Article

Carcinogenic Content of PM$_{10}$-Bound PAHs in University Classrooms and Outdoors at an Urban Location in Rome, Italy, during Winter Working and Not-Working Days

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Abstract: To assess the contribution of carcinogenic Polycyclic Aromatic Hydrocarbons (PAHs) in ambient air, EU Directive 2004/107/EC indicates to monitor relevant carcinogenic PAHs in PM$_{10}$ fraction other than benzo(a)pyrene at a limited number of measurement sites. This indication refers to outdoor environments, and the environmental air quality being taken as a reference also for indoors, it can be extended to indoor environments. In this work, the contribution of carcinogenic PAHs bound to PM$_{10}$ has been evaluated in winter in two classrooms of a University campus in Rome with the aim of studying the relationship with the outdoors and with working activity. PM$_{10}$-boundPAHs were monitored over five different periods selected to distinguish Weekend from daytime and nighttime Weekdays, separated into two parts of the week. Data aggregated over Weekend and Weekdays allowed calculating of the concentration of carcinogenic PAHs, the mass contribution to PM$_{10}$, the Infiltration Factor, the indoor to outdoor Ratio, and the Total Carcinogenic Potency by Toxicity Equivalent Factors, for "not-working" and "working" days. In addition, some indications on contributions to the source have been obtained from the chemical profile normalized to the maximum value of concentration, which also provides the source fingerprint compound. Indoor PAH concentrations were lower than outdoor, and both accumulated as the week progressed. Although the two indoor environments were on the same floor and had a similar volume, they presented different contribution to PM$_{10}$ and infiltration capacity, both higher during Weekend than on Weekdays. The analysis of indoor and outdoor chemical profiles normalized to the maximum concentration indicated an external source infiltrating the indoors environment. During Weekdays, the indoor *fingerprint* compound changed compared to that observed during Weekend, probably due to an additional contribution of local "fresh-traffic" source. The calculation of Total Carcinogenic Potency gave indoor values always lower than outdoor, confirming in the two classrooms different dynamics for carcinogenic PAHs. Moreover, the Total Carcinogenic Potency on Weekdays was twice that of Weekend, meaning a higher toxicological impact when urban "fresh-traffic" source is added. The present study shows that the dynamics of PM$_{10}$-related carcinogenic PAHs can be different within adjacent classrooms of a building and during working and not-working days. This evidence suggests the possibility of a potential different impact on occupant exposure to be taken into account in planning monitoring programs of indoor pollution.

Keywords: urban indoor; total carcinogenic potency; BaP equivalent; source fingerprint; infiltration factor

1. Introduction

Polycyclic Aromatic Hydrocarbons (PAHs) are products of incomplete combustion of different organic materials that can be found in the air both as gases and bound to PM, and can be natural or artificial (e.g., coal, oil, petrol, wood) [1].

Main anthropogenic sources of PAHs include residential heating and motor vehicle exhaust, as well as industrial activity (coal gasification and liquefying plants, carbon

black, coal-tar pitch and asphalt production, coke and aluminum production, catalytic cracking towers and activities in petroleum refineries) [2]. The distribution between air and particulate phases depends on chemical-physical properties of PAHs, e.g., adsorption of soot carbon, the major mechanism governing gas/particle partitioning [3]. Microclimatic parameters and concentration of airborne atmospheric oxidants regulate the distribution between the two phases [4–6]. Toxicologically, occupational exposure to PAHs causes diverse effects either for short-term exposure or for long-term, as well as residential exposure, even if in the latter case the evidence for a short-term effect is more weak than that for long-term [7,8]. Long-term exposure may have effects on the reproductive system with regard to neurotoxic, cardiorespiratory and immune effects [9]. PAHs are important sources of oxidative stressors interacting with lipids during lipid peroxidation, and some congeners are already recognized endocrine-disrupting compounds [10,11]. Carcinogenicity is the most harmful characteristic for human health and there is evidence that prenatal exposure to carcinogenic PAHs is associated with intrauterine growth restriction in humans [12,13].

Due to the above concerns, USEPA, 2005, has included a mix of 16 PAHs in a list of priority pollutants. At the level of European Union, to assess the contribution of benzo(a)pyrene in ambient air, the EU Directive 2004/107/EC has established a target value for PAHs for the protection of human health [14]. The target is defined in terms of PM_{10} benzo(a)pyrene (BaP) concentration which is used as a marker substance for PAHs generally (the BaP annual mean value may not exceed 1 ng/m^3). BaP is used as an indicator of carcinogenic hazard in polluted environments because it is the most commonly investigated PAH [15,16]. Despite the role of BaP, the EU Directive 2004/107/EC also intends to monitor other relevant polycyclic aromatic hydrocarbons at a limited number of measurement sites. These compounds include at least: benzo(a)anthracene, benzo(b)fluoranthene, benzo(j)fluoranthene benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene and dibenz(a,h)anthracene. These six congeners, compounds of four to six fused benzene rings, in addition to chrysene and benzo(ghi)perylene, which is not classifiable regards human carcinogenicity, are substances of very high concern because of their persistent, bio-accumulative, toxic and persistent and very properties. Therefore, utmost care must be taken [17]. These compounds, the object of the present paper, are listed in Table 1. The paper takes up concerns regarding classification and properties of the above components based on the Regulation on Classification, Labelling and Packaging (CLP) [18]. The focus is on EU regulation (EC No. 1272/2008), by which the European classification system of chemicals (and mixtures thereof) has been aligned with the Globally Harmonized Chemical Classification and Labelling System. Although the CLP Regulation lists the classification (and labelling) of chemicals according to the type and severity of the identified hazards regardless of their use (chemical-physical, toxicological, ecotoxicological effects), in this context it allows a continuation of the classes of hazard to human health that are recognized in European regulation.

CLP classification should not be confused with the risk assessment by which hazard characteristics are related. In this respect, as regards non-occupational exposure to environmental concentrations of PAHs, the WHO (World Health Organization) in the last report on Indoor Air Quality (2010) indicated that no threshold could be defined for a safe exposure to PAHs, warning of the risk of exposure occurring in all indoor environments. [16]. However, choosing a single carcinogen indicator to represent the carcinogenic potency of a fraction of PAH compounds could lead to an underestimation of the carcinogenic risk due to the contribution of additional components. Moreover, due to the PAH differences in bioavailability, carcinogenicity or metabolism, addressing the risk of exposure for such additional contributions is a challenging task, but specific guidelines are difficult to achieve because of many factors complicating the evaluation of their carcinogenic potential. Therefore, guidelines are able to specify a risk estimate as a basis for policy makers, but no safe level can be recommended [19].

Table 1. Name (abbreviation), molecular weight and Harmonized Classification and properties of concerns of the target PAHs.

Compound	Molecular Weight	Harmonised Classification—Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation) or Notified Classification and Labelling According to CLP Criteria (*)	Properties of Concerns (**)
benzo(a)anthracene (BaA)	228.3	- may cause cancer (H350) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410)	C, PBT
benzo(ghi)perylene (BghiP)	276.3	not classifiable as to human carcinogenicity - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410) - may cause long lasting harmful effects to aquatic life (H413)	PBT
benzo(b)fluoranthene (BbF)	252.3	- may cause cancer (H350) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410)	C, POP
benzo(j)fluoranthene (BjF)	252.3	- may cause cancer (H350) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410)	C
benzo(k)fluoranthene (BkF)	252.3	- may cause cancer (H350) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410)	C, PBT, POP
benzo(a)pyrene (BaP)	252.3	- may cause an allergic skin reaction (H317) - may cause genetic effect (H340) - may cause cancer (H350) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410) - may damage fertility. May damage the unborn child (H360FD)	PBT, vPvB
chrysene (CH)	228.3	- may cause cancer (H350) - suspected of causing genetic defects (H341) - very toxic to aquatic life (H400) - very toxic to aquatic life with long lasting effects (H410)	C, M, PBT
dibenz[a,h]anthracene (DahA)	278.3	- may cause cancer (H350) - very toxic to aquatic life, -very toxic to aquatic life with long lasting effects	C
indeno[1,2,3-cd]pyrene (IP)	276.3	- suspected of causing cancer (H351)	POP

(*) Hazardous Substances Data Bank (HSDB), (https://echa.europa.eu/it/substance-information/-/substanceinfo accessed on 27 April 2021). (**) Properties of concerns: C (Carcinogenic), M (Suspected to be Mutagenic), PBT (Persistent, Bio-accumulative and Toxic), vBvP (very Persistent and very Bio-accumulative (vPvB), POP (Persistent Organic Pollutant).

To evaluate the carcinogenic potency of a PAH mixture, it is possible to relate each component to the potency of BaP. For this purpose, Nisbet et al. 1992 [20] ranked carcinogenic compounds using data from cancer tests, first establishing Toxicity Equivalency Factors (TEFs) aimed at calculating the carcinogenic potency BaP equivalent of a certain number of congeners. The sum of the equivalent concentrations of compounds of concern gives the Total Carcinogenic Potency (TCP) of the mixture. Several TEFs have been proposed since, which differ by the weight of the contribution of each congener to total toxicity, even for carcinogenicity or mutagenicity potency [7,21–23]. These differences can

influence the TCP, depending on the source of PAHs that lead to a different mixture relative to the composition.

The aim of this work was to evaluate the dynamics and the carcinogenic potency of carcinogenic PAHs bound to the PM10 fraction in two classrooms of the University Sapienza of Rome and their relation to the outdoors. The choice of this type of indoor environment, where there is no direct source of carcinogenic PAH from internal combustion sources, is important because it allows for a better evaluation of the influence of external sources on the occupants' exposure, for both students and workers. With the aim also of investigating relations with working activity for the impact that this may have on human exposure, winter sampling was carried out over five different periods, selected to distinguish Weekend from days and nights of Weekdays, as representative of "not-working" and "working days".

In order to evaluate the PAH levels and dynamics both indoors and outdoors, the airborne concentration, the mass contribution to PM10, the Infiltration Factor and the Indoor to Outdoor concentrations ratio have been evaluated. In addition, some indication of contributions to the source have been obtained from the chemical profile, normalized to the maximum value of concentration, which also provides the source fingerprint compound. The potential carcinogenic content of the target PAHs was evaluated by calculating the Total Carcinogenic Potency by Toxicity Equivalency Factors, which has also been related to the content of benzo(a)pyrene

2. Materials and Methods

2.1. Study Design

This study is part of the INAIL Project Integrated Evaluation of Indoor Particulate Exposure (VIEPI) and its sampling design has been well described elsewhere [24]. In the framework of Activity 5 (chemical and biological characterization of PM_{10}), one of the three short-term intensive campaigns, November–December 2017, has been assumed for the chemical speciation of PAHs in the PM_{10} fraction collected in two classrooms, A4 (A4) and the Computer Room (CR), and outdoors at ground floor (OUT) of the Department of Physics of University Sapienza in Rome. A4 and CR are located on the same floor of the building and both look out on a street with high traffic density during weekdays, about 50 m away, from orthogonally-orientated windows (Figure 1). The two classrooms have a similar volume of about 400 m^3 but different geometry, A4 of a frontal didactic amphitheater-like shape and CR of a laboratory type with laptop workstations. A4 has two doors and windows that can be opened, as does CR. Moreover, A4 has natural ventilation and presents an access to an external security staircase, whilst CR is equipped with air conditioners, these latter not working during the winter campaign. The two classrooms are also distinguished by frequency of students, because in A4 4 there are lessons from Monday to Friday, while in CR these only occur on a few days a week.

The short-term intensive sampling campaign lasted for six weeks, from 4 November to 17 December of 2017. The monitoring schedule consisted of five periods a week as reported in Table 2. Such a sampling organization allows the obtaining of enrichment of PM_{10} on quartz filters, sufficient to increase the measurement sensibility and simultaneously leading to a consideration of five target periods during a week. These five Periods, from P1 to P5, are suitable to investigate PM_{10}-bound PAHs during Weekends (P1), Days (from 09:00 to 18:00) (P2 and P4) and Nights (from 18:00 to 09:00, P3 and P5), as respectively representative of holidays, working hours during the week (including lessons) and nightly hours when the rooms were empty, still during the week. The above sampled schedule also allows aggregation of data on a Weekend (P1) and Weekdays basis (from P2 to P5), which are the two target periods of this work, as representative of "not-working" and "working" days, respectively.
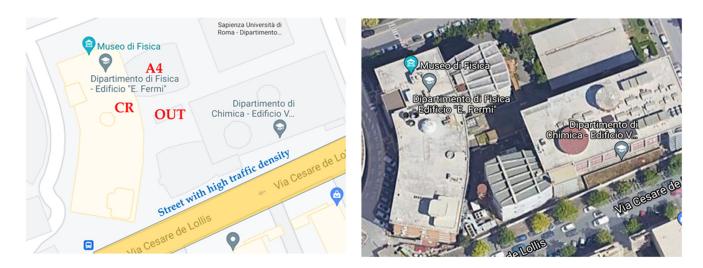
Figure 1. Location of A4, CR and OUT at University Sapienza in Rome.

Table 2. Monitoring schedules.

Period	Days of Week	Sampling Duration (h)	Time Intervals
P1	Saturday + Sunday	48	Saturday 09:00 to Monday 09:00
P2	Monday + Tuesday day	18	Monday from 09:00 to 18:00+ Tuesday from 09:00 to 18:00
P3	Monday + Tuesday night	30	Monday from 18:00 to 09:00+ Tuesday from 18:00 to 09:00
P4	Wednesday + Thursday + Friday day	27	Wednesday from 09:00 to 18:00+ Thursday from 09:00 to 18:00+ Friday from 09:00 to 18:00
P5	Wednesday + Thursday + Friday night	45	Wednesdayfrom 18:00 to 09:00 + Thursday from 18:00 to 09:00 + Friday from 18:00to 09:00

2.2. PM$_{10}$-Bound PAHs Collection and Analysis

By means of size resolved experiments, it has been demonstrated that the distribution of PAHs belonging to the EPA priority list is unimodal and centered at 0.4 μm size as fraction of PM [25]. According to YuJian et al. 2012 [26], for the same mixture PAH size distributions can be described by five modes:

Aitken mode (mass median aerodynamic diameters (MMAD): $\sim$0.05 μm,
Accumulation Mode, AM I (MMAD 0.13–0.17 μm,);
Accumulation Mode, AM II (MMAD 0.4–0.45 μm);
Accumulation Mode, AM III, (MMAD 0.9–1.2 μm,);
Coarse mode (MMAD: 4–6 μm).

Based on such results, PAHs with four to six fused rings are mainly abundant in the PM size range 0.13–1.2 μm, and only one congener, BaA (four fused rings) shows a significant presence in the coarse mode also. Liaud et al. 2021 also report that high molecular weight PAHs were mainly associated with the finest particles [27]. Therefore, PAHs in Table 1 can be considered as mainly associated with the Accumulation Mode.

In the short-term intensive campaign, November–December 2017, PM$_{10}$ was collected by sampling air in parallel on Quartz, Teflon and Polycarbonate filters, with the main contribution of the Operative Unity of Institute for Atmospheric Pollution of the National Research Council (IIA-CNR), Rome, Italy. Three silent pumps operating at 10 L/min flow rate (Silent, FAI Instruments, Rome, Italy) were placed in each environment and set to simultaneously sample PM$_{10}$, including outdoors at the ground level of the building.

CNR-IIA performed different types of chemical and biological analysis [24]. For the target campaign, the Department of Medicine, Epidemiology, Hygiene of Workplaces and Environment of INAIL, at the Laboratory of Chemical Agents Risk, Monte Porzio Catone Research Center, Rome, analyzed the quartz filters (TISSUQUARTZ 2500QAT, 47 mm, PALL Italia, Buccinasco, Italy) for the PAHs content. The mass of PM_{10} to which PAH are bonded, was instead gravimetrically determined by the CNR group on Teflon filters with the method described by Tofful et al. 2021 [28].

Resulting in a total of 93 sampled filters, 31 quartz filters for each environment were extracted with organic solvent, cleaned via column chromatography on alumina and determined through GC-MSD (SIM) (6890N Agilent Technologies, 5973N Agilent Technologies) by means of isotopic PAHs as internal standards, as described elsewhere [29]. The analytical method was validated by using the certified urban dust (SRM 1649a, from the National Institute of Standards and Technology, NIST), Gaithersburg, MD, as described by EURACHEM [30].

Despite the possibility of a partial loss of the most volatile components moving from particle to vapor fraction during the sampling [31–35], it has been demonstrated that during winter the sampling efficiency is higher than 99% for the five to seven fused-ring congeners, being higher than $83 \pm 7\%$ for BaA and $87 \pm 6\%$ for CH (four fused-rings) [36].

So far, it has been assumed that the following components quantitatively observed on PM_{10} are representative of carcinogenic bound PAHs: BaA, BbF, BjF, BkF, BaP, IP, DBahA and BghiP (Table 1). As the analytical procedure does not allow separation of the isomer BbF from j and k, their sum was completed (BbjkF). Hereafter, the resulting mixture bound to PM_{10} was composed of seven components, briefly called cPAHs (carcinogenic PAHs).

The lower limit of quantitation (LLOQ) ranged from 0.072 ng/sample (BaA) to 0.446 ng/sample (IP) and the Extended Uncertainty $U_{k=2}$ from 5.4 % to 13.3 % for BbjkF and DahA, respectively.

2.3. Infiltration Factor, Residual Indoor Concentration

The Infiltration Factor (IF) was derived by the slope of the linear regression analysis of indoor concentrations vs those outdoors. The intercept gave the residue indoor concentration (C_0)

$$C_{PAHs}^{IND} = IF \cdot C_{PAHs}^{OUT} + C_0 \tag{1}$$

2.4. PAHs Total Carcinogenic Potency and Relative Potency Factor Calculation

Single congener concentration was used to calculate the TCP of the mixture relative to BaP. For this purpose, the method using TEF has been applied. TEF is addressed at sharing a common mechanism of action of the structurally related compound, allowing the concentration of PAHs other than BaP to be converted to an equipotent concentration of BaP, BaP equivalent (BaP_{eq}).

The first step of the procedure consisted in calculating BaP_{eq} by Equation (2) [20,37]. Summing up BaP_{eqs} provided the potential cancer risk associated with the target mixture, TCP_{cPAHs}, according to Equation (3). Dividing TCP concentration by BaP gives the Relative Potency Factor according to (4).

$$BaP_{eq\_i} = C_{PAH_i} \cdot TEF_i \tag{2}$$

where, for the *i*th congener, BaP_{eq_i} is the equipotent concentration in ng/m^3, C_{PAH_i} the corresponding airborne concentration in ng/m^3 and TEF_i the Toxicity Equivalency Factor in ng/m^3.

$$TCP_{cPAHs} = \sum_{i=1}^{7} BaP_{eq\_i} \tag{3}$$

$$RPF = TCP/BaP \tag{4}$$

For calculating BaP_{eq}, the procedure of TEF from Nisbet et al. 1992 [20] has been adopted, whose scheme is shown in Table 3.

Table 3. TEF values from Nisbet et al.

	BaA	CH	BbF	BjF	BkF	BaP	IP	DahA	BghiP	Estimated BbjkF
TEF [(1)]	0.1	0.01	0.1	-	0.1	1	0.1	5	0.01	0.08

[(1)] Nisbet, I.C.T.; Lagoy, P.K. Toxic Equivalency Factors (TEFs) for Polycyclic Aromatic Hydrocarbons (PAH)s. Regul. Toxicol. Pharmacol. 1992, 16, 290–300. [20].

Because BbF was not analytically separated from isomers j and k, TEF for the sum BbjkF was derived by calculating the mean values of the corresponding TEFs weighted for the relative contribution of each isomer. For this purpose, mean values of 49.5%, 26.5% and 24.5% were respectively used to weight the contribution of BbF, BjF and BkF (average values of similar percentage mass composition from concentrations measured in Rome and Zagabrie for urban winter PM_{10} [38,39]). The resulting TEF for BbjkF is reported in the last column of Table 3.

3. Results and Discussion

3.1. Analysis of cPAHs Concentration and Mass Contribution to PM_{10}

Individual concentration of congeners bound to PM_{10} measured in A4, CR and OUT, averaged over the six weeks of sampling, are reported separately for Periods P1 to P5 in Table 4 along with their sum (cPAHs). The average over the entire sampling period is also reported.

Table 4. Average concentration of PAH congeners and their sum over periods P1 to P5 in A4, CR and OUT.

A4								
c (ng/m^3)	**BaA**	**CH**	**BbjkF**	**BaP**	**IP**	**DahA**	**BghiP**	**cPAHs**
P1	0.14	0.16	1.62	0.58	0.60	0.06	0.88	4.04
P2	0.04	0.10	0.47	0.18	0.52	ND(*)	0.65	1.96
P3	0.20	0.21	1.27	1.00	1.45	0.06	1.68	5.86
P4	0.11	0.13	0.63	0.41	0.82	0.02	1.08	3.21
P5	0.29	0.27	1.85	1.49	1.72	0.11	2.76	8.49
Total Average *n*=31	**0.16**	**0.17**	**1.18**	**0.73**	**1.01**	**0.05**	**1.40**	**4.69**
CR								
c (ng/m^3)	**BaA**	**CH**	**BbjkF**	**BaP**	**IP**	**DahA**	**BghiP**	**cPAHs**
P1	0.20	0.23	1.91	0.77	0.90	0.09	1.30	5.39
P2	0.13	0.13	0.61	0.38	0.69	0.02	0.83	2.79
P3	0.37	0.34	1.95	2.01	2.48	0.21	3.09	10.4
P4	0.31	0.27	1.16	1.18	1.61	0.10	2.07	6.71
P5	0.33	0.31	2.05	1.87	2.18	0.20	3.08	10.0
Total Average *n*=31	**0.26**	**0.26**	**1.55**	**1.23**	**1.55**	**0.12**	**2.05**	**7.02**
OUT								
c (ng/m^3)	**BaA**	**CH**	**BbjkF**	**BaP**	**IP**	**DahA**	**BghiP**	**PAH**
P1	0.22	0.25	2.22	0.69	0.76	0.08	1.10	5.26
P2	0.26	0.32	1.21	0.56	0.82	0.25	1.13	4.29
P3	0.49	0.56	3.06	2.08	2.56	0.15	3.38	12.1
P4	0.36	0.37	1.52	1.23	0.79	0.10	1.17	5.44
P5	0.82	0.90	4.62	2.69	3.33	0.25	4.50	16.9
Total Average *n*=31	**0.42**	**0.47**	**2.52**	**1.42**	**1.62**	**0.16**	**2.22**	**8.68**

(*) Not Determined (ND): all data resulted below LLOQ = 0.446 ng/sample.

Results of Table 4 show that PAH levels in A4 are always lower than in CR and both the indoor values are lower than outdoor. The total mean of cPAH concentrations indoors ranged from 1.96 ng/m^3 (A4, P2) to 10.4 ng/m^3 (CR, P3); outdoors, from 4.29 (P2) ng/m^3 to 16.9 (P5) ng/m^3, the latter being the highest value averaged over the six sampling weeks.

The difference in cPAH concentrations between night and day is on average about 180%. This result seems to be in accordance with the indoor accumulation process during the nighttime, when a very high stationary condition occurs.

The lowest mean concentrations of congeners were measured for DahA, BaA and CH, which together contributed to about 10% of the total mass of cPAHs. Higher mean contributions were observed for BghiP (six aromatic fused benzene rings) at 27.9%, followed by BbjkF (five fused rings) (26.1%) and IP (six fused rings) (20.8%). These compounds are characteristic of car exhausts [40,41] and abundant mainly in PM size smaller than 1.2 μm [27], linked to local and fresh emission from incomplete combustion processes. BaP contributed to the total mass by approximately 16%, in accordance with the results of a previous study in Rome by Romagnoli et al. 2014 [42], which were 18% for twelve home sampling sites, higher than those calculated for similar outdoor winter PAHs mixture in Zagreb (Croatia) and Belgrade (Serbia) at about 11%. [43,44].

The relative mass contribution of each congener to the target mixture averaged over the entire sampling campaign (*n* = 31) in A4, CR and OUT is showed in Figure 2.
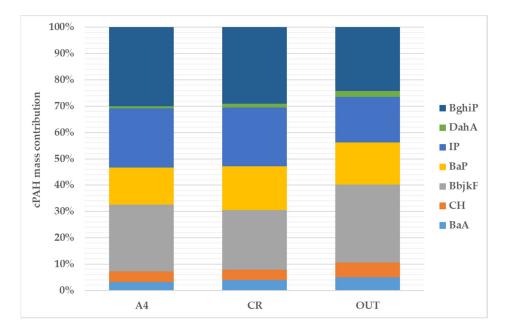

Figure 2. Relative mass contributions of cPAH compounds to the target mixture.

The total cPAH concentrations characterizing the actual mixture were compared to those found in Rome in previous studies. The target PAHs being mainly associated with the finest particles, results can be compared to data obtained from PM$_{10}$ for similar mixtures in indoor living/working environments. Figure 3 shows that the mean values of cPAH concentrations in A4, CR and OUT are comparable to those measured in Rome, in winter, at schools, homes and outdoors (about 6 to 8 ng/m^3 indoors, 8 to 11 ng/m^3 outdoors) [29,43,44].
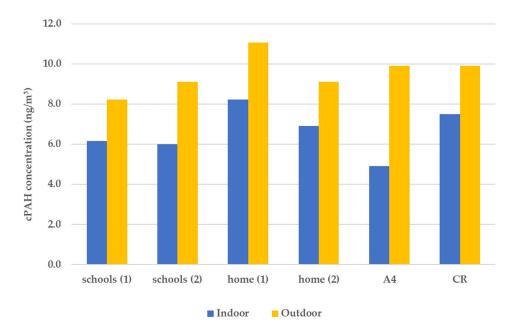
Figure 3. Literature and current data for winter cPAH concentrations measured in Rome in indoor and outdoor environments.

Figure 4 shows cPAH concentrations for the overall winter sampling campaign. Figure 4a shows, in all the environments, that levels for Weekends (P1) are lower than the previously cumulated Wednesday + Thursday + Friday nights (P5). The scatter plot Figure 4b indicates that higher concentrations of CR were similar to those outdoors, while those in A4 were lower. cPAHs over Weekends reached values lower than 10 ng/m^3 in both A4 and CR.
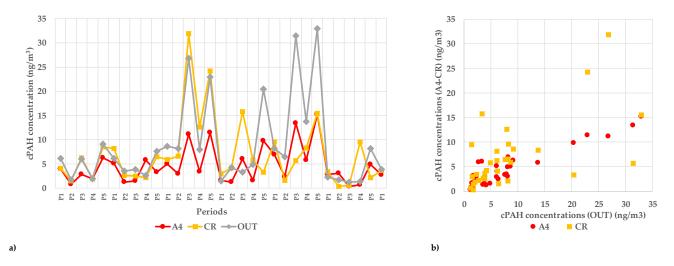

a)

b)

Figure 4. cPAH concentrations throughout the scheduled winter campaign. (**a**), trend over the six weeks of sampling for A4, CR and OUT. (**b**), scatter plot of A4 and CR vs OUT.

The above trend was investigated in terms of mass contribution of cPAHs to mass of PM_{10} (MC) for values averaged over the Periods P1 (Weekends) and P2-P3-P4-P5 (Weekdays): $\overline{cPAHs}(\mu g)/\overline{PM_{10}}(\mu g)\cdot10000 = MC_{0/000}$. Results are shown in Figure 5.
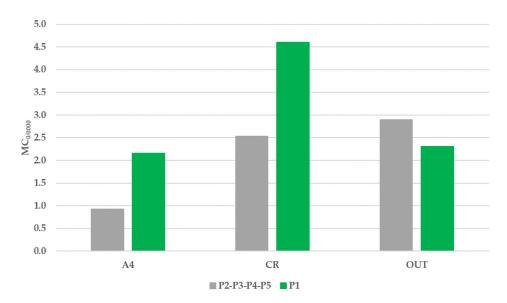
Figure 5. Mass contribution of cPAHs to mass of PM_{10} ($MC_{0/000}$) during Periods P1 and P2-P3-P4-P5 for A4, CR and OUT.

The total mass of cPAHs represents a very small quantity of that of PM_{10}, (maximum mean value about $5_{0/000}$, for CR during P1). In detail, different levels of mass contribution of cPAHs were measured in the two classrooms and A4 was confirmed as also having the lowest $MC_{0/000}$. The pattern of Figure 5 shows indoor values of $MC_{0/000}$ higher for Weekend than for Weekdays, during which re-suspended particles not containing cPAHs contribute to a decrease in the ratio of cPAHs/PM_{10}. The outdoor levels, instead, seem to indicate an increasing contribution from cPAHs during working days.

Study of Mean cPAH Concentrations over the Week

The accumulation of cPAHs over time during the week has been investigated. For this purpose, a detailed analysis of the difference between the first and the second part of the week has been carried out. The sampling periods P2 and P3 represent the first part of Weekdays (Monday + Tuesday), and P4 and P5 the second (Wednesday + Thursday + Friday): hereafter, they are briefly defined as first Weekdays (first-Weekdays) and second Weekdays (second-Weekdays), respectively, to be distinguished from Weekend (Saturday + Sunday). Therefore, cPAH concentrations in A4, CR and OUT were averaged over P2-P3 and P4-P5 to be compared to those of P1. The corresponding percentage differences, $\Delta\%$ *first-Weekdays* and $\Delta\%$ *second-Weekdays* were calculated by Equations (5) and (6), respectively:

$$\Delta\%_{first-Weekdays} = \frac{C_{first-Weekdays} - C_{Weekend}}{C_{Weekend}} \cdot 100 \tag{5}$$

$$\Delta\%_{second-Weekdays} = \frac{C_{second-Weekdays} - C_{Weekend}}{C_{Weekend}} \cdot 100 \tag{6}$$

Results are reported in Table 5.

Table 5. Percentage differences of cPAH concentrations between first-Weekdays and Weekend, second-Weekdays and Weekend.

	A4	CR	OUT
$\Delta\%$ *first-Weekdays*	−3.2	23	56
$\Delta\%$ *second-Weekdays*	45	55	112
Average	21	39	84

Results of Table 5 indicate that from Weekend to Weekdays an increase of cPAH concentrations occurs. From the first part of the week (first-Weekdays) to the second (second-Weekdays), outdoor cPAHs increase by about two times. The concentrations indoors also increase, but in a less pronounced manner (on average Δ% indoors is about 30%). This similarity of indoor and outdoor dynamics is stronger in the case of CR, in which cPAHs double in the transition from first-Weekdays to second-Weekdays, just as for OUT.

By comparing the percentage differences observed for cPAH concentrations with those available for PM_{10} in the same target environments (Tofful et al. 2021), cPAHs present different dynamics to PM_{10}. In fact, the indoor concentrations of PM_{10} exceeded those outdoors during night and weekends. Moreover, Tofful indicates that the soil contribution indoors increases from Weekend to Weekdays [28]. The observation that the mass contribution of cPAHs to PM_{10} indoors decreases during the weekdays (while outdoors it increases), as shown in Figure 4, is in accordance with this result.

Taking into account the similar volumes of the two classrooms (A4 570 m^3, CR 450 m^3), the previous consideration on soil contribution leads to the conclusion that indoor concentration of PM_{10} depends also on the presence and movements of people in the classrooms. The dynamic obtained for cPAHs, different from those of PM_{10}, confirms the presence of an indoor soil contribution (not containing cPAHs) to PM_{10}.

3.2. Infiltration Factor, Residual Indoor Concentration and Indoor to Outdoor Ratio

The linear regression analysis to derive IFs and C_0 concentrations according to Equation (1) were carried out for data aggregated over periods P1 (Weekend) and P2-P3-P4-P5 (Weekdays): the curves for A4 and CR are shown in Figure 6.
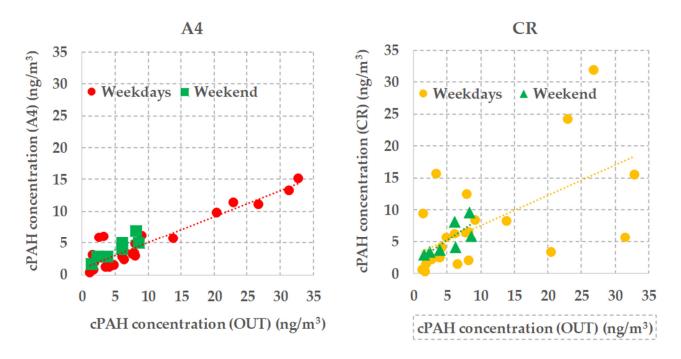

Figure 6. cPAH concentrations indoor vs. outdoor.

The coefficients of linear correlations (r) of Equation (1) are reported in Table 6, together with the slopes (IFs) and intercepts (C_0). A4 has a better fit than CR, this last presenting a greater infiltration capacity. In A4, IF and C_0 during Weekends were higher than during Weekdays; the percentage of C_0 to the mean value was 25% for WE and 18% for Weekdays.

Table 6. Coefficients of linear correlation, IFs and C_0 concentrations from the linear regression analysis between indoor and outdoor concentrations.

		Weekend	Weekdays
	IF	0.58	0.41
A4	C_0 (ng/m^3)	0.97	0.89
	r	0.90	0.94
	IF	0.71	0.47
CR	C_0 (ng/m^3)	1.67	2.95
	r	0.75	0.59

A greater IF difference between Weekend and Weekdays was registered in CR, with percentage of residual concentration to mean value higher than A4, at 31% and 39%, respectively, for the two periods.

Both the rooms' IFs were higher during Weekend, when the classrooms are empty, suggesting that the windows were left open; the residual mean indoor concentration was about 28%.

In addition to the infiltration factor, the ratio between indoor and outdoor cPAH concentrations was calculated and was then compared with that of PM$_{10}$. For this purpose, the PM$_{10}$ concentrations provided by Tofful et al. 2021 for the same environments, A4, CR and OUT [28], averaged over November and December were used.

Results are shown in Table 7.

Table 7. Total average I/O Ratio for cPAH and PM$_{10}$ concentrations for A4 and CR.

	I/O Ratio	
	cPAHs	PM$_{10}$
A4	0.54	1.22
CR	0.81	0.75

The differences in the I/O Ratios between A4 and CR of both cPAHs and PM$_{10}$ confirm the different dynamics of these rooms

3.3. Study of Chemical Profiles

The combination of the seven components of the PAH mixture produces 31 chemical profiles for each environment that address the impact of the cPAHs' main sources.

In order to provide a chemical overview of the cPAHs' signature, for each profile the net concentration of the ith (I = 1 to 7) component was normalized to the highest value (C_{max}). The resulting ratios C_i/C_{max} give 31 new profiles, normalized to the maximum value (Supplementary Materials, Table S1, together the correspondent maximum value used for the normalization). These represent the mixture independently from the intensity of the sources and also allow the identification of its molecular fingerprint, corresponding to the Ratio $C_i/C_{max} = 1$.

The normalized profiles averaged over Weekends and Weekdays are reported in Table 8: the bold values represent the molecular fingerprints. Is to be noted that averaging the ratios over different periods can provide C_i/C_{max} different from the unity: nevertheless, the fingerprint will still be identified by the maximum value registered.

Table 8. Normalized profiles of cPAHs, for A4, CR and OUT. The bold values identify the mixture fingerprint. The mean maximum values are also reported in ng/m^3 along with the corresponding compound.

		C_{max} (ng/m^3)	Compound	C_{BaA}/C_{max}	C_{CH}/C_{max}	C_{BbjkF}/C_{max}	C_{BaP}/C_{max}	C_{IP}/C_{max}	C_{DahA}/C_{max}	C_{BghiP}/C_{max}
A4	**Weekend**	1.62	BbjkF	0.08	0.10	**1.00**	0.34	0.38	0.03	0.57
	Weekdays	5.22	BghiP	0.09	0.12	0.65	0.39	0.76	0.02	**0.99**
CR	**Weekend**	2.01	BbjkF	0.10	0.12	**0.96**	0.38	0.47	0.05	0.69
	Weekdays	9.69	BghiP	0.13	0.12	0.69	0.49	0.70	0.05	**0.93**
OUT	**Weekend**	2.22	BbjkF	0.09	0.11	**1.00**	0.29	0.34	0.04	0.50
	Weekdays	9.08	BbjkF	0.17	0.18	**0.86**	0.44	0.61	0.08	0.84

Table 8 allows the identifiaction of two fingerprints, BbjkF and BghiP, varying along the sampling periods, indoors and outdoors. Except for BaA and CH, which are the lighter four fused aromatic ring compounds, mostly originating from domestic heating or biomass burning, the "heavy" PAHs with five or more fused rings are characteristic of car exhausts [40,41,45,46]. Because BbF, BghiP and IP are known to be generated prevalently from car exhausts, the above result for the actual measurements are coherent with this origin [47]. In this regard, a detailed analysis follows.

During Weekends, when background winter urban sources with "low-traffic" contribution occur in the target environments, BbjkF was the mixture fingerprint (C_i/C_{max} about 0.98), followed by BghiP (0.58) and IP (0.40)).

During Weekdays, outdoor C_i/C_{max} was still centered on BbjkF, with a second well marked maximum on BghiP, while the indoor highest mean ratio was BghiP (0.92) followed by BbjkF (0.73) and IP (0.69). So during Weekdays, the cPAHs' fingerprint of winter outdoor background sources (BbjkF, "low-traffic") tends to change to BghiP, probably because of the additional contribution of a "fresh-traffic" source.

This hypothesis is supported by the net increasing of outdoor BaP from Weekend to Weekdays, which rises from 13% to 17%. It is reported, in fact, that the addition of fresh sources, locally released (not related to transport) is accompanied by an increase in the BaP content [48].

To investigate the correlation between all the indoor and outdoor profiles and between all A4 and CR profiles, a cross correlation analysis was carried out, using in total 434 data for each correlation (Supplementary Materials, Table S2). The Pearson's coefficients were calculated for P1 and for P2-P3-P4-P5 to represent sources typical of Weekends and Weekdays; in P1, both the indoor fingerprints are well correlated with that of the outdoor (A4-OUT and CR-OUT, r = 0.99) and also with each other (A4-CR, r = 0.95). These results, in addition to those provided by the ratios C_{ind}/C_{out}, indicate that during Weekend the main external source enters the indoor environment unchanged, even if a lower amount of cPAHs enters A4 than CR (C_{ind}/C_{out} 0.77 and 1.02, respectively). A higher variability between indoor and outdoor is instead observed during Weekdays, with r values 0.78 for A4-OUT and 0.88 for CR-OUT: a lower amount of cPAHs still enters A4 than CR (C_{ind}/C_{out} 0.51 and 0.82, respectively).

The indication of a different source contribution in the two periods is also justified by the analysis of the mass contribution of cPAH to PM$_{10}$ (Figure 5). In fact, due to the addition of "fresh traffic", a greater mass contribution of cPAH is observed outdoors during Weekdays, while indoors the phenomenon is less evident due to the increased mass of PM$_{10}$ (not containing cPAHs) that is carried (or re-suspended) by people entering the classrooms.

The individuation of chemical fingerprints for the cPAH mixture may provide information on the toxicological impact of human exposure in the target indoor environments. To investigate this aspect, the evaluation of the carcinogenic potency of the mixtures has been carried out.

3.4. Toxicity Equivalency to BaP

Concentrations of PAH congeners were used to calculate BaP equivalents according to Equation (2). From BaP$_{eq}$ concentrations, firstly toxicological profiles for the mixtures

of concern were obtained. Secondly, BaP_{eqs} were used to calculate the Total Carcinogenic Potency (TCP) using Equation (3).

The toxicological profiles averaged over Weekends and Weekdays are reported in Figure 7. Based on these profiles, a major contribution of BaP in determining the carcinogenic potency of the mixtures occurred, either during Weekend or Weekdays, supporting the choice of BaP as a suitable indicator for assessing the contribution of carcinogenic PAHs in ambient air. BaP, being only 16% of the mass of the target mixture, presented the highest toxicological outcome, weighing on average about 57% of the toxicological profile: this value is in accordance with literature data for PM_{10} in urban areas, which was 54% in in Kuala Lumpur [49] and about 58% in Belgrade Metropolitan [50].
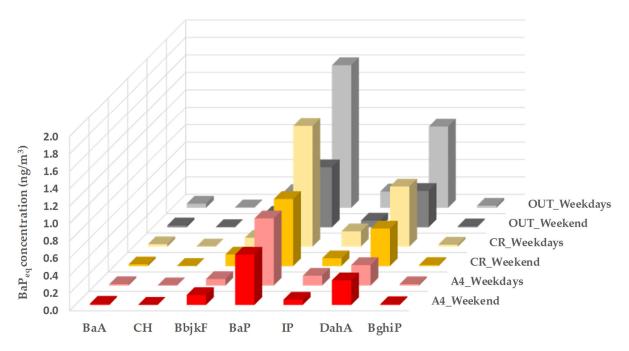

Figure 7. Toxicological profiles, BaP_{eq} based, for A4, CR and OUT.

DahA, which instead presented the lowest mass contribution (1.6%), gives the second highest contribution to the total toxicity, with a mean value of 26.5%, followed by IP and BbjkF, with 7.2% and 7.0%, respectively.

While the study of fingerprint by means of the normalized chemical profiles aimed at identifying whether outdoor sources entered the indoor environments, the toxicological profiles provide information on the individual contribution of congeners to the total carcinogenic property of the mixture. This also enables study of how this contribution varies during the week.

Thus, while BghiP was found to be the indoor fingerprint during Weekdays, its contribution to the toxicity of the mixture is negligible (1%) compared to that of other congeners, due to its low toxicity (Bghip is "not classifiable as a human carcinogen").

The Total Carcinogenic Potency concentrations and the relative Potency Factors (RPF) averaged over Weekend and Weekdays for A4, CR and OUT are summarised in Table 9.

Table 9. Total Carcinogenic Potency concentrations and Relative Potency Factor for A4, CR and OUT.

	TCP (ng/m^3)		RPF	
	Weekend	Weekdays	Weekend	Weekdays
A4	1.06	1.22	1.83	1.59
CR	1.46	2.41	1.90	1.96
OUT	1.37	3.02	1.99	1.84

On average, lower indoor TCPs were observed than outdoors, with CR values always higher than A4 and Weekend values higher than those calculated for Weekdays. All the TCPs were closer to each other during Weekend. With reference to the difference between Weekdays and Weekend, TCPs during "working" days were higher than during "not-working" ones (outdoors by about 2.2 times), probably due to the addition of "fresh-traffic" sources. Toxicity ratios among the three environments were the same for either TCP or BaP (on average, 0.60 and 0.65 respectively). However, it should be emphasised that the carcinogenic potency of the mixture expressed by the RPF is on average 1.9 (Weekend) and 1.8 (Weekdays), about twice that of BaP.

So far, although BaP can be considered as a proper indicator of the carcinogenic content of PAHs in ambient air, adopting it as a unique indicator can lead to an under-estimation of the carcinogenic risk due to the contributions of other PAHs. Considering the Total Carcinogenic Potency of PM is an important task as far as the human exposure to carcinogenic compounds is concerned. In European urban atmospheres, TCP values higher than the actual were observed outdoors for winter periods, according to higher BaP levels. For example, in Zagreb, Croatia, and Sarajevo, Yugoslavia, TCPs measured from December 2017 to February 2018 were 4.5 ng/m^3 and 10.0 ng/m^3, respectively [43] and again in Zagreb TCPs of 3.66 ng/m^3 and 5.039 ng/m^3 for PM$_{10}$ were measured in winter at Urban residential and Urban traffic locations, respectively [51]. The highest value for TCP from the literature is that calculated in Zagabria in winter: 12 ng/m^3, supported by an average percentage contribution of BaP to the total carcinogenic potency of 61.72% [52].

Comparable TCP of 2.648 ng/m^3 was obtained in winter in Total Suspended Particles (TSP) measured in Istanbul, Turkey, but on the basis of 16 PAHs belonging to the EPA Priority List [53]. Moreover, Romagnoli et al. 2017 found in Crotone, Italy, TCP values lower than in the present study: 0.161 ng/m^3 in October for an urban-industrial site, with an average BaP concentration 0.06 ng/m^3, contributing about 8% to the total mass of PAHs [54].

4. Conclusions

Many studies have been carried out about the PAHs bound to particulate matter, to analyze the contribution of combustion sources and assess human exposure both in living and working environments, or examine their indoor dynamics in relation to outdoors. In the frame of the VIEPI Project, carcinogenic PM$_{10}$-bound PAHs were measured in two adjacent indoor environments of the Department of Physics of University Sapienza, in Rome and in the nearby outdoor environment. The characteristic of these indoor environments, where no direct source of internal combustion is expected, allowed consideration of the influence of external sources on the presence of carcinogenic PAH and the consequent impact on the exposure of the occupants. Moreover, the sampling schedule, distinguishing weekend periods and weekdays, allowed study of the carcinogenic PAHs in the two classrooms both on "working" and "not-working" days.

As for the concentrations of cPAH measured at night, they were always higher than during the day and would require a more in-depth treatment to be well explained, outside the scope of the present study. The application of numerical simulation models could help in this [55,56].

Although the two classrooms are on the same floor of the building, in general A4 is less contaminated than CR and different dynamics have been observed for PAHs. On Weekdays, the Infiltration Factor was almost similar indoors (0.41 and 0.47 for A4 and CR, respectively) while it changed over the Weekend (0.58 for A4 versus 0.71 for CR). The mean I/O concentration Ratios were 0.54 for A4 and 0.81 for CR.

Analysis of the fingerprint of the sources indicates the same compound outdoors and indoors on Weekend (BbjkF), confirming that external sources are entering the indoor environment. However, during Weekdays a different fingerprint compound was recorded indoors, probably related to human activity during working days.

In order to estimate the carcinogenic potency in the target environments and the differences between Weekend and Weekdays, the Total Carcinogenic Potency has been calculated. This was different in the two classrooms and higher on Weekdays than on Weekend (average internal TCP of 1.82 ng/m^3 as against 1.26 ng/m^3, respectively). The coefficient of variation calculated for the average of the three values of TCP recorded in both classrooms and outdoors was 16.8 for Weekend against 50.3 for Weekdays, indicating that during working days this is more variable.

These results suggest the need for monitoring more than one indoor environment inside a building and of distinguishing Weekend to Weekdays for a proper evaluation of the occupants' exposure.

Closely related to TCP data, the ratios between TCP and BaP concentrations provided the Relative Potency Factors (RPFs) of the carcinogenic PAHs. In accordance with Directive 2004/107/EC, the calculated RPFs confirmed that BaP is a good indicator of the carcinogenic PAH content in relation to PM in ambient air.

However, the choice of including carcinogenic PAHs other than BaP in the exposure assessment leads to a better estimation of the carcinogenic risk of exposure in indoor environments during working days.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su131910790/s1 Table S1: Single profile of cPAH mixture for each period of concern, normalized to the maximum value of concentration, C$_{max}$ (ng/m^3), for A4, CR and OUT, Table S2: Matrices of cross correlation analysis of profiles of cPAH mixtures normalized to the maximum value of concentration in each period of concern.

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