



## Article

# BTEXS Concentrations and Exposure Assessment in a Fire Station

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**Abstract:** The aim of this study was to evaluate benzene, toluene, ethylbenzene, xylene, and styrene (BTEXS) concentrations in the changing room and garage in a fire station located in the Upper Silesian agglomeration (Poland), to compare them with the concentrations of the same compounds in the atmospheric air (outdoor background) and to assess the health exposure to BTEXS among firefighters and office workers in this unit. BTEXS samples were collected during the winter of 2018 in parallel in the garage, in the changing room, and outside, using sorption tubes filled with activated carbon. The average total BTEXS concentrations in the changing room and garage were over six times higher than those in the atmospheric air in the vicinity of the fire station. At each sampling site, toluene and benzene had the highest concentrations. According to the diagnostic indicators, the combustion of various materials and fuels was the source of BTEXS inside, while outside, the sources were the combustion of fuels and industrial activity. The carcinogenic risk related to benzene inhalation by the firefighters and office employees in the monitored unit exceeded the acceptable risk level value of  $7.8 \times 10^{-6}$  per  $1 \mu\text{g}/\text{m}^3$  by more than 20 times.

**Keywords:** BTEXS; health exposure; occupational risk; markers of exposure; air quality

## 1. Introduction

Firefighters are often exposed to very high concentrations of various products of combustion and pyrolysis, including substances in a gaseous phase adsorbed on ambient particulate matter (PM-bound). The toxic substances found in fire smoke are most often polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOC) (including BTEXS), hydrogen cyanide (HCN), and several other organic and inorganic compounds [1–3]. Exposure to these compounds has been linked to a higher risk of specific cancers and cardiovascular diseases and thus acute and chronic effects that result in increased fire fighter mortality and morbidity [2,4–6]. The International Agency for Research on Cancer (IARC) assigns the profession of firefighter to group 2B, meaning “possibly carcinogenic to humans” [7]. Although firefighters use personal protective equipment during rescue and firefighting operations, such as gloves, coats, flash hoods, and breathing apparatus, this equipment can also serve as a secondary source of exposure.

Some non- or semi-volatile compounds released during fires may settle and/or condense on protective equipment and exposed skin, leaving a greasy residue or film; then (e.g., when removing the equipment), these compounds may penetrate the body directly through the skin and eyes or through inhalation. Volatile organic compounds, including BTEXS, usually remain in the vapor phase. However, some of them can partition into a solid phase and condense onto the skin where they become available for deposition into the human body [8]. In addition, gaseous substances, especially VOCs such as HCN and the most volatile PAH, can penetrate into the interior space of the turnout gear [9] and then undergo the phenomenon of off-gassing in fire truck cabins and storage areas, such as changing rooms

and garages [2,10,11]. In this way, firefighters can be exposed to these substances not only during firefighting operations but also during their return from action or while resting in their fire stations. Leaving clothes and equipment in the changing room or garage without first decontaminating them may facilitate the accumulation of toxic substances and transfer them to other fire station rooms, such as bedrooms or offices [12–14]. Accordingly, not only firefighters extinguishing fires but also dispatchers, commanders, and office workers working in fire stations can be exposed to toxic combustion products.

Compounds of the BTEXS group are considered to be indicators of human exposure to volatile organic compounds [15]. Measuring the total concentration of BTEXS and the individual compounds from this group (as the main pollutants released during fires) is necessary to assess the threats to firefighter health, as well as the work environment. The most dangerous compounds from the BTEXS group are benzene and ethylbenzene, which are classified by the International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1). Exposure to these substances is linked to an increased risk of leukemia and hematopoietic cancers [7,16–18]. Toluene and xylene are non-carcinogenic, but they may produce adverse reproductive effects, especially when exposure is chronic at low to high concentrations [18,19].

While research on the concentrations of pollutants released during fires and assessments of the health risks to firefighters have been the subject of many global studies since the 1980s [2], the presence of combustion products in fire stations is a less well-trodden topic. There is little research in this area. Studies that are available focus on PAH and VOC concentrations in structural firefighting ensembles [10] as well as in turnout gear [3,20] at fire stations in Brisbane (Australia), Philadelphia, and Illinois (United States); and the concentrations of polybrominated diphenyl ethers (PBDEs), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) in dust samples collected by a vacuum cleaner at twenty fire stations in California [13]. These studies were among the first to indicate the problem of high concentrations of toxic combustion products in fire stations.

The investigations described in this paper are the next stage of the multi-site study regarding the concentration of combustion products in fire station rooms. In the first stage of study, the concentrations of PAHs in garages and changing rooms at two selected fire stations belonging to the Polish National Fire Service were analyzed and compared to the concentrations of PAHs in the atmospheric air outside these units [14]. The goal of this work was to determine the ambient concentrations of BTEXS (benzene, toluene, ethylbenzene, xylene, and styrene) in a selected fire station in Poland, compare them with the outdoor background concentrations of BTEXS, and assess the health risks of the exposure to BTEXS (occupational carcinogenic and non-carcinogenic risks) between two groups of employees (firefighters and office workers) in the state fire service unit.

## 2. Materials and Methods

### 2.1. Sampling Site

The municipal headquarters of the state fire service, where the research was conducted, is located in the center of the Silesian voivodeship (50°16′1.401″ N, 18°51′40.607″ E). The building is located among old (100–150 years old) and low-rise (several-story) buildings. The apartments in the vicinity of the fire brigade building are mainly heated with hard coal and are largely inhabited by a low-income population. Therefore, a large number of people in the area burn poor quality fuel in their furnaces and produce waste. The property is located 50 m from voivodeship road no. 925 and about one kilometer from the A4 highway. The fire brigade building is a three-story building heated by a solid fuel stove that uses pellet fuel. The building was thoroughly rebuilt in the 1960s. The first floor of the building consists of a garage, changing rooms, a gym, and a workshop. The second floor contains commanders' offices, a common room, and social rooms for firefighters. On the third floor, there are a dispatch center and office rooms. The building also has two kitchens (with gas stoves) where the firefighters prepare meals. Each firefighter participating in fire-fighting operations has special clothing, gloves, and a balaclava, which offer external protection during all rescue and fire-fighting activities, as well as

during exercises. Thus, this clothing is particularly exposed to the effects and absorption of all types of chemical compound. After a 24-h shift, the firefighter stores his or her clothes in lockers located in the changing room. Due to the relatively high cost of these clothes, firefighters usually have only one or two sets of clothes, and these clothes are washed no more than once a month.

In the fire brigade building, the highest BTEXS emissions likely occur when parking fire vehicles in the garages due to the lack of engine exhaust hoods. An additional internal source of BTEXS could also be the building and its finishing materials (paints, wallpaper, and floor coverings), as well as the varnishes, glues, and solvents used during maintenance work, which also release compounds from the VOC group into the environment.

The BTEXS concentrations were measured in November 2018. BTEXS samples were taken on five consecutive business days (Monday–Friday) simultaneously:

- In the garage: five available places for the parking of rescue and fire-fighting vehicles and special vehicles; the area is about 550 m<sup>2</sup> and has no air cleaning system or natural ventilation; the aspirator was placed on a shelf at a height of about 2 meters from the ground, in the middle of the room, in an area distant from parking cars.
- In the changing room: an area about 30 m<sup>2</sup>, with no air purification system or natural ventilation; this area is used to store the firefighters' special clothes and personal equipment; the aspirator was placed on a shelf about 2 m above the ground in the center of the room.
- Outside the fire station: the aspirator was placed in a specially prepared casing on a platform (scaffolding) at a height of about 3.5 m from the ground and approximately 3 m from the building, with the building side shielded from the direct impact of the emissions from parking cars. The casing only covered the aspirator, which had no effect on sampling. It was intended to protect the device against rain. Tubes to collect BTEXS, attached to the device with a silicone tube, were placed outside the casing.

Three GilAir Plus aspirators from the Gilian company were used to conduct this research. These devices are designed to sample air, dust, and gaseous pollutants. The aspirator has the function of regulating the air flow in the range of 20 to 5000 mL/min. The flow stabilization system allows one to maintain a constant flow with an accuracy of 5% in a temperature range of 0–40 °C. During the tests, especially at night, the ambient air temperature dropped a few degrees below zero. Therefore, adequate protection (the casing with the heater) of the aspirator used for sampling outside was provided. Anasorb CSC Lot 2000 sorption tubes were used to collect compounds from the BTEXS group. These tubes were filled with sorbent-activated carbon from coconut shells and were intended to take up a wide spectrum of organic compounds [21,22].

After breaking the glass protection on both sides, the measuring tube was placed in a silicone tube connected to the aspirator. The manufacturer of the sorption tubes requires an air flow of 200 mL/min. Considering the capacity of the sorbent used and the expected BTEXS concentrations (previous tests), it was assumed that the BTEXS intake per tube can last a maximum of 4 h. After this time, the tube was changed. In total, 6 tubes were used in one measurement place for one day, which provided 24 h of measurement per day. In total, during a continuous period of five days of measurements, the samples were collected in 90 tubes. After a measurement, each tube was sealed with special plugs on both sides, wrapped with aluminum foil, and stored in a refrigerator at about 2 °C until analysis.

## 2.2. BTEXS Analysis

Details of the BTEXS analysis can be found in [22,23]. Briefly, to isolate the BTEXS adsorbed on the activated carbon, carbon disulphide extraction (Sigma Aldrich, St. Louis, MO, USA; CS<sub>2</sub> Chromasolv for HPLC; purity > 99.9%) was used. Sorbent from the 6 tubes used to collect BTEXS during one day was poured into a glass jar, and then 3 mL of solvent (CS<sub>2</sub>) was added and extracted in an ultrasonic bath for 10 min. The extract thus prepared was analyzed using a gas ionization detector (GC-FID) Trace 1300 GC from Thermo Scientific (Waltham, MA, USA). The separation was carried out using a

Supelco Wax 10 capillary column ( $60\text{ m} \times 0.53 \times 10^{-3}\text{ m} \times 1 \times 10^{-6}\text{ m}$ ). The carrier gas flow (helium) was 1 mL/min using the split function (split ratio 1:10), and the gas flow in the FID detector was as follows: air—350 mL/min; hydrogen—35 mL/min; and make-up (nitrogen)—40 mL/min. The detector temperature was 310 °C, and the dispenser temperature was 150 °C. In total, 1 µL of the sample was injected in each case for the GC-FID analysis. The determination of each sample was repeated twice. The difference in readings between the two measurements did not exceed 5%. The following temperature program was used in the chromatograph oven: 50 °C maintained for 10 min followed by a temperature increase at a rate of 30 °C/min up to 170 °C; the temperature was then maintained at 170 °C for one minute. The analysis time was approximately 15 min. The concentrations of individual BTEXS species (benzene, toluene, ethylbenzene, m-xylene, p-xylene, o-xylene, and styrene) were quantified based on an external calibration standard mixture (Sigma Aldrich; MISA Group 17 Non-Halogen Organic Mix). A five-point calibration using standards between 1 and 25 µg/mL was performed for quantifying the BTEXS species in collected samples. These standard solutions were used to produce calibration curves. The correlation coefficients for standards curves were 0.99. The retention times were 5.234, 10.124, 14.754, 14.854, 14.982, 16.350, and 17.463 min, for benzene, toluene, ethylbenzene, m-xylene, p-xylene, o-xylene, and styrene, respectively. The limit of quantification for the method was set to 0.05 µg/sample. The repeatability of the method was 5%; the expanded uncertainty was 25% ( $k = 2$ ). The recovery values of the BTEXS constituents ranged from  $90 \pm 4\%$  to  $98 \pm 3\%$  ( $n = 10$ ).

### 2.3. Health Risk Assessment

The health exposure assessment related to the inhalation of BTEXS compounds (excluding styrene) among the firefighters and office workers at a fire station in Poland was developed based on the methodology developed by the United State Environmental Protection Agency (US EPA) [24]. This assessment of the health exposure includes an assessment of the occupational carcinogenic risk (CR) associated with benzene inhalation, which was calculated according to Equations (1) and (2) [25], and an assessment of the occupational non-carcinogenic risk in terms of the threshold mechanisms of the toxic effects produced by compounds from the BTEXS group (expressed as hazard quotients, HQ), which were calculated according to Equations (1) and (3) [17].

$$EC = (CA \times ET \times EF \times ED)/AT \quad (1)$$

$$CR = IUR \times EC \quad (2)$$

$$HQ = EC/(RfC \times 1000 \text{ µg/mg}) \quad (3)$$

where CA is the chemical concentration (µg/m<sup>3</sup>). The other variables used in Equations (1)–(3) are explained in Table 1.

In the calculations, we assumed that inhalation constitutes 50% of all intake [26]. The risk assessment was carried out for the period of professional activity of the two groups of firefighters: (1) active (i.e., those involved in firefighting) and (2) office workers. Exposure duration (ED) and exposure frequency (EF) were assessed on the basis of interviews and observations. It was assumed that firefighters participating in rescue and firefighting operations perform 24-h shifts three times a week, while office workers work eight hours a day, five days a week. In 2018, firefighters from the analyzed unit responded to 643 fires (33 times in November 2018) [27]. Moreover, we assumed that both firefighters and office employees spend 50% of the work shift in conditions such as in the garage, while the remaining 50% of time is spent in conditions such as in the changing room. During the day, firefighters use, among others, the workshop and gym, which are located next to the changing room and garage. Office rooms and a dispatch room are also located next to or directly above these rooms. Therefore, we have adopted a simplification that in these rooms, BTEXS concentrations are comparable to those in the changing room and garage. The values of the individual parameters used to calculate the carcinogenic and non-carcinogenic risks are presented in Table 1.

**Table 1.** Values of the factors used for the health risk assessment.

Variable	Definition	Firefighters	Office Workers	Reference
EC	Exposure concentration ( $\mu\text{g}/\text{m}^3$ )	Average from the changing room and garage concentrations		Sampling
ET	Exposure time (hours/day)	24	8	Interview
EF	Exposure frequency (days/year)	104	250	Interview
ED	Exposure duration (years)	20	20	Interview
AT	Averaging time = average time in hours per exposure period (h)	175,200	175,200	[24]
IUR	Inhalation Unit Cancer Risk	$7.8 \times 10^{-6}$ per $1 \mu\text{g}/\text{m}^3$ *		[26]
RfC	Reference concentration (RfC) ( $\text{mg}/\text{m}^3$ )	$3 \times 10^{-2}$ for benzene; 5 for toluene; 1 for ethylbenzene; $1 \times 10^{-1}$ for xylene		[17]

\* The U.S. EPA provides two values of Inhalation Unit Cancer Risk (IURs) for benzene:  $2.2 \times 10^{-6}$  to  $7.8 \times 10^{-6}$  per  $1 \mu\text{g}/\text{m}^3$ . The higher IUR was used to obtain the maximum estimate of cancer risk from benzene exposure.

### 3. Results and Discussion

#### 3.1. BTEXS Concentrations

The mean concentrations and standard deviations for the BTEXS compounds are presented in Table 2. The highest total BTEXS concentration averaged over the whole measurement period ( $\Sigma\text{BTEXS}$ ) was recorded in the changing room ( $925.2 \mu\text{g}/\text{m}^3$ ). However, this value was only slightly higher than that in the garage ( $893.1 \mu\text{g}/\text{m}^3$ ). The average  $\Sigma\text{BTEXS}$  in both the changing room and the garage was over six times higher than the  $\Sigma\text{BTEXS}$  outside the unit ( $139.6 \mu\text{g}/\text{m}^3$ ). Most of the BTEXS compounds, except for xylenes, had higher concentrations in the changing room than in the garage. The concentration of individual BTEXSs in the changing room and garage on different measurement days varied notably. This is demonstrated by the high standard deviations of BTEXSs, especially toluene and ethylbenzene. However, every measurement day, the concentrations of benzene, toluene, ethylbenzene, xylenes, and styrene were many times higher both in the changing room and garage than in the atmospheric air (outdoors; the differences were statistically significant,  $p < 0.05$ ; Table 2). Therefore, it can be assumed that the fluctuations in BTEXS concentrations may be related to the number and/or type of fires that the firefighters had to deal with on particular days. In November 2018, firefighters from the analyzed unit participated in extinguishing 33 fires and fighting 60 local threats [27].

In addition, the large differences between the BTEXS concentrations in the fire station rooms and in the surroundings suggest that the main sources of BTEXSs in the changing room and garage were the combustion products settled on uniforms, personal protective equipment, and the equipment used during firefighting. The standard deviations for the BTEXS concentrations in the garage were smaller than those in the changing room. Outside, the proportions of standard deviations relative to the average concentrations were very high—higher than those for the measurements inside. The BTEXS concentrations outside the fire station, although many times lower than those inside, were several times higher than, for example, the BTEXS concentrations observed in other urban areas, such as Tri-City, Tczew (Poland) [28], Hamburg (Germany) [29], or Pamplona (Spain) [30]. It is likely that this is related to the fact that the ambient air in the southern part of Poland (Upper Silesia) is more polluted than the air in other parts of the country. This pollution is caused by mining activities and intensified heating processes, especially since the measurements were conducted in winter [31].

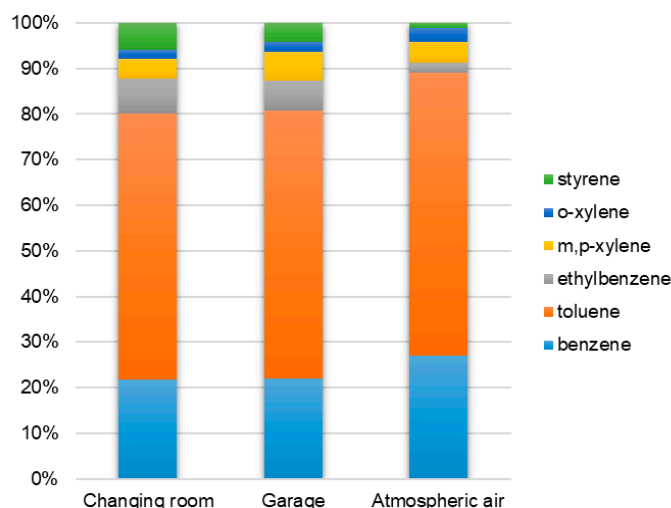


**Table 2.** Mean concentrations of benzene, toluene, ethylbenzene, xylene, and styrene (BTEXS) ( $\mu\text{g}/\text{m}^3$ ) in the changing room, in the garage, and outside the fire station in Poland.

	Changing Room		Garage		Outdoor	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Benzene	201.3 *	48.9	196.6 *	92.0	37.8	16.1
Toluene	538.8 *	178.1	524.7 *	105.3	86.5	35.3
Ethylbenzene	71.6 *	45.8	58.9 *	16.2	3.1	1.5
m,p-Xylene	41.0 *	30.7	55.4 *	20.4	6.3	8.3
o-Xylene	17.2 *	11.1	20.3 *	10.5	4.4	2.9
Styrene	55.2 *	24.5	37.3 *	10.5	1.5	0.4
$\Sigma$ BTEXS	925.1	339.1	893.1	254.9	139.6	64.5

\* Indoor and outdoor concentrations of BTEXS in the case of changing room or garage are statistically significantly different (according to the Mann–Whitney U test;  $p < 0.05$ ).

The BTEXS profiles (i.e., the percentages of individual BTEXS compounds in the total BTEXS concentration) in the changing room and garage were very similar. However, they differed from the BTEXS profile for the atmospheric air outside the fire station (Figure 1). In both rooms and outside, toluene had the highest share in  $\Sigma$ BTEXS (58% in the changing room, 59% in the garage, and 62% outdoors). In the whole measuring period, toluene concentrations were in the range  $265\text{--}703\text{ }\mu\text{g}/\text{m}^3$  in the changing room,  $425\text{--}692\text{ }\mu\text{g}/\text{m}^3$  in the garage, and  $51\text{--}131\text{ }\mu\text{g}/\text{m}^3$  in the atmospheric air. Benzene had the second largest share in  $\Sigma$ BTEXS (an average of 22% both in the changing room and the garage and 27% in the atmospheric air). It should be noted that toluene and benzene concentrations are reduced through their reactions with OH radicals, with the rate constant of toluene being approximately five times larger than that of benzene [32]. This explains the differences in the concentrations of these compounds. The average percentage of ethylbenzene and styrene among the BTEXSs inside the garage and the changing room was about four times higher than that outside. This suggests an internal source of these compounds in the analyzed rooms.

**Figure 1.** Mean profiles of the BTEXSs in the indoor (changing room and garage) and outdoor air at the selected fire station in Poland.

### 3.2. Origin of BTEXs Inside and Outside the Fire Station

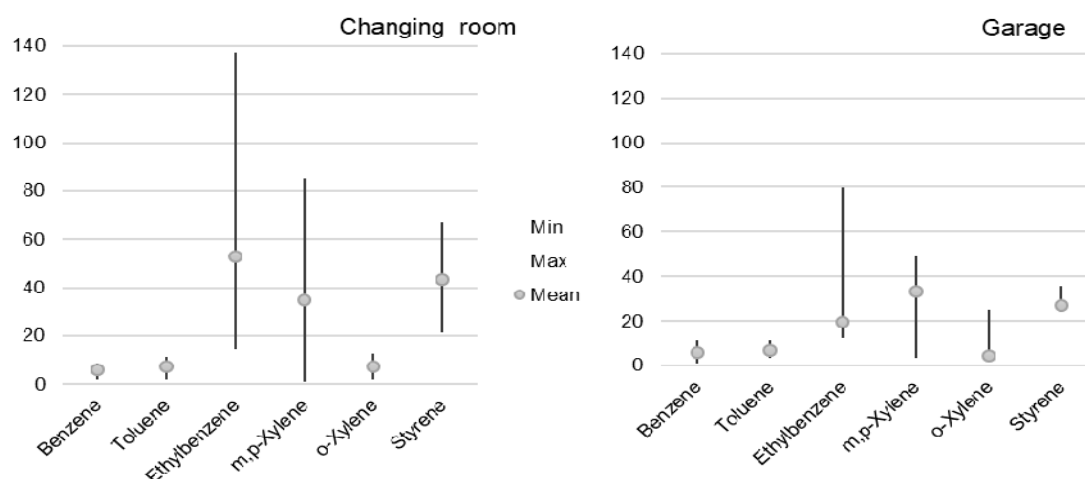
Diagnostic indicators, which are the ratios of individual BTEXS concentrations, offer a preliminary assessment of the origin of individual compounds from the BTEXS group present in the indoor and outdoor air of the state fire service unit (Table 3). The ratio of toluene/benzene = 2.7 indicates local emissions of toluene and benzene in the changing room and garage, likely due to the

combustion of liquid fuels [32–34]. However, the low values of the indicators m,p-xylene/benzene and o-xylene/benzene ( $<0.5$ ) in comparison to [31,33,34] testify to other BTEXS sources in these rooms. Low m,p-xylene/benzene and o-xylene/benzene values indicate greater photochemical degradation and, therefore, suggest that a sampling site is being influenced by emissions that originated some distance away [32]. It can, therefore, be assumed that the main sources of BTEXS in the fire station rooms are the gases released during fires, which settled on the uniforms and equipment. For the outdoor measurements, the indicators toluene/benzene = 2.3 (outdoor) and m,p-xylene/ethylbenzene = 2 indicate the combustion of liquid fuels as a BTEXS source in the atmospheric air [32,34]. The obtained indicators are two times lower than other results in this field, such as those in Sarnia (Canada), where the impact of traffic emissions on BTEXS concentrations was clearly demonstrated [32]. High concentrations of benzene alongside relatively low indicators of m,p-xylene/benzene and o-xylene/benzene may also indicate additional industrial sources of BTEXS outside the fire station. An analysis of the environment of the sampling site indicates that these sources are likely related to the coal mining and storage processes taking place at a distance of about 5 km from the fire station, as well as the combustion of fuels in home boiler rooms [34,35]. It is difficult to clearly determine which of the sources listed, both inside and outside, has the greatest impact on shaping BTEXS concentrations. More detailed data could provide Pearson's correlations between the BTEXS concentrations, but this would require more measurements [32,36].

**Table 3.** Diagnostic indicators for the three sampling locations.

Indicator	Changing Room	Garage	Outdoors
Toluene/Benzene	2.7	2.7	2.3
Ethylbenzene/Benzene	0.4	0.3	0.1
m,p-Xylene/Benzene	0.2	0.3	0.2
o-Xylene/Benzene	0.1	0.1	0.1
m,p-Xylene/Ethylbenzene	0.6	0.9	2.0

Information on the origins of the BTEXS compounds is also provided by the I/O ratios calculated for the entire measurement period, presented in Figure 2. The average I/O ratios were in the range of 6.2–53.1. The values of the I/O ratios confirm that the BTEXS concentrations mainly originate from internal sources. The higher I/O ratios in the changing room than in the garage also suggest that the source of BTEXSs here could be residue on the uniforms, helmets, and gloves used during firefighting but also contaminated furniture (e.g., wardrobes for clothes and equipment shelves) [37]. The lower average I/O ratios obtained for benzene and toluene relative to the rest of the BTEXS compounds mean that, in addition to internal sources, the concentrations of these compounds are also likely affected by the infiltration of outdoor air, especially considering the fact that the changing room is located next to the garage, where the door is often opened. Ethylbenzene, styrene, and xylenes, whose I/O ratios are the highest and have the highest fluctuations relative to other BTEXSs, likely come from fires. The above observations are confirmed by the literature and other research conducted in this field around the world. Benzene is the second most frequently identified compound in over 80% of the fires tested, and the next most frequently occurring compounds during fires are toluene, xylenes, and ethylbenzene [3,10,38–40]. Furthermore, the presence of styrene may result from the thermal decomposition and combustion of polystyrene (plastics) [40]. The concentrations of individual compounds from the BTEXS group depend on the type of material burned, the phase of the fire [10], the type of fire (flame vs. flameless), the location of the fire, the meteorological conditions, and the distance from the fire [38,41]. The conducted research provides the basis for future research, which should also include an analysis of the ventilation solutions in fire stations and a study of other factors, such as PM concentration and the chemical composition of particulate matter, which would facilitate a more accurate assessment of the impact of the environment on BTEXS concentrations.



**Figure 2.** Ranges and average values of the I/O ratios in the two rooms of the fire station calculated on the basis of the average set of five 24-h BTEXS concentrations.

It is difficult to compare the obtained results with the results presented in the literature, where different methods were used, or sampling was conducted at different stages of the fire. Nevertheless, Table 4 summarizes several examples of such results from other researchers. The BTEXS concentrations in a fire station in Upper Silesia were several times higher than the BTEXS concentrations collected by Kirk and his team from the outer layer of the structural firefighting ensembles at various stages of a fire [10] and then from decontaminated and non-decontaminated turnout gear during the pre-fire and post-decon periods [3]. In addition, the toluene and ethylbenzene concentrations measured by these authors in both the garage and the changing room were higher than the concentrations of these compounds in the post-fire phase in Fent et al.'s study [3]. The BTEXS concentrations in the changing room and garage in the analyzed unit were also several dozen times higher than those in selected nursery schools in Poland [36] and Turkey [42], and the atmospheric air of urbanized areas in Poland, Germany, and Spain [28–30]. However, they were lower than the concentrations in the atmospheric air in the vicinity of waste dumps or at oil distribution stations [16,17].

**Table 4.** Concentration ranges of the BTEXS compounds ( $\mu\text{g}/\text{m}^3$ ) measured at different locations.

References		Benzene	Toluene	Ethylbenzene	m,p-Xylene	o-Xylene	Styrene
Vehicle (engine) fire smoke—start-up of fire/overhaul [39]		5200/11,000	1400/3800	150/410	-	-	830/1600
Vehicle (cabin) fire smoke—start-up of fire/overhaul [39]		60,000/380	10,000/950	1400/120	-	-	14,000/450
Combustion of forest fuel—flaming phase [38]		93	45	18	21	-	
Outer layer of firefighting ensembles [10]	Pre-exposure	0.6–4.4	4.3–4.9	1.1–2.1	3.0–7.3		2.1–3.5
	Post exposure	13.0–88.0	38–80	1.7–15.0	7.7–20.0		41.0–88.0
	Post-laundering	0.4–0.7	0.3–18.0	0.9–2.4	3.6–7.9		1.3–3.9
Firefighter's personal protective equipment [3]	Decontaminated turnout gear during pre-fire/post-fire/post-decon	0.5/250/9	0.5/150/5	0.5/20/0.5	0.5/15/1		0.5/400/9
	Non-decontaminated turnout gear during pre-fire/post-fire/simultaneous with the post-decon periods	0.5/250/20	0.5/100/11	0.5/20/1	0.5/15/3		0.5/500/50

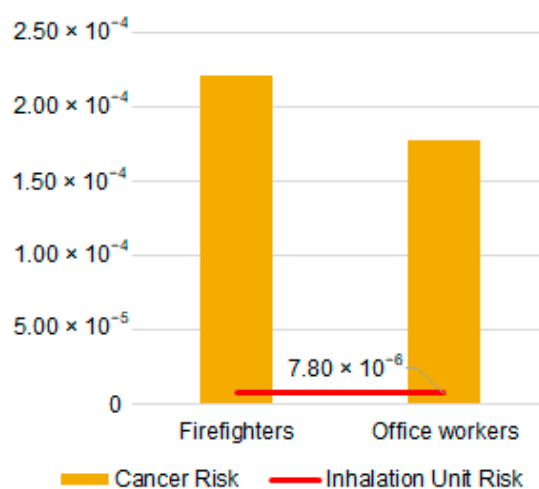


Table 4. Cont.

References	Benzene	Toluene	Ethylbenzene	m,p-Xylene	o-Xylene	Styrene
Stations of an oil distribution company (Iran) [17]	1847.00	3570.00	758.00	560.00	-	-
Landfill ambient air (Turkey) [16]	5.6–3137.8	23.4–10234.4	4.9–3717.1	7.9–7464.3	-	-
Nursery school (Turkey) [42]	1.60	26.20	0.70	1.10	0.81	-
Nursery school—outdoors (Turkey) [42]	1.23	6.11	-	-	-	-
Nursery school (Gliwice) [36]	1.37	1.19	2.11	0.72	3.31	0.44
Nursery school—outdoors (Gliwice) [36]	1.24	0.76	0.22	0.32	0.14	0.21
Gdańsk-Gdynia-Sopot (Poland)—tri-city urban area [28]	4–6	6–12	2–6	4–14	1–5	-
Hamburg (Germany)—urban area [29]	1.1–1.6	4.5–4.9	-	1.2–1.8	-	-
Pamplona (Spain)—urban area [30]	1.4–5.6	5.2–24.1	0.75–3.6	1.2–5.0	0.98–4.7	-

### 3.3. Assessment of Occupational Carcinogenic and Non-Carcinogenic Risks Associated with Exposure to BTEXS

The carcinogenic risk associated with the inhalation of benzene was calculated as  $2.21 \times 10^{-4}$  for firefighters participating in firefighting activities and  $1.77 \times 10^{-4}$  for office employees of the fire station (Figure 3). Both values are above acceptable cancer risk levels according to the Inhalation Unit Cancer Risk (IUR) ( $>7.6 \times 10^{-6}$ ) [26,43,44]. The differences in risk values result from the different durations of working shifts between the individual exposure groups. Firefighters participating in rescue and firefighting operations perform 24-h shifts three times a week, while office workers work eight hours a day, five days a week. In the carcinogenic risk assessment, only benzene concentrations were used, while the concentrations of other pollutants, such as PAH or PM-bound substances, were not taken into account. In addition, the concentrations that prevail during fires were not taken into account. Firefighters use breathing apparatus and other personal protective equipment when extinguishing fires, but there are situations when they take that equipment off, such as during exterior operations (e.g., pump operations), immediately after extinguishing fires, when collecting equipment, or in fire truck cabins during their return from action. It can be assumed that then BTEXS concentrations are higher than in the garage or changing room [3]. Therefore, the risk may be even higher than calculated. Studies also show that the health exposure associated to hazardous combustion products does not only apply to firefighters extinguishing fires but also to dispatchers, commanders, and secretaries (i.e., people whose work rooms are often located near garages and changing rooms).



**Figure 3.** Cancer risk assessment results for exposure to benzene for various groups of fire service workers.

The occupational non-carcinogenic risk (adverse health effects)—expressed by the hazard quotient (HQ)—associated with exposure to compounds, for the BTEXS group of firefighters involved in firefighting and fire station office employees, was in the range of 0.01–0.76 (Table 5). This indicates an acceptable risk for non-carcinogenic effects in each scenario considered. However, as is the case for carcinogenic risk, risk modeling does not include the concentrations of other pollutants, such as PAH, which may also occur in fire station rooms [14].

**Table 5.** Non-cancer risk assessment results for exposure to BTEXS for various groups of fire service workers.

BTEXS	Firefighters	Office Workers
Benzene	0.94	0.76
Toluene	0.02	0.01
Ethylbenzene	0.01	0.01
Xylene	0.10	0.08

The carcinogenic risk calculated for firefighters and office workers was about 10 times higher than the risk calculated for fuel workers and cashiers at gasoline stations in Thailand [24] but about two times lower for firefighters and three times lower for office workers than the average lifetime cancer risk calculated for petroleum product distributors working at stations belonging to an Iranian company [17]. The non-carcinogenic risk for fuel workers (HQ = 0.80 for benzene) is lower than that for firefighters and higher than that for office workers, while that for cashiers at the gasoline station (HQ = 0.01 for benzene) is many times lower than that for firefighters and office workers [25]. Two-times higher non-carcinogenic risk values were recorded for petroleum product distributors in Iran [17] than for firefighters. The above comparisons are for reference only due to the different periods of exposure and averaging.

#### 4. Conclusions

The concentrations of individual compounds from the BTEXS in the changing room and garage are several to several dozen times higher than the concentrations of these substances in the atmospheric air outside the fire station. Both firefighters and office workers staying under measured conditions are at risk of carcinogenic exposure that exceeds an acceptable level. Among the entire BTEXS group, toluene and benzene had the highest concentrations. According to the diagnostic indicators, the combustion of various materials and fuels was the source of BTEXS inside, while the combustion of fuels and industrial activity was the source of those outside. This research provides the following conclusions:

- Firefighters are exposed to combustion products not only during fires but also during rest between activities because they stay in rooms that are heavily contaminated with combustion products released during the off-gassing of stored clothes and equipment at the fire station.
- Although volatile compounds evaporate quickly, some of them are off-gassed during the storage of equipment. Therefore, the clothing and equipment used during fire extinguishing should be systematically decontaminated.
- The level of health risk (carcinogenic and non-carcinogenic) for office workers indicates that office rooms and dispatch rooms should be located as far as possible from the rooms in which the equipment is stored, i.e., far from changing rooms and garages. Moreover, in these rooms, efficient ventilation should be ensured.
- The obtained results demonstrate the need for more extensive research aimed at pollution control in various fire station rooms, such as offices and bedrooms, including measurements of the concentrations of gaseous pollutants, particulate matter, and its components, including toxic metals and polycyclic aromatic hydrocarbons.

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