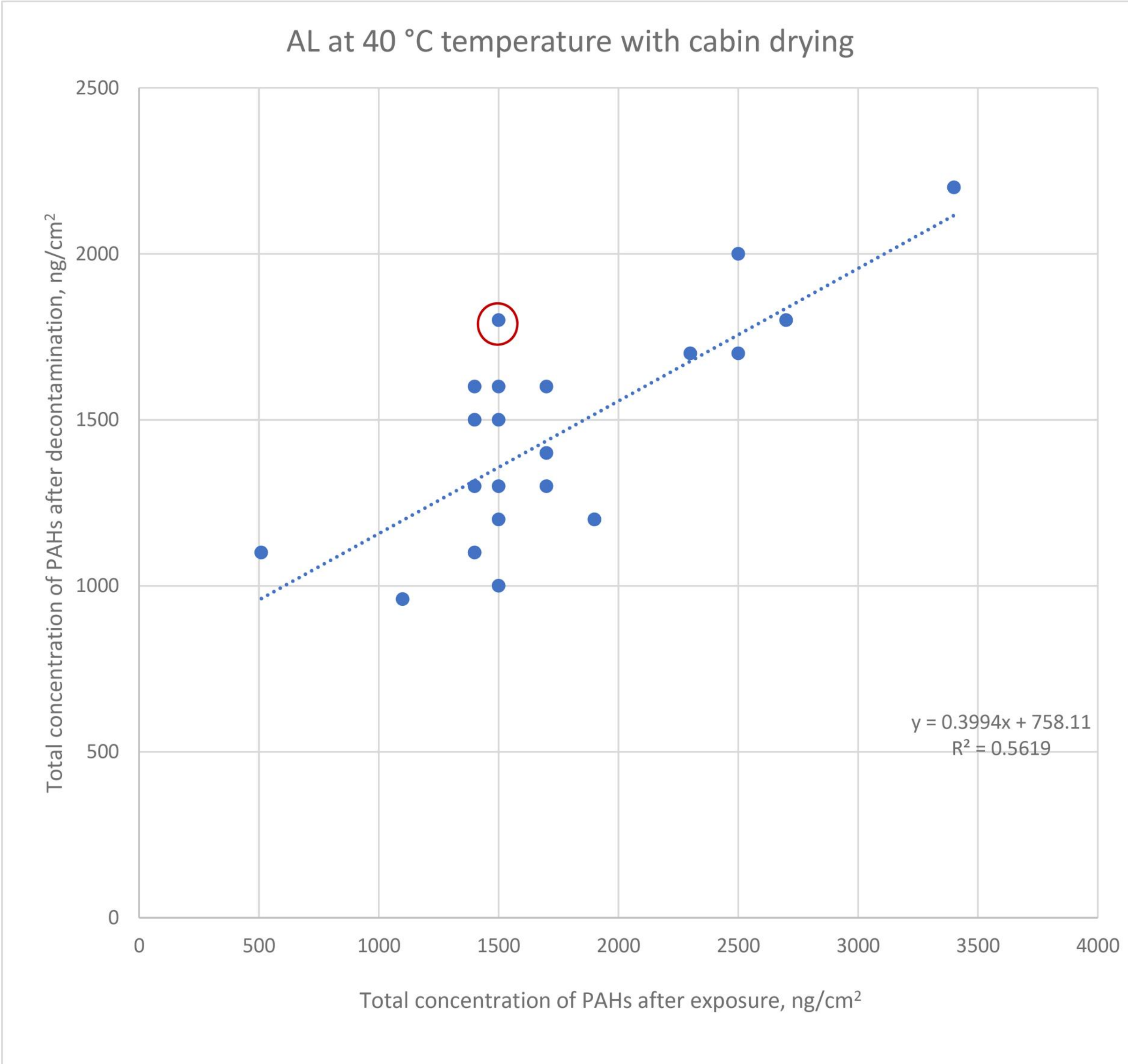

Figure 1. The correlation between the total concentration of PAHs in patch samples measured after exposure and decontamination.

levels of the middle layers averaged between 870 and 1,800 ng/cm^2. The contamination level before application of the AL technique at 60 °C with tumble dryer combined with hydrogen peroxide treatments showed, on average, a PAH contamination of 210 ng/cm^2. In outer layers, mean concentrations were 110 to 300 ng/cm^2, and in the inner layers, 6 to 20 ng/cm^2 (Table 2).

After decontamination, the order of the contamination levels between layers remained the same. Mean contamination levels in the middle layers ranged between 770 and 1,600 ng/cm^2, but after decontamination by the LCO_2, the mean contamination level was 250 ng/cm^2. Contamination levels after AL at 60 °C with tumble dryer combined with H_2O_2 technique showed on mean contamination level of 190 ng/cm^2. In outer layers, mean contamination levels were 15 to 59 ng/cm^2, and in the inner layers, 1.0 to 12 ng/cm^2 (Table 2).

The European Commission has issued Regulation No. 1272/2013 to protect consumer health from risks associated with exposure to PAH compounds by establishing concentration limits for PAHs in products (European Commission 2013). The following PAH compounds were considered in the drafting of the restriction: benzo[a]pyrene, benzo[e]pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, and dibenzo[a,h]anthracene. New products containing any of those PAH compounds at concentrations exceeding 1 mg/kg are prohibited from entering the marketplace. This restriction applies to materials that come into direct, prolonged, or short-term repeated contact with human skin, such as clothing. All

Table 2. The average concentration of total PAHs in different layers after exposure and decontamination with different techniques.

Layer	Decontamination method	Sample pairs (N)	Number of outliers	After exposure (ng/cm^2)		After decontamination (ng/cm^2)		Number of exceedances of 1 mg/kg for individual PAH compounds	
				avg	SD	avg	SD	after exposure	after decontamination
Outer	AL 40 °C	32	1	220	210	50	20	8/54	0/54
Middle	AL 40 °C	22	0	1800	610	1500	330	30/36	27/36
Inner	AL 40 °C	22	3	9.6	8.1	4.6	3.0	0/36	0/36
Outer	AL 60 °C, C	27	3	170	180	49	27	5/54	0/54
Middle	AL 60 °C, C	18	2	1600	420	1500	460	30/36	26/36
Inner	AL 60 °C, C	18	3	11	8.1	5.1	1.3	0/36	0/36
Outer	AL 60 °C, D	30	4	110	88	52	17	4/54	0/54
Middle	AL 60 °C, D	20	1	870	720	770	620	26/36	22/36
Inner	AL 60 °C, D	18	5	7.9	8.4	5.7	4.6	0/36	0/36
Outer	LCO_2	15	2	120	70	25	6,1	3/54	0/54
Middle	LCO_2	10	1	1600	410	250	62	29/36	5/36
Inner	LCO_2	10	1	10	5.6	3.4	1.6	0/36	0/36
Outer	$AL^{\dagger} + O_3$	12	0	120	85	15	6.5	3/54	0/54
Middle	$AL^{\dagger} + O_3$	8	0	1500	340	1100	180	30/36	20/36
Inner	$AL^{\dagger} + O_3$	8	1	6.0	2.7	1.0	0.8	0/36	0/36
Outer	LO_3	15	5	300	220	59	15	19/54	0/54
Middle	LO_3	10	0	1800	320	1600	300	33/36	28/36
Inner	LO_3	10	2	13	7.6	8.7	7.2	0/36	0/36
Outer	$AL^{\dagger} + H_2O_2$	15	1	120	100	43	18	6/54	0/54
Middle	$AL^{\dagger} + H_2O_2$	10	0	210	160	190	130	6/36	6/36
Inner	$AL^{\dagger} + H_2O_2$	10	3	20	18	12	14	0/36	0/36

C = cabin drying, D = tumble drying. † = aqueous laundering 60 °C temperature with tumble drying.

the layers will not directly contact the skin, but the possibility of cross-contamination between layers may pose health risks for the firefighters. Hot conditions, sweating, and finally occlusion effects under the firefighting coat can still contribute to an increased dermal exposure risk (Everaert et al. 2023). To get guidelines for assessment of the results, the same threshold value (1 mg/kg) was applied uniformly to each measured PAH. Because an occupational threshold value for existing, rather than new materials, could not be defined, and the potential synergistic effects of PAHs are not clear in this context, the authors used a uniform threshold value to ensure a precautionary approach in the assessment of PAH toxicity. Measured PAH concentrations were compared to the threshold value of 1 mg/kg after contamination. The average was calculated for each PAH compound ($n = 18$) separately for the outer, middle, and inner layers ($n = 54$, 36, and 36, respectively). The average number of exceedances in the outer, middle, and inner layers was 7/54, 26/36, and 0/36, respectively. After decontamination, the average number of exceedances in the outer, middle, and inner layers was 0/54, 19/36, and 0/36, respectively (Table 2).

Cleaning efficiencies

Figure 2 illustrates cleaning efficiencies and standard deviations of different decontamination techniques in the layers, and the decontamination methods marked with an asterisk (*) indicate a significant difference compared to aqueous laundering (AL) at 60 °C temperature with tumble drying. In the outer layers, average cleaning efficiencies with AL at 40 °C and 60 °C using the cabin dryer were 63% and 60%, respectively. There was no significant difference between water washing at 60 °C or 40 °C in any of the layers ($p = 1.00$ and 0.44, respectively). The mean cleaning efficiency with AL at 60 °C with tumble drying was 23%. AL combined with H_2O_2-treatment exhibited a mean cleaning efficiency of 42%. The LO_3- and LCO_2- techniques yielded 71% and 74% cleaning efficiencies, respectively. The AL combined with O_3 chamber treatment showed an 84% cleaning efficiency (Figure 2). In outer layers, the LCO_2, AL + O_3, and LO_3 cleaning efficiencies were significantly better than AL at 60 °C with tumble drying (p = <0.01, 0.04, and < 0.01, respectively).

In the middle layers, the mean cleaning efficiency of the LCO_2 technique was 84%. These results differed significantly ($p < 0.01$) from other methods (Figure 2). In addition, the standard deviation was small, indicating that the results were consistent. The AL + O_3 chamber and LO_3 techniques showed mean cleaning efficiencies of 24% and 10%, respectively. The AL method at 40 °C and at 60 °C with cabin drying achieved cleaning efficiencies of 10% and 9%, respectively. In the inner layers, cleaning efficiencies showed similar profiles between the decontamination techniques as in the outer layers (Figure 2).

The total cleaning efficiency for LMW PAHs and HMW PAHs with all methods was assessed from the samples in the middle of the back and chest. Samples

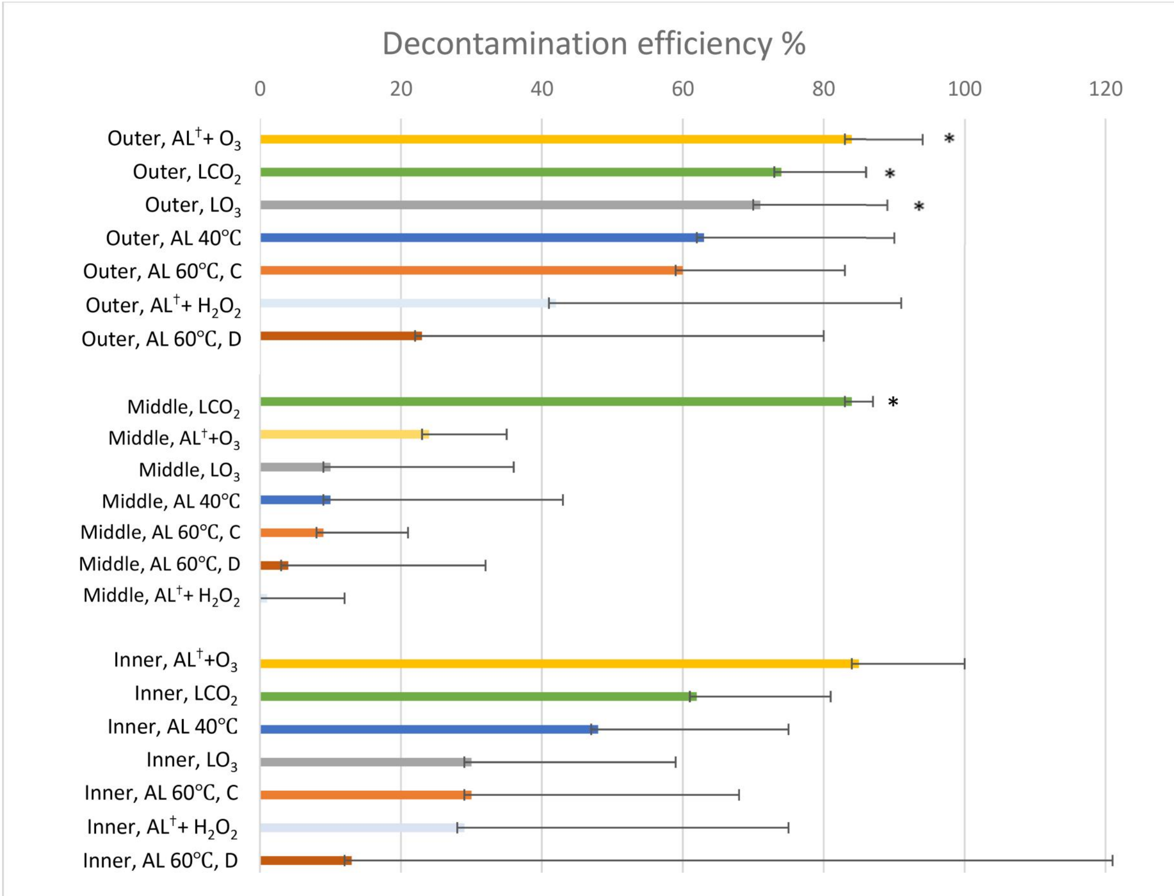

Figure 2. Decontamination efficiencies and their standard deviation with different techniques in different layers. *Statistically significant difference compared to aqueous laundering (AL) at 60 °C temperature with tumble drying (D). † = aqueous laundering 60 °C temperature with tumble drying.

were selected for their concentration ranges, ensuring the existence of both LMW and HMW PAHs in all samples. The mean cleaning efficiency for LMW PAHs varied from 29% to 44% and from 8.5% to 15% for HMW PAHs (Figures 3 and 4).

The effects of the molecular weight of PAHs were also tested with the LCO_2 technique using similar samples as above, and comparing decontamination results to average contamination levels. The cleaning efficiencies for LMW PAHs ranged from 95.6% to 96.0% and 79.4% to 80.8% for HMW PAHs (Figures 3 and 5).

Profiles of individual PAHs

The average profiles of individual PAHs for all methods and layers after contamination are shown in Figure 3. Almost all concentrations of individual PAHs in the middle layers exceeded 1 mg/kg. Exceptions to that were 1-methylnaphtalene, 2-methylnaphthalene, and dibenzo[a,h]anthracene. The concentrations of the phenantrene, fluoranthene, and pyrene were 12-, 9.1-, and 8.5-fold higher, respectively.

The average profile of individual PAHs for all methods and layers, excluding middle layers after contamination, is illustrated in Figure 6. Individual concentrations of benzo[a]anthracene and benzo[a]pyrene reached the EU Commission threshold value (1 mg/kg) in the outer layers, as well as benzo[k]fluoranthene in the outer layers, but average concentrations fall below the threshold. All measured concentrations from inner layers were below 1 mg/kg (Figure 6).

The average profiles of individual PAHs for all methods and layers after decontamination are shown in Figure 4. Most measurements of individual PAHs in middle layers exceeded the 1 mg/kg threshold, except naphthalene, 1-methylnaphtalene, 2-methylnaphthalene, fluorene, and dibenzo[a,h]anthracene. The concentrations of the phenanthrene, fluoranthene, and pyrene were 9.3-, 7.7-, and 7.2-fold higher than the threshold, respectively.

The average profile of individual PAHs for all methods and layers, excluding middle layers after

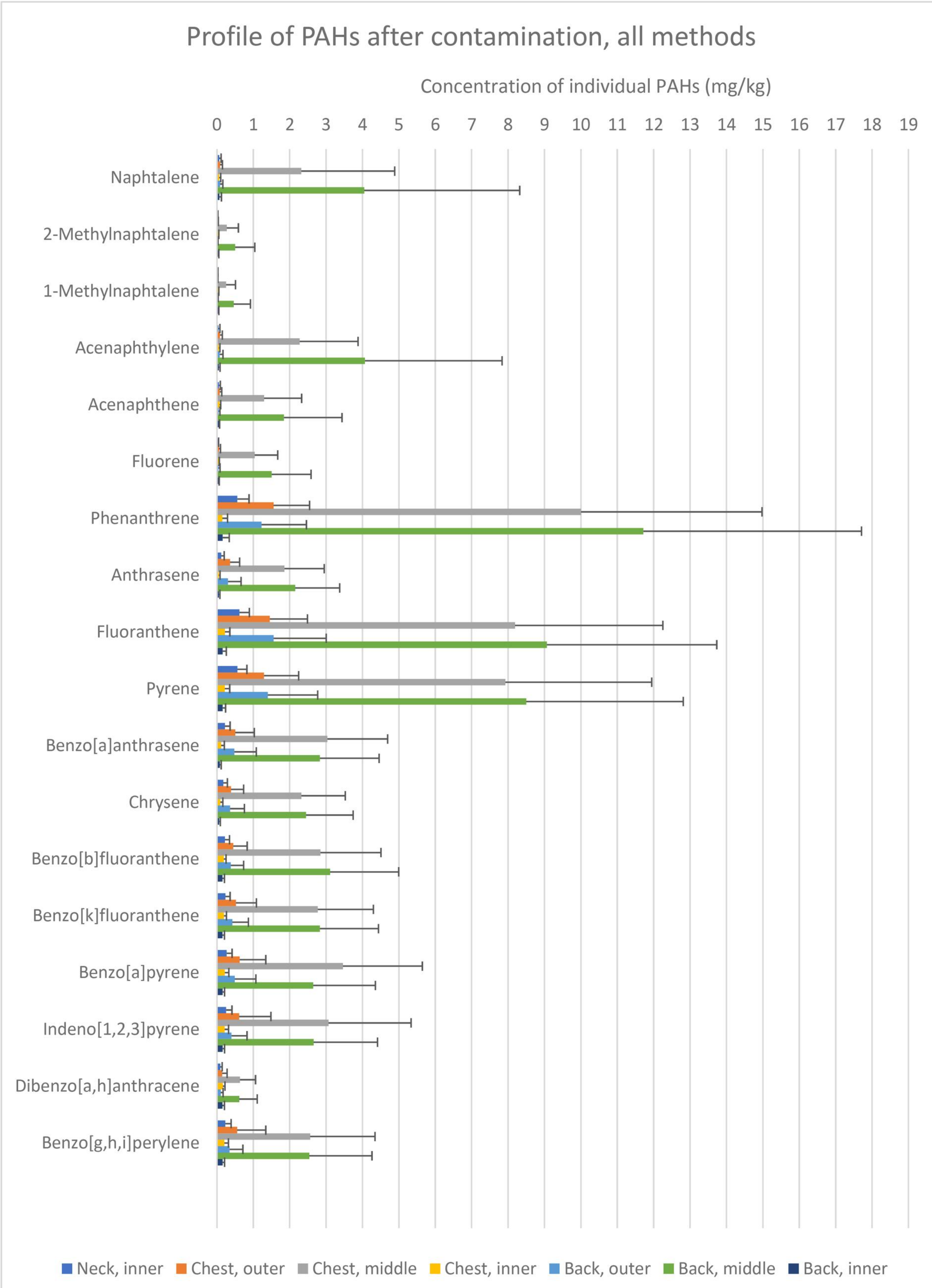

Figure 3. Profile of PAHs after contamination of all methods, all layers included.

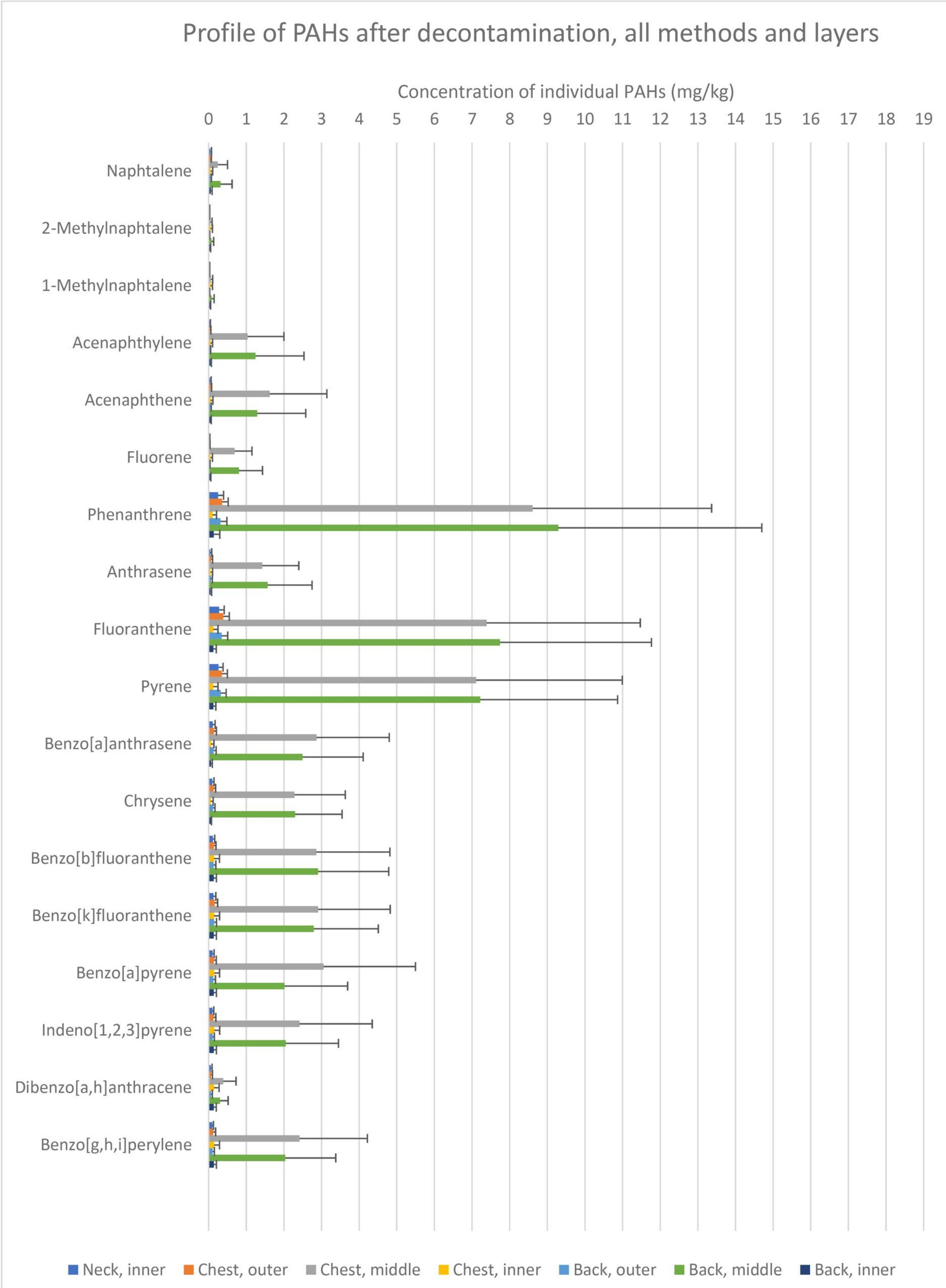

Figure 4. Profile of PAHs after decontamination of all methods, all layers included.

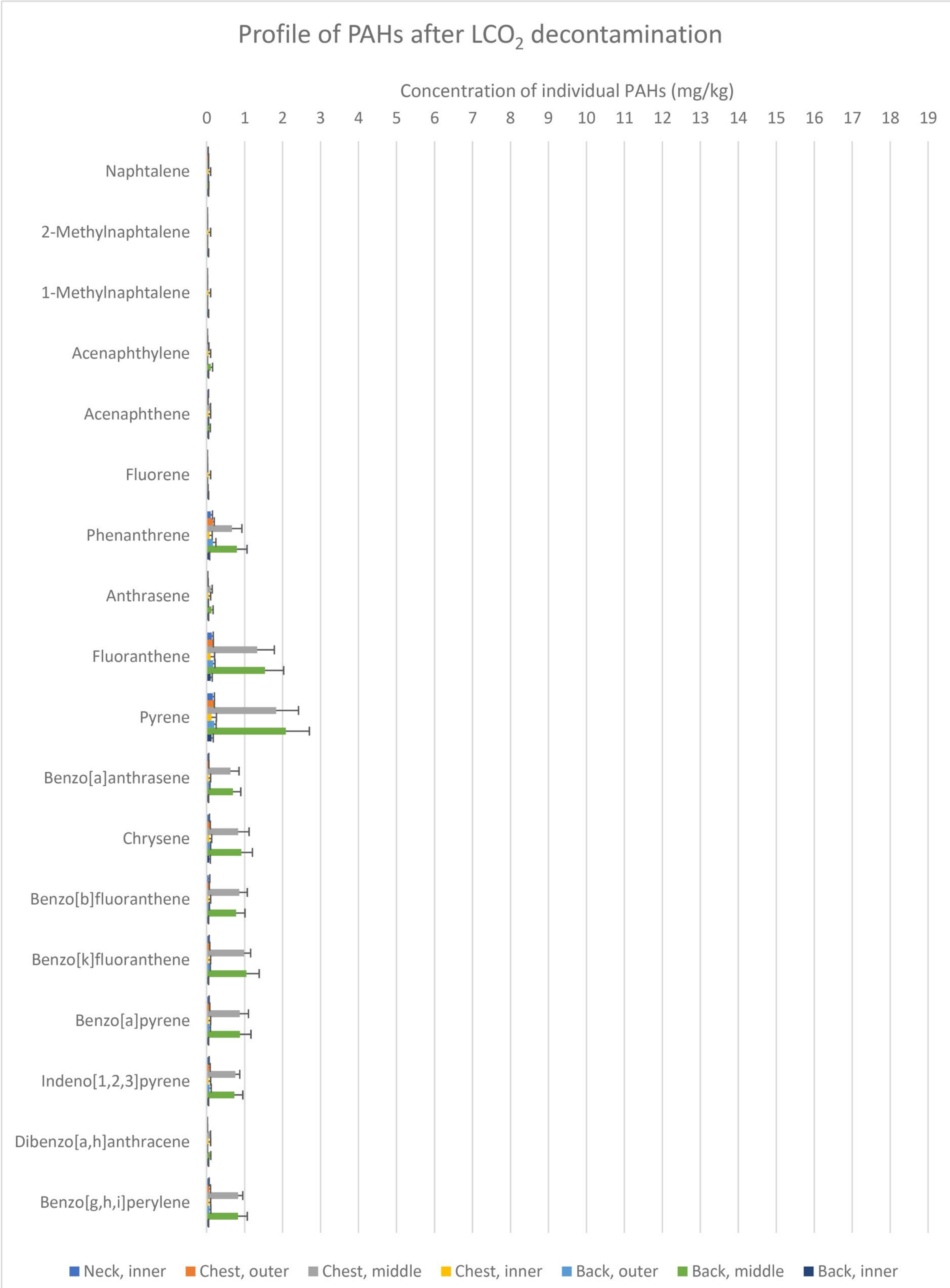

Figure 5. Profile of PAHs after decontamination with the LCO_2 technique, all layers included.

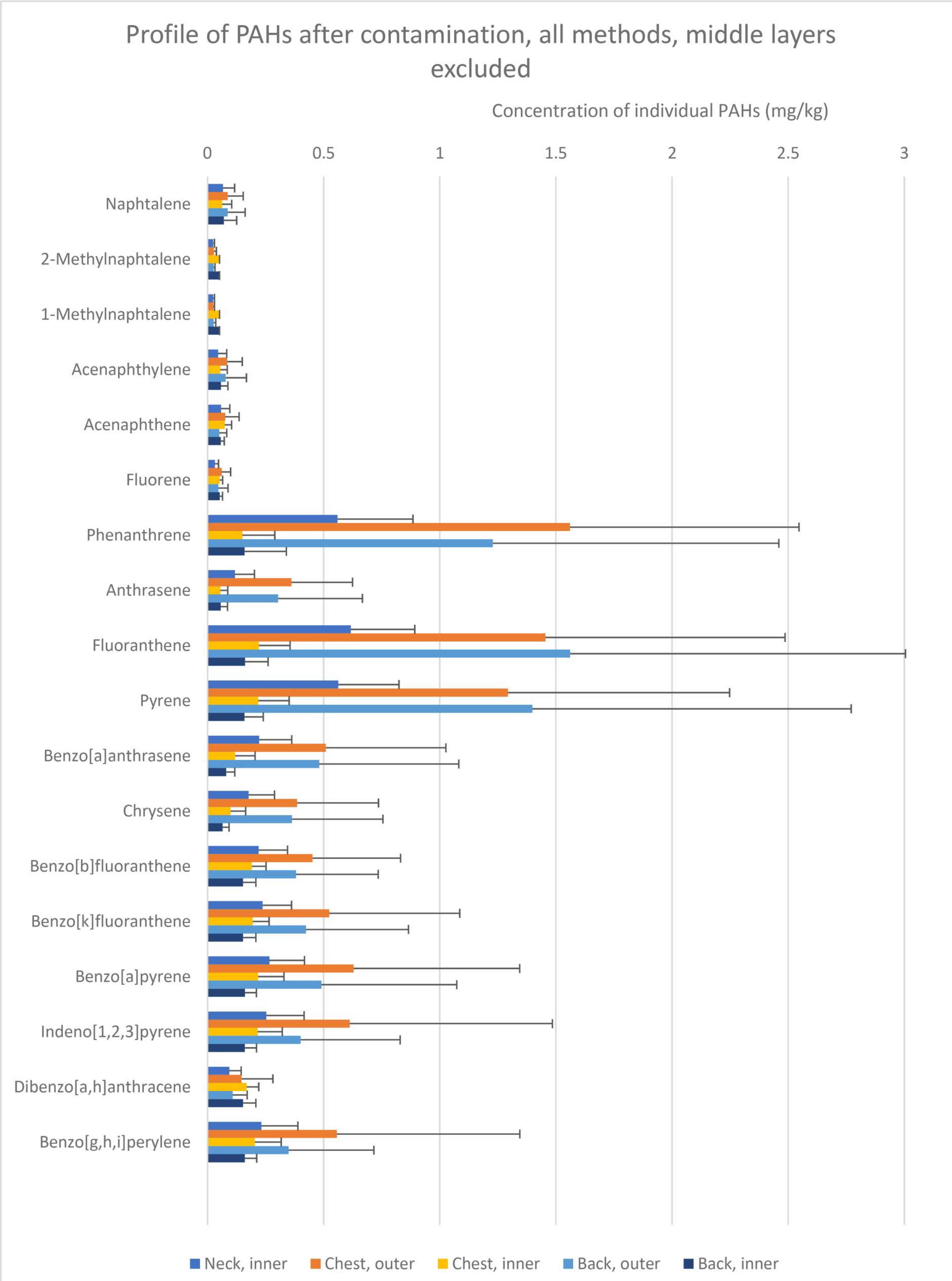

Figure 6. Profile of PAHs after contamination of all methods, middle layers excluded.

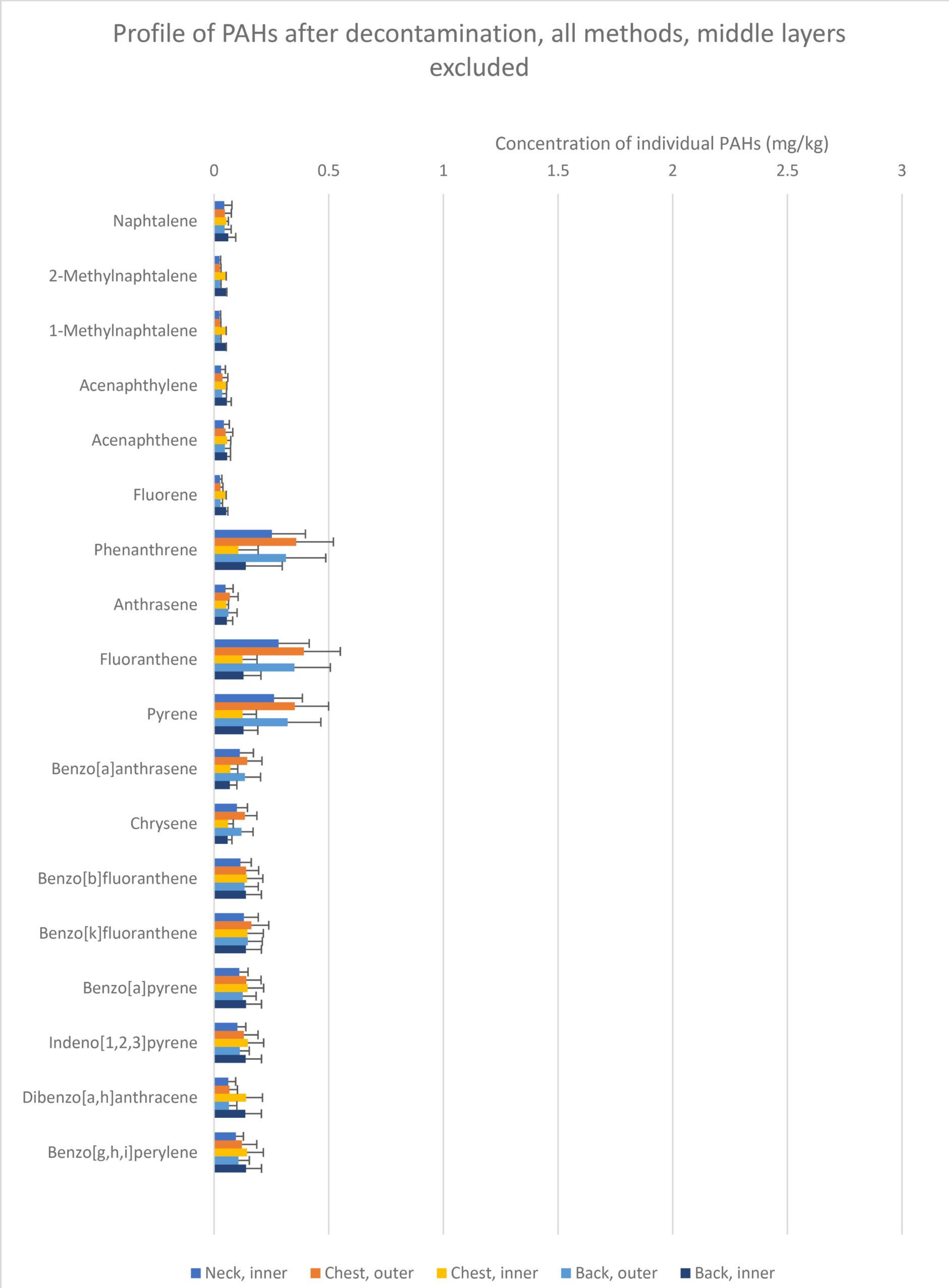

Figure 7. Profile of PAHs after decontamination of all methods, middle layers excluded.

decontamination, is illustrated in Figure 7. All individual PAH concentrations fell below the 1 mg/kg threshold (Figure 7).

Discussion

Contamination levels

After re-exposure of these turnout gear coats, the highest concentrations of PAHs were measured in the middle layers, the second highest in the outer layers, and the lowest in the inner layers of the coats. The order of the contamination levels in different layers was consistent with the results obtained in a previous study (Instituut Fysieke Veiligheid 2018; Kirk and Logan 2015). The highest detected PAH levels from the middle layers in both studies might be explained by the poor cleaning efficiency of the AL used for these turnout gears. On the other hand, the lowest concentrations were measured in the inner layers, indicating the tested coats were still able to provide necessary protection against PAHs, although they were at the end of their lifecycle. There was a moderate correlation followed by the Pearson method (r^2=0.56) between the contamination results after contamination and after decontamination, as is shown in Figure 1. This same trend was also detected in an earlier study (Instituut Fysieke Veiligheid 2018).

Measured individual PAHs concentrations in the inner layers remained below the EU threshold value (1 mg/kg) for new firefighting clothing, and in the outer layers, only some individual PAHs reached the threshold value. However, the concentrations of PAHs in the middle layers exceeded the EU threshold value, and although the role of the middle layers in cross-contamination is not defined, it has been shown that washing contaminated turnout gear together with less contaminated sets results in cross-contamination and poor cleaning efficiencies (Instituut Fysieke Veiligheid 2018).

Cleaning efficiencies for conventional methods

National Fire Protection Association (NFPA) 1851 Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting has standard guidelines and requirements for inspecting, cleaning, and maintaining firefighter turnout gear. AL is the most widely used, although previous studies have indicated that it is insufficient at removing compounds like PAHs from turnout gears (Banks et al. 2021; Keir et al. 2020). In Finnish fire and rescue departments, AL is the most commonly used decontamination/cleaning method. Therefore, it was considered important in this study to test the cleaning efficiencies of AL at 40 °C and 60 °C temperatures using drying in a tumble dryer or cabinet. The outer layers were selected as the most reliable indicator of cleaning efficiency because their sufficiently high concentration range minimizes the impact of analytical uncertainty on result accuracy. Decontamination tests for the outer layers showed that cleaning efficiencies of AL at 40 °C and 60 °C with drying in a cabinet were 63% and 60%, respectively. Increasing the temperature did not significantly improve cleaning efficiency. Similarly, in a corresponding American study, an average cleaning efficiency for PAHs was 69%. They used fabric samples artificially contaminated with a known amount of PAHs, and the samples were decontaminated with AL at 40 °C temperature using cabinet drying (Girase et al. 2023). Hossain and Ormond tested a presoaking method to enhance the cleaning efficiency of AL and simultaneously tested without presoaking at 40 °C temperature using cabinet drying. The cleaning efficiency for HMW and PAHs for LMW PAHs was 13% and 73%, respectively (Hossain and Ormond 2024). In a previous Dutch-Finnish study, the cleaning efficiency of all three layers was on average 40%, which is consistent with the findings of this study (Instituut Fysieke Veiligheid 2018).

In the middle layers, the cleaning efficiency of AL at 40 °C and at 60 °C temperatures with cabinet drying achieved cleaning efficiencies of 10% and 9%, respectively. This was a similar finding to the findings of a Dutch-Finnish study (Instituut Fysieke Veiligheid 2018).

In the inner layers, the cleaning efficiency profile followed a similar trend to that of the outer layers, although the significantly lower PAH concentrations after contamination posed challenges for reliably assessing decontamination efficiency. The consequence was a high degree of variability in the data, as illustrated in Figure 2. This was also consistent with the findings of a Dutch-Finnish study (Instituut Fysieke Veiligheid 2018).

Unexpectedly, decontamination by AL at 60 °C using tumble drying showed a cleaning efficiency of 23%. It seemed that tumble drying resulted in a decreased cleaning efficiency. Tumble drying may vaporize some PAHs and may lead to cross-contamination between layers. On the other hand, the poor cleaning efficiency might be explained by contamination of the laundry from possible impurities accumulated in the dryer. Although decontamination by AL increases mechanical action on the garments and would be expected to increase effectiveness in removing particulate contamination (Girase et al. 2023), the opposite occurred for the AL 60 °C and tumble-drying method.

The results show that temperature alone did not determine cleaning efficiency. Modern detergents can effectively clean turnout gear at lower temperatures, reducing the risk of heat-related degradation. During the wash cycle, water reached the target temperature (60 °C) in only 15 min. Other influential factors included the number of pre-washes, main wash duration, rinse cycles, and water volumes. Regular maintenance of washing machines is also critical to maximizing cleaning effectiveness.

Cleaning efficiencies for advanced methods combined with AL

Finnish fire departments use ozonation chambers to reduce smoke odors in turnout gear, while paramedics use H_2O_2 treatments to disinfect ambulances. Combining these methods with AL may further reduce PAH concentrations. Ozonation effectively removes semi-volatile and volatile PAHs from outer layers but is generally ineffective in the middle layers. Moreover, ozone chamber cleaning can produce oxygenated PAHs, which may be more harmful than the original compounds (Lucena et al. 2021).

Decontamination efficiency for LCO_2

One of the most promising advanced methods for decontamination of turnout gears is the LCO_2. It demonstrated the highest cleaning efficiency (84%) in the most challenging middle layers. In the inner layers, the results of the LCO_2 followed a similar trend to those observed in the outer layers.

In the American study, fabric pieces were artificially exposed to PAH compounds and cleaned with the LCO_2, resulting in a cleaning efficiency of 95% (Girase et al. 2023). The Polish study also measured the concentrations of PAH compounds in regularly used turnout gear coats after use of the AL and LCO_2 methods and concluded that LCO_2 cleans more effectively compared to AL. Based on their results with the LCO_2, the concentrations of individual PAHs were less than 20% of the EU Commission's threshold for PAH concentrations in new clothing (EU Commission 2013).

Profile of PAHs after conventional and advanced decontamination

In this study, phenanthrene, fluoranthene, and pyrene were the most abundant individual PAH compounds. Phenanthrene is an LMW PAH, and fluoranthene and pyrene are HMW PAHs. The measured PAH profile in this study was consistent with those in earlier studies evaluating decontamination of gear from exposure during training conditions and in structural fires (Instituut Fysieke Veiligheid 2018; Kirk and Logan 2015).

In this study, the cleaning efficiency for PAHs indicated approximately 20–30% lower cleaning efficiency for HMW PAHs compared to LMW PAHs. These results are consistent with those from a previous study (Hossain et al. 2023). Hossain and Ormond (2024) tested the cleaning efficiency of AL with a full-scale method at 40 °C temperature using cabinet drying. The cleaning efficiency for HMW PAHs and LMW PAHs was 13% and 73%, respectively. Girase et al. (2023) also assessed differences between the cleaning efficiencies of LMW and HMW PAHs using AL at 40 °C with cabinet drying. Cleaning efficiencies for phenanthrene (LMW), pyrene (HMW), and benzo[a]-pyrene (HMW) were 92%, 58%, and 36%, respectively.

The impact of PAH molecular weight on cleaning efficiency was also evaluated using the LCO_2 technique. Similar samples were used as in previous tests, and results were compared to average contamination levels. The cleaning efficiencies for LMW PAHs indicated about a 10% difference in cleaning efficiency. Girase et al. (2023) also assessed the difference in cleaning efficiencies between LMW and HMW PAHs using the LCO_2 technique. The cleaning efficiencies for phenanthrene (LMW), pyrene (HMW), and benzo[a]pyrene (HMW) were 94%, 98%, and 99%, respectively (Girase et al. 2023). The results of this study differed from those, but the lack of mechanical action in the LCO_2 process has been claimed to limit its effectiveness in removing HMW PAHs (Girase et al. 2023).

It is important to note that HMW PAHs are significantly more toxic compared to LMW PAHs (Barbosa et al. 2023). Therefore, they may play a more important role in the assessment of PAH mixture toxicity than LMW PAHs. Consequently, future efforts should focus increasingly on improving cleaning efficiency, particularly for HMW PAH compounds.

Limitations

Turnout gear coats were contaminated during standard firefighting training exercises under conditions designed to be as consistent as possible. Because the exposures and contamination took place under real-fire conditions, the level of contamination was not uniform across all turnout gear coats. As a result, PAH concentrations varied between garments, potentially affecting both cleaning efficiency and the resulting PAH profiles. Furthermore, differences in the usage history of the coats likely contributed to the variability in contamination levels.

Consistency across the turnout gear was achieved in hot firefighting exercises by burning pure wood. In real fire scenarios, the levels of PAHs may exceed what was found in this training environment. In modern fires, building materials, furnishings contain substances that produce increasingly toxic chemical mixtures that likely affect PAH levels in smoke.

Low PAH concentrations in the inner layers suggest that turn out gear coats provided effective protection, even at the end of their lifecycles. However, the low levels found in the inner layers led to greater variability in the results, making it more difficult to assess cleaning efficiency compared to the middle and outer layers. Additionally, differences in storage time after exposure may have influenced LMW PAH levels, as these compounds evaporate more readily than HMW PAHs.

Conclusion

Firefighters are exposed to mixtures of toxic compounds, and the complexity of these compounds has increased in modern fires. Traditional decontamination methods may no longer be sufficient to offer sufficient protection for firefighters. Developing more advanced cleaning methods and reassessing traditional methods has become increasingly important. This study's findings demonstrated poor cleaning efficiency for AL, but PAH contamination fell under the EU commission threshold value in the inner and outer layers of the turnout gear coats. It is essential to assess whether the EU Commission's threshold value is sufficient to protect firefighters from PAH exposure. After decontamination, the middle layers still had unacceptable concentrations of accumulated PAHs, and due to that, it is crucial to assess whether these compounds can re-contaminate firefighter gear and continue to expose firefighters.

More advanced techniques are needed to improve the cleaning efficiency of protective gear. AL will be the main washing method in the future, so it would be necessary to evaluate how the washing program affects the cleaning results and how it could be optimized. It is also urgently needed to clarify whether advanced and oxidative treatments affect harmful compounds and whether the treatments change the nature of the chemical substances to an even more harmful form.

Recommendations

Protective gear should be cleaned promptly after contamination to prevent impurities from adhering and to improve washing results. To reduce exposure, contaminated coats should be isolated at the scene in self-dissolving laundry bags or sealed garbage bags and transported separately from the vehicle cabin. SCBA should be worn as long as possible during equipment removal, with at least a filter mask as the minimum protection.

Turnout gear should be sorted and washed based on the level of contamination and always separately from daily station garments to prevent cross-contamination. Washing machines and dryers must also be regularly cleaned and maintained to reduce the risk of cross-contamination.

Additional treatments may enhance cleaning results, but the equipment should be thoroughly ventilated before reuse. Before ozonation, it is also essential to ensure that the turnout gear is completely dry to prevent potential material damage.

Cleaning turnout coats with LCO_2 technology showed 74% cleaning efficiency for the outer layers, but it was particularly effective on the most difficult to clean middle layers, 84%, being the best cleaning technique. To preserve the properties of the turnout gear and maximize their service life, it would be valuable to carry out deep cleaning of the turnout gear once or twice a year with the LCO_2 technique. Szmytke et al. had the same recommendation (Szmytke et al. 2022).

To ensure that cleaning processes are more effective in the near future, more attention must be paid to the decontamination efficiency of HMW PAHs, because they showed poor cleaning efficiency, and also their toxicity potency is higher than LMW PAHs.

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References

Abrard S, Bertrand M, De Valence T, Schaupp T. 2019. French firefighters' exposure to Benzo [a] pyrene after simulated structure fires. Int J Hyg Environ Health. 222(1):84–88. doi: 10.1016/j.ijheh.2018.08.010.

Banks AP, Wang X, Engelsman M, He C, Osorio AF, Mueller JF. 2021. Assessing decontamination and laundering processes for the removal of polycyclic aromatic hydrocarbons and flame retardants from firefighting uniforms. Environ Res. 194:110616. doi: 10.1016/j.envres.2020.110616.

Barbosa F, Jr, Rocha BA, Souza MCO, Bocato MZ, Azevedo LF, Adeyemi JA, Santana A, Campiglia AD. 2023. Polycyclic aromatic hydrocarbons (PAHs): updated aspects of their determination, kinetics in the human body, and toxicity. J Toxicol Environ Health B Crit Rev. 26(1):28–65. doi: 10.1080/10937404.2022.2164390.

Barbut F, Menuet D, Verachten M, Girou E. 2009. Comparison of the efficacy of a hydrogen peroxide dry-mist disinfection system and sodium hypochlorite solution for eradication of clostridium difficile spores. Infect Control Hosp Epidemiol. 30(6):507–514. doi: 10.1086/597232.

Demers PA, DeMarini DM, Fent KW, Glass DC, Hansen J, Adetona O, Andersen MH, Freeman LEB, Caban-Martinez AJ, Daniels RD, et al. 2022. Carcinogenicity of occupational exposure as a firefighter. Lancet Oncol. 23(8):985–986. doi: 10.1016/S1470-2045(22)00390-4.

ECDC Technical Report. 2020. Infection prevention and control for COVID-19 in healthcare settings-first update. 12th March 2020.

EU. 2013. Commission Regulation (EU) No 1272/2013 of 6 December 2013 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards polycyclic aromatic hydrocarbons. *Official Journal of the European Union L 327/1*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013R1272.

Everaert S, Schoeters G, Claes K, Raquez J, Buffel B, Vanhaecke T, Moens J, Laitinen J, Van Larebeke N, Godderis L. 2023. Balancing acute and chronic occupational risks: the use of nitrile butadiene rubber undergloves by firefighters to reduce exposure to toxic contaminants. Toxics. 11(6):534. doi: 10.3390/toxics11060534.

Fent KW, Eisenberg J, Snawder J, Sammons D, Pleil JD, Stiegel MA, Mueller C, Horn GP, Dalton J. 2014. Systemic exposure to PAHs and benzene in firefighters suppressing controlled structure fires. Ann Occup Hyg. 58(7):830–845. doi: 10.1093/annhyg/meu036.

Fent KW, Evans DE, Booher D, Pleil JD, Stiegel MA, Horn GP, Dalton J. 2015. Volatile organic compounds off-gassing from firefighters' personal protective equipment ensembles after use. J Occup Environ Hyg. 12(6):404–414. doi: 10.1080/15459624.2015.1025135.

Fent KW, LaGuardia M, Luellen D, McCormick S, Mayer A, Chen I-C, Kerber S, Smith D, Horn GP. 2020. Flame retardants, dioxins, and furans in air and on firefighters' protective ensembles during controlled residential fire-fighting. Environ Int. 140:105756. doi: 10.1016/j.envint.2020.105756.

Fent KW, Toennis C, Sammons D, Robertson S, Bertke S, Calafat A, Pleil J, Wallace M, Kerber S, Smith D, et al. 2020. Firefighters' absorption of PAHs and VOCs during controlled residential fires by job assignment and fire attack tactic. J Expo Sci Environ Epidemiol. 30(2):338–349. doi: 10.1038/s41370-019-0145-2.

Fijan S, Skerget M, Knez Z, Sostar-Turk S, Neral B. 2012. Determination the disinfection of textiles in compressed carbon dioxide using various indicator microbes. J Appl Microbiol. 112(3):475–484. doi: 10.1111/j.1365-2672.2011.05216.x.

Girase A, Thompson D, Ormond R. 2023. Comparative analysis of the liquid Co_2 washing with conventional wash on firefighters' personal protective equipment (PPE). Textiles (Basel). 2(4):624–632. doi: 10.3390/textiles2040036.

Holmgaard R, Nielsen JB. 2009. Dermal absorption of pesticides: evaluation of variability and prevention. Copenhagen (Denmark): Danish Environmental Protection Agency. https://www2.mst.dk/udgiv/publications/2009/978-87-7052-980-8/html/helepubl_eng.htm#kap01_eng.

Hossain MT, Girase AG, Ormond RB. 2023. Evaluating the performance of surfactant and charcoal-based cleaning products to effectively remove PAHs from firefighter gear. Front Mater. 10(May):2023. doi: 10.3389/fmats.2023.1142777.

Hossain MT, Ormond RB. 2024. Assessing the impact of pre-soaking to enhance laundering efficacy of firefighter turnout gear. Toxics. 12(8):544. doi: 10.3390/toxics12080544.

Instituut Fysieke Veiligheid. 2018. Exposure to smoke. An overview report of the studies to the exposure routes, contamination and cleaning of the turn-out gear and the skin barrier function. Report to Brandweer Nederland from the Instituut Fysieke Veiligheid, Zoetermeer.

Jones K, Cocker J, Dodd L, Fraser I. 2003. Factors affecting the extent of dermal absorption of solvent vapours: a human volunteer study. Ann Occup Hyg. 47(2):145–150. doi: 10.1093/annhyg/meg016.

Keir JL, Akhtar US, Matschke DM, White PA, Kirkham TL, Chan HM, Blais JM. 2020. Polycyclic aromatic hydrocarbon (PAH) and metal contamination of air and surfaces exposed to combustion emissions during emergency fire suppression: implications for firefighters' exposures. Sci Total Environ. 698:134211. doi: 10.1016/j.scitotenv.2019.134211.

Kirk KM, Logan MB. 2015. Firefighting instructors' exposures to polycyclic aromatic hydrocarbons during live fire training scenarios. J Occup Environ Hyg. 12(4):227–234. doi: 10.1080/15459624.2014.955184.

Laitinen J, Mäkelä M, Mikkola J, Huttu I. 2010. Firefighting trainers' exposure to carcinogenic agents in smoke diving simulators. Toxicol Lett. 192(1):61–65. doi: 10.1016/j.toxlet.2009.06.864.

Laitinen J, Mäkelä M, Mikkola J, Huttu I. 2012. Firefighters' multiple exposure assessments in practice. Toxicol Lett. 213(1):129–133. doi: 10.1016/j.toxlet.2012.06.005.

Levasseur JL, Hoffman K, Herkert NJ, Cooper E, Hay D, Stapleton HM. 2022. Caracterizing firefighter's exposure to over 130 SVOCs using silicone wristbands: a pilot study comparing on-duty and off-duty exposures. Sci Total Environ. 834:155237. doi: 10.1016/j.scitotenv.2022.155237.

Lucena M, Zapata F, Mauricio F, Ortega-Ojeda F, Quintanilla-López F, Weber I, Montalvo G. 2021. Evaluation of an ozone chamber as a outine ethod to econtaminate firefighters' PPE. Int J Environ Res Public Health. 18(20):10587. doi: 10.3390/ijerph182010587.

Madsen S, Normile-Elzinga E, Kinsman R. 2014. CO_2—based cleaning of commercial textiles. The world's first CO_2 solution for cleanroom textiles. Final Report for California Energy Commission from CO_2 Nexus Inc. March 2014 CEC-500-2014-083.

Magnusson S, Hultman D. 2015. Healthy firefighters—the Skellefteå model improves the work environment. Karlstad (Sweden): Swedish Civil Contingencies Agency. p. 35–36.

Marín-Sáez J, López-Ruiz R, Liébanas F, Peralta M, Frenich A. 2024. From flames to lab: a robust non-destructive sampling method for evaluating PAH exposure in firefighters' personal protection equipment. Microchem J. 207(2024):111909. doi: 10.1016/j.microc.2024.111909.

Martin O. 2023. Synergistic effects of chemical mixtures: how frequent is rare. Curr Opin Toxicol. 36:100424. doi: 10.1016/j.cotox.2023.100424.

Mayer AC, Fent KW, Bertke S, Horn GP, Smith DL, Kerber S, La Guardia MJ. 2019. Firefighter hood contamination: efficiency of laundering to remove PAHs and FRs. J Occup Environ Hyg. 16(2):129–140. doi: 10.1080/15459624.2018.1540877.

Probert C, Nixon E, Ormond RB, Baynes R. 2024. Percutaneous absorption of fireground contaminants: naphthalene, phenanthrene, and benzo[a]pyrene in porcine skin in an artificial sweat vehicle. Toxics. 12(8):588. doi: 10.3390/toxics12080588.

Stec AA, Dickens KE, Salden M, Hewitt FE, Watts DP, Houldsworth PE, Martin FL. 2018. Occupational exposure to polycyclic aromatic hydrocarbons and elevated cancer incidence in firefighters. Sci Rep. 8(1):2476. doi: 10.1038/s41598-018-20616-6.

Stec A, Wolffe T, Clinton A. 2020. Minimising firefighters' exposure to toxic fire effluents. Best Practice Report. University of Central Lancashire. Commissoned by Fire Brigades Union, Kingston Upon Thames (UK). https://www.fbu.org.uk/publications/minimising-firefighters-exposure-toxic-fire-effluents-best-practice-report

Szmytke E, Brzezińska D, Machnowski W, Kokot S. 2022. Firefighters' protective clothing—water cleaning method vs liquid CO_2 method in aspect of efficiency. Architect Civil Eng Environ. 15(2):169–176. doi: 10.2478/acee-2022-0024.

Taeger D, Koslitz S, Käfferlein H, Pelzl T, Heinrich B, Breuer D, Weiss T, Harth V, Behrens T, Brüning T. 2023. Exposure to polycyclic aromatic hydrocarbons assessed by biomonitoring of firefighters during fire operations in Germany. Int J Hyg Environ Health. 248:114110. doi: 10.1016/j.ijheh.2023.114110.

Therkorn JH, Mathewson BA, Laursen CJ, Maberti S, Aizenberg V, Dinkelacker BT, Rege S. 2024. Methods to assess dermal exposures in occupational settings: a scoping review. Ann Work Expo Health. 68(4):351–365. doi: 10.1093/annweh/wxae015.

Trabaris M, Laskin J, Weisel C. 2012. Effects of temperature, surfactants and skin location on the dermal penetration of haloacetonitriles and chloral hydrate. J Expo Sci Environ Epidemiol. 22(4):393–397. doi: 10.1038/jes.2012.19.

Van den Eijnde W, Heus R, Falcone D, Peppelman M, van Erp P. 2020. Skin barrier impairment due to the occlusive effect of firefighter clothing. Ann Work Expo Health. 64(3):331–337. doi: 10.1093/annweh/wxaa005.

Wolffe T, Turrell L, Robinson A, Dickens K, Clinton A, Maritan-Thomson D, Stec A. 2023. Culture and awareness of occupational health risks amongst UK firefighters. Sci Rep. 13(1):97. doi: 10.1038/s41598-022-24845-8.