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# Review of environmental airborne pyrene/benzo[a]pyrene levels from industrial emissions for the improvement of 1-hydroxypyrene biomonitoring interpretation

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## ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous pollutants of significant public health concern, with several that are highly toxic to humans, including some proven or suspected carcinogens. To account for the high variability of PAH mixtures encountered in occupational settings, adjusting urinary 1-hydroxypyrene (1-OHP) levels by the total airborne pyrene (PyrT)/benzo[a]pyrene (BaP) ratio is essential for human biomonitoring (HBM). Given the complexity and cost of systematically monitoring atmospheric levels, alternative approaches to simultaneous airborne and HBM are required. The aim of this review was to catalog airborne PyrT/BaP ratios measured during different industrial activities and recommend 1-OHP-dedicated biological guidance values (BGV). A literature search was conducted. Seventy-one studies were included, with 5619 samples pertaining to 15 industrial sectors, 79 emission processes, and 213 occupational activities. This review summarized more than 40 years of data from almost 20 countries and highlighted the diversity and evolution of PAH emissions. PyrT/BaP ratios were highly variable, ranging from 0.8 in coke production to nearly 40 in tire and rubber production. A single PyrT/BaP value cannot apply to all occupational contexts, raising the question of the relevance of defining a single biological limit value for 1-OHP in industrial sectors where the PyrT/BaP ratio variability is high. Based upon the inventory, a practical approach is proposed for systematic PAH exposure and risk assessment, with a simple frame to follow based upon specific 1-OHP BGVs depending upon the occupational context and setup of a free PAH HBM interactive tool.

## KEYWORDS



Polycyclic aromatic hydrocarbons; PAH; exposure; risk assessment; human biomonitoring; 1-hydroxypyrene; occupational


## Introduction

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous pollutants of significant public health concern (Barbosa et al. 2023; Louro et al. 2022). PAHs are formed during the incomplete combustion of organic materials such as environmental tobacco smoking, industrial emissions, fossil fuels, wood, petroleum products, residential heating, and even food preparation (Barros, Oliveira, and Morais 2023; Mallah et al. 2022; Zhang et al. 2021). PAHs are released into the environment as a mixture of both anthropogenic and natural origins, with the former being predominant (Barbosa et al. 2023; Haber et al. 2022). There are more than a thousand PAHs composed of two or more fused aromatic rings. PAHs with low molecular weight (2–3 rings) are abundant in the gaseous phase, while four-ring PAHs are distributed in both particulate and gaseous

phases. PAHs with a high molecular weight (>5 rings) are abundant in the particulate phase and more toxic (Barbosa et al. 2023; Mallah et al. 2022).

Sixteen PAHs were classified as priority contaminants by the United States Environmental Protection Agency (US EPA) owing to their toxicity (Mallah et al. 2022), while several PAHs were classified as probable or possible carcinogens by the International Agency for Research on Cancer (IARC) (Cattley et al. 2023; IARC 2024). Benzo[a]pyrene (BaP) is the only PAH currently classified as carcinogenic to humans (IARC Group 1) (IARC 2024; Louro et al. 2022). Three PAHs (cyclopenta[cd]pyrene, dibenz[a,h]anthracene, and dibenzo[a,l]pyrene) are categorized as probably carcinogenic to humans (IARC group 2A), while 12 PAHs (anthracene, benzo[a]anthracene, benz[j]aceanthrylene,

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benzo[b]fluoranthene, benzo[c]phenanthrene, benzo[j]fluoranthene, benzo[k]fluoranthene, chrysene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, indeno[1,2,3-cd]pyrene, and naphthalene) are classified as possibly carcinogenic to humans (IARC group 2B). Nine alkylated PAH derivatives are categorized as probable or possible carcinogens, in particular 5 derivatives of pyrene, namely 1-nitropyrene (group 2A), 1,3-dinitropyrene (group 2B), 1,6-dinitropyrene (group 2B), 1,8-dinitropyrene (group 2B), and 4-nitropyrene (group 2B). In addition, some PAH mixtures and occupations are classified as carcinogenic by IARC, with outdoor air pollution, aluminum production, coke production, diesel engine exhaust, firefighter, iron and steel founding, mineral oils (untreated or mildly treated), rubber manufacturing industry, and soot in Group 1. Bitumen (during roofing), carbon electrode manufacture, and frying (emissions from high temperatures) are classified in Group 2A, while bitumen (during mastic asphalt work and road paving), gasoline engine exhaust, and printing processes are designated as Group 2B.

The continuous emission of PAHs represents a constant concern for individual and population health. Human exposure to PAHs arises from a broad range of emission sources. PAHs can enter the body through different absorption pathways, including inhalation, dietary intake, and dermal exposure. Occupational PAH exposures represent the main concern. Indeed, workers are more frequently exposed to higher levels and for longer periods of their lives than the general population (Louro et al. 2022). Millions of workers are exposed to PAHs, including road pavers, firefighters (mainly wildland), aluminum, silicon, or electrode production workers (Barbosa et al. 2023; Barros, Oliveira, and Morais 2023; Cherry et al. 2023; Louro et al. 2022; Mallah et al. 2022; Taeger et al. 2023; Valière et al. 2022; Wallace et al. 2019). However, PAH exposures differ greatly from one industrial sector to another (Maitre et al. 2018; Valière et al. 2022). The primary routes of occupational exposure are inhalation and, to a lesser extent, dermal contact.

Assessing the potential toxicological impact of PAHs on human health requires monitoring PAH levels. Two complementary approaches may be used: air monitoring and human biological monitoring (HBM). The use of HBM has become more

common in recent years because this approach takes into account all uptake pathways and efficiency of personal protective equipment (PPE). The predominant PAH metabolites include urinary mono-hydroxylated metabolites. 1-Hydroxypyrene (1-OHP), the main urinary metabolite derived from pyrene (Pyr), is the most widely used PAH biomarker to assess human exposure to PAHs (Barbosa et al. 2023; ECHA 2022; Ifegwu and Anyakora 2016; Jeng and Pan 2014; Jongeneelen 2014; Louro et al. 2022; Taeger et al. 2023). 1-OHP has been extensively employed as a bioindicator over the past 30 years (ACGIH, 2020; Louro et al. 2022; SCOEL 2016; Taeger et al. 2023). The measurement of 1-OHP for PAH HBM is recommended by many health agencies around the world (ACGIH, 2020; HSE 2024; SCOEL 2016). 1-OHP is considered a sensitive and specific marker of PAH exposure (ECHA 2022; Ifegwu and Anyakora 2016; Jeng and Pan 2014; Louro et al. 2022). However, 1-OHP does not directly reflect carcinogenic PAH exposure (Jongeneelen 2014; Louro et al. 2022), unlike direct metabolites of BaP such as 3-hydroxybenzo[a]pyrene (3-OHBP). Analysis of 3-OHBP has been developed later and requires a more sensitive analytical technique than 1-OHP due to levels that are 1000–10,000-fold lower (Barbeau, Maitre, and Marques 2011; Rögner et al. 2021). Hence, contrary to 1-OHP, analysis of 3-OHBP is not easy and not readily available to most labs because this technique requires either sophisticated pre-analytical (automated solid-phase extraction) or analytical methods (mass tandem spectrometry), precluding its systematic use in occupational settings (ECHA 2022; Ifegwu and Anyakora 2016; Louro et al. 2022). The predominance of the fecal over urinary excretion pathway for BaP metabolites contributes to very low urinary 3-OHBP levels. The use of urinary 1-OHP seemed to be more protective than that of urinary 3-OHBP and airborne BaP (Valière et al. 2022). Urinary 3-OHBP was found not relevant for occupational groups with low PAH exposure levels and might lead to underdiagnoses for assessing health risk (Valière et al. 2022). Contrary to other PAH metabolites (e.g., urinary naphthalene metabolites), urinary 1-OHP is not markedly influenced by confounding factors, such

as smoking and other environmental sources (Persoons et al. 2020). In addition, associations between 1-OHP and genotoxic effects (e.g., high-frequency cells, sister chromatid exchanges), DNA adduct levels, and urinary 8-oxo-7,8-dihydro-2-deoxyguanosine (a biomarker of biologically effective dose of DNA damage) have been reported in workers in several industries (Jeng and Pan 2014; Jongeneelen 2014). The remainder of this review will focus on the most widely used PAH HBM approach (1-OHP) as this chemical has been extensively utilized for studying PAH exposure in multiple occupational and environmental settings globally for several decades (Ifegwu and Anyakora 2016; Jeng and Pan 2014; Jongeneelen 2014; Louro et al. 2022; SCOEL 2016; Taeger et al. 2023; Valière et al. 2022) and is recommended by several health agencies (ACGIH 2020; ECHA 2022; HSE 2024).

To the best of our knowledge, no apparent biological limit value (BLV) exists for 1-OHP (Jongeneelen 2014; Louro et al. 2022). Several health agencies proposed different biological reference values. The Scientific Committee on Occupational Exposure Limits (SCOEL) suggests a biological reference value, derived from the background levels of the general population, of 0.5 µg/g creatinine (= 0.65 µg/L) (ECHA 2022; SCOEL 2016). The German Research Foundation (DFG) sets a biological reference value, derived for nonsmokers from a correlation between urinary 1-OHP and BaP in the air, of 0.3 µg/g creatinine (= 0.39 µg/L) (ECHA 2022). The British Health & Safety Executive (HSE) recommends a technical value of 4 µmol/mol creatinine (= 10 µg/L) based upon the 90<sup>th</sup> percentile value of a survey of workplaces with exposure to PAH (HSE 2024). The Finnish Institute of Occupational Health (FIOH) recommends a biological reference value (“action limit”) of 12 nmol/l creatinine (= 2.62 µg/L) based upon the 90<sup>th</sup> percentile from the biomonitoring results, measured for coke oven workers ( $n = 32$ ) with good industrial practices in 2008 in Finland (ECHA 2022). The only existing biological guidance value (BGV) for 1-OHP is the value proposed by ACGIH of 2.5 µg/L (ACGIH 2020). However, the BGV from ACGIH was mainly based upon data coke production. In order to account for different relative proportions of total

Pyr (PyrT, sum of both gaseous and particulate pyrene) and BaP in PAH industrial mixtures encountered in a broad spectrum of industrial sectors and occupational contexts, it has been proposed to adjust the urinary 1-OHP BGV (ACGIH) by the airborne PyrT/BaP ratio of a specific exposure context using the following equation:  $BGV_{ACGIH} = 1OHP \times \frac{Pyr/BaP}{2.5}$  (ACGIH 2020). Jongeneelen (2014) recommended adjusting urinary 1-OHP levels when the PyrT/BaP ratio lies in the 1.5–4.5 range and not adjusting otherwise. Adjustment of 1-OHP concentration by the PyrT/BaP ratio requires air sampling due to highly variable ratios observed in various occupational groups (Valière et al. 2022). Given the complexity and cost of systematically monitoring atmospheric levels, alternative approaches to simultaneous airborne and urine HBM are required (Valière et al. 2022), such as an inventory of the PyrT/BaP ratio according to industrial activities.

This review attempted to catalog PyrT/BaP ratios according to industrial activities that might benefit human health risk assessment resulting from PAH exposure by facilitating PAH exposure assessment in occupational contexts when the most widely used PAH HBM approach (urinary 1-OHP monitoring) is conducted. This inventory/database may be a useful resource for physicians, risk assessors, risk managers, practitioners, industry practitioners, decision-makers, and sanitary agencies. Indeed, it might serve as a valuable resource for the establishment of BGVs and BLVs. In addition, a user-friendly and interactive online tool was created to: 1) make the inventory/database easily findable, accessible, interoperable, and re-usable; and 2) help in the implementation/calculation of BGVs and facilitate the interpretation and risk assessment of PAH from HBM. Hence, our presented investigation aimed to offer a practical approach for systematic PAH exposure and risk assessment, with a simple frame to follow based upon the occupational context and most frequently used biomonitoring approach (urinary 1-OHP monitoring). Our findings may support the improvement of 1-OHP biomonitoring interpretation, which is essential for enabling a more accurate PAH exposure assessment, as well as an earlier detection and prevention of PAH-related adverse health effects.

## Materials and methods

### *Literature search strategy and selection criteria*

The literature search was conducted using the PubMed search engine in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) criteria. To reduce the bias induced by daily database changes, all data collection (literature retrieval and data download) was conducted and completed on the same day, February 10, 2022. The search was repeated in October 2023 to include publications from 2022. The search query consisted of 88 terms, including MeSH and relevant free-text terms related to PAHs, occupation, airborne exposure, exposure monitoring, language, and terms excluded (supplemental information). The search was limited to peer-reviewed publications written in English or French that dealt with airborne PAH exposure monitoring in occupational settings. In order to guarantee the representativeness of the included publications, the search results were filtered by language, title, abstract, and paper content to exclude irrelevant articles (Table S1). Papers that did not report the PyrT/BaP ratio or both airborne BaP and either PyrT or both gaseous pyrene (PyrG) and particulate pyrene (PyrP) levels from long-term sampling (>2 h) were excluded.

Three independent authors (AC, AM, and PP) collectively performed data collection, with one (AC) responsible for operation and two others (AM and PP) responsible for the check. Filtered data were then cleaned up and validated to exclude any publications with no relevance to the main subject of investigation in this study. Disagreements were discussed, followed by a joint full review of the articles of concern, which led to inclusion or exclusion.

The literature search yielded 3188 records that had been published. Irrelevant and duplicate records (3117) were excluded, leaving a total of 71 articles that were analyzed (Figure 1). No attempt to conduct an analysis of the scientific content of the identified records was undertaken because it was outside the scope of this study. In addition, no data quality analysis (qualitative or quantitative) of the studies compiled from this investigation was made.

### *Data extraction from published studies*

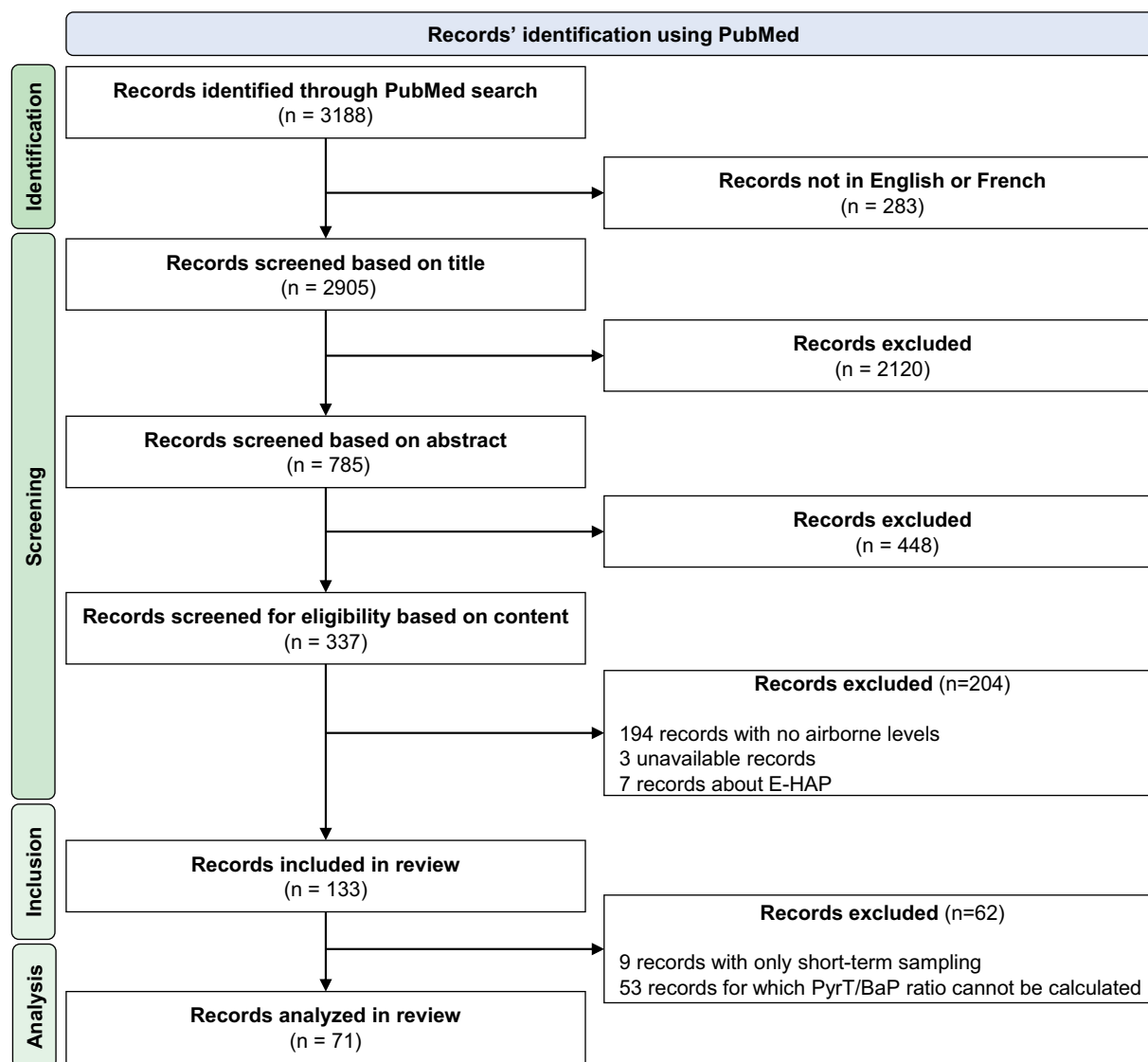
The author's name, publication year, geographical location, occupational context, sampling year(s), sampling device/technique (e.g., type of particulate filter), sampling strategy (e.g., time, flowrate), number of samples, airborne BaP levels, airborne Pyr levels (gaseous, particulate, and/or total), PyrT/BaP ratio, and other relevant information were all extracted from the included studies using MS Excel.

### *Data extraction from Exporisq-HAP*

The Exporisq-HAP database (E-HAP) is one of the most comprehensive existing databases on exposure to PAHs (Petit 2022). E-HAP provides a detailed picture of airborne PAH exposures and urinary metabolite levels encountered in the French industrial landscape over the last 25 years (Maître et al. 2018; Petit et al. 2017; Valière et al. 2022). Because the authors of this review own E-HAP, the latest E-HAP data available to them was employed instead of extracting E-HAP data from published peer-reviewed publications. From the 2650 airborne samples available in the E-HAP database, 2213 (83.5%) samples providing both airborne concentrations of BaP and PyrT were included and analyzed.

### *Data management/wrangling*

Data extracted from the literature and E-HAP were used to construct a database of PyrT/BaP ratios in various occupational contexts. To harmonize/standardize and make the retrieved data comparable, occupational context and sampling device/technique were coded in the same manner as E-HAP. Briefly, the occupational context was structured into similar exposed groups (SEGs) of three hierarchical levels of increasing description (Petit et al. 2017), with the first level (referred to as sector throughout the paper) predominantly related to the characteristics of products/raw materials (e.g., engine exhaust emissions, carbon electrodes, or bitumen fume). Each sector was then subdivided into subgroups (referred to as processes) with information that referred to exposure source characteristics (e.g., job titles, posts, locations, and/or



**Figure 1.** PRISMA flow chart depicting the literature search and the evaluation process for finding relevant records.

operations with different emission sources). Processes were split into subgroups (referred to as activities) with information that usually corresponded to a task or a series of homogeneous tasks. Sectors, processes, and activities were the least, intermediate, and most accurate levels of description of the occupational context, respectively. The same person (AM) responsible for the coding of E-HAP performed the coding harmonization. Because the sampling strategy (e.g., duration, technique) exerts a marked impact on airborne BaP and Pyr levels, only sampling strategies that may be directly comparable were included in the data analysis. To that end, only sampling using either an Amberlite XAD-2 resin cartridge, chromosorb-102, or polyurethane foam (PUF) to

collect gaseous PAHs and either fiber glass, polytetrafluoroethylene (PTFE), Teflon, quartz, or acrylic copolymer membrane filters to collect particulate PAHs were considered in data analysis.

#### ***PyrT/BaP ratio calculation***

PyrT/BaP ratios were calculated only when the ratio was not already reported in the publication. When absent or not reported, the PyrT/BaP ratio was calculated only if PyrT or both PyrP and PyrG levels were reported and if the statistics (e.g., geometric mean, median) used to report BaP and Pyr levels were the same in the paper. In addition, in cases where BaP and/or Pyr levels were inferior to the limit of detection/quantification, the PyrT/BaP

ratio was not calculated. Whenever possible, the distribution of the PyrT/BaP ratio was calculated using the reported distribution statistics, such as the number of samples, arithmetic mean, and arithmetic standard deviation in the case of a normal distribution. For lack of anything better, when it was not possible to recreate the distribution of PyrT/BaP ratios, an empirical rule to select a single PyrT/BaP ratio was utilized from the data reported. Because PAH levels often follow a lognormal distribution (Rappaport 1991), when possible, the use of the geometric mean (GM) over other statistics was prioritized. When GMs were not available, in priority, the median, arithmetic mean, and, at last resort, the  $(\text{minimum} + \text{maximum})/2$  ratio were used. Occupational contexts (sectors, processes, and activities) with less than 5 samples are presented but not discussed in this review.

### **Creation of an online tool – PAH HBM tool**

A free, user-friendly, and interactive web application named PAH HBM tool was created (<https://exporisk-timc.imag.fr/PAH/>) to make the inventory of PyrT/BaP ratios easy to retrieve, accessible, interoperable, and re-usable. This tool may facilitate and aid the wider implementation and calculation of BGVs as well as interpretation of 1-OHP values. More information regarding the PAH HBM tool is available in the supplemental information. Data analysis, all calculations, and the creation of the PAH HBM tool were performed with R software 4.1.2<sup>®</sup> (R Core Team, Vienna, Austria) for Windows 10<sup>®</sup>.

## **Results**

### **Characteristics of the included samples**

#### **Geographic scale/scope**

A total of 5619 samples from 19 countries were available, with 3406 (60.6%) that were extracted from the literature and 2213 (39.4%) from E-HAP. Amongst published data, most samples were collected in Finland ( $n = 1011$ , 29.9%), followed by Italy ( $n = 472$ , 13.9%), Germany ( $n = 421$ , 12.4%), Norway ( $n = 416$ , 12.2%), and Taiwan ( $n = 224$ , 6.58%) (Figure 1). Regarding E-HAP, most samples were from France ( $n =$

2193, 99.1%), and a few from Brazil ( $n = 20$ , 0.90%) (Figure 1).

#### **Time period**

Regarding data from the literature, the oldest study dates back to 1981 and pertains to aluminum production (Bjorseth, Bjorseth, and Fjeldstad 1981). Most papers were published since 2000 (81.3%), with 62.7% since 2005, 36% since 2010, and 16% since 2015 (Figure 2). Most samples were reported between 1995 and 2015 ( $n = 2991$ , 87.8%). Data from E-HAP were more recent, with only 5.2% of samples that were prior to 2005 and with most samples recorded between 2005 and 2019 ( $n = 1969$ , 89%).

#### **Occupational contexts**

There was a broad range of occupational contexts reported, with 15 sectors, 79 processes, and 213 activities (Figure 3). The sectors included: aluminum production; coke production; silicon production; aluminum, steel, and plastic foundries; manufacturing of carbon products; creosote application (railroad maintenance with the replacement of creosote-impregnated wood ties); catering; combustion processes (e.g., cement plant, firefighter, chimney sweeper, or food smoking); engine exhaust emissions; ink production and printing companies; use of tar and bitumen for roofing and road paving; silicon carbide production; tire and rubber production; use of lubricating oils; and waste management.

The diversity of occupational contexts was higher in E-HAP than in the literature. Most sectors were common between data from the literature and E-HAP, with only two sectors from E-HAP (silicon production and creosote application) that were not found in the literature. Regarding the processes, 27 (34%) were shared between both data sources, while 14 (18%) were only found in the literature, and 38 (48%) were only available in E-HAP. Regarding the activity, there were 33 (16%) activities that were found in both the literature and E-HAP, while 39 (18%) and 141 (67%) were exclusive to the literature and E-HAP, respectively.

#### **Sampling strategy**

For E-HAP, the sampling technique has remained the same since its inception, with the



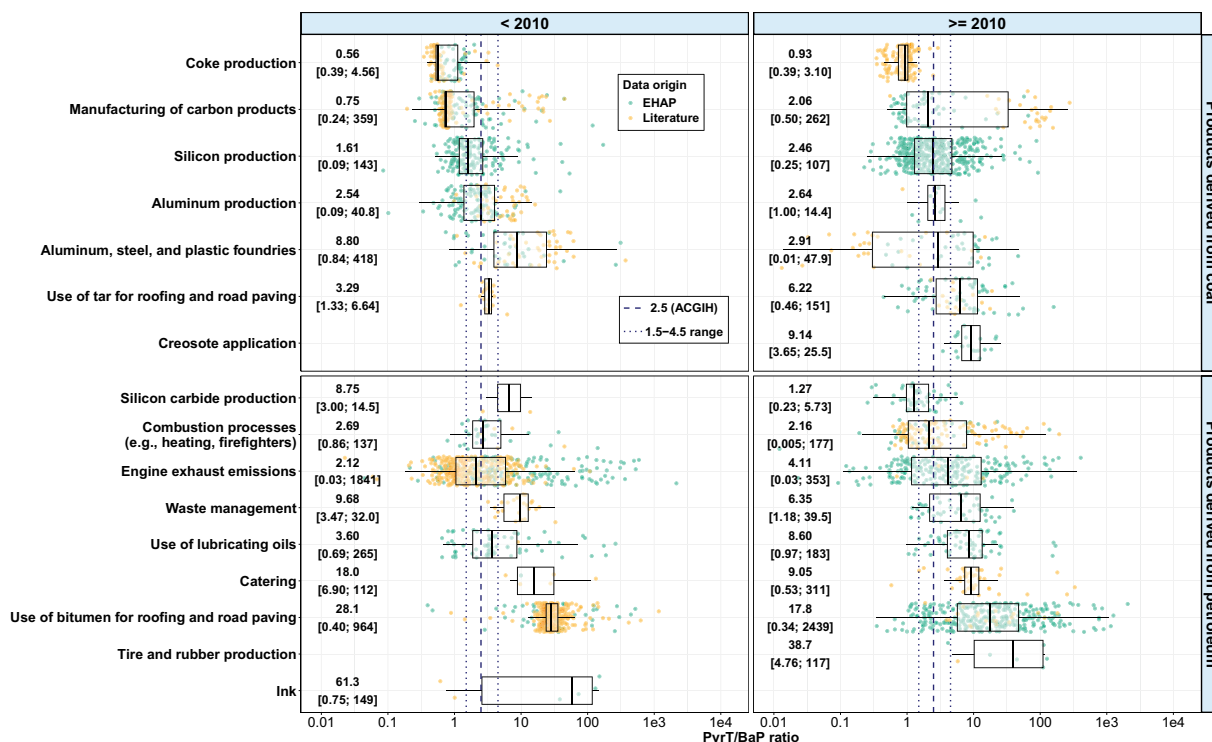


Figure 2. PyrT/BaP ratios at the sector scale depending on the sampling period Green points refer to data from E-HAP while yellow points refer to data from the literature.

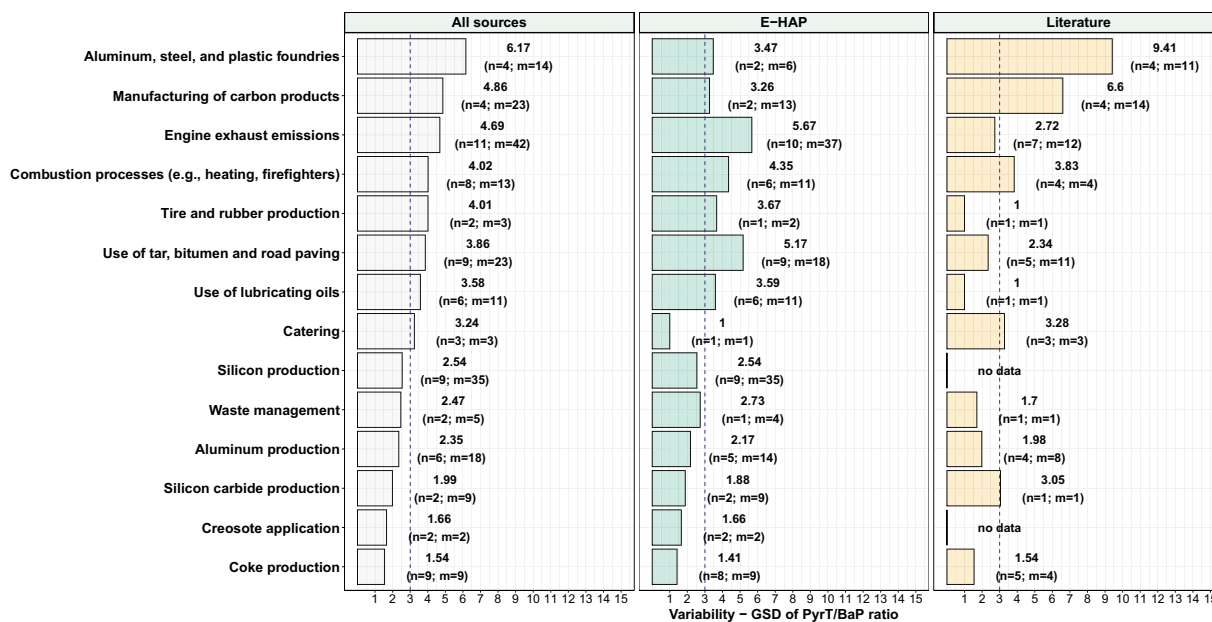
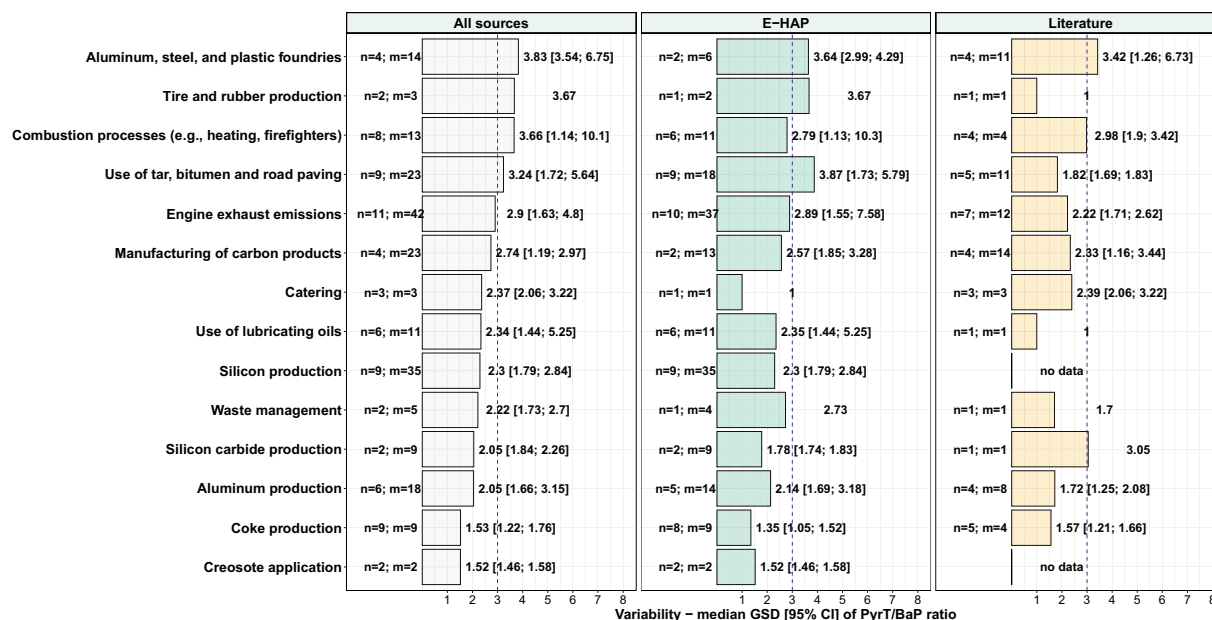


Figure 3. Comparison of the variability of PyrT/BaP ratios between sectors GSD: geometric standard deviation, n: number of processes within a sector, m: number of activities within a sector.

use of a combined aerosol-vapor sampler made of an Amberlite XAD-2 resin cartridge to trap gaseous PAHs and a 37-mm-diameter quartz filter to trap particulate PAHs (Maitre et al. 2018; Petit et al. 2017). Regarding data reported

in the literature, many sampling techniques were used (Figure 4). The most used technique to collect gaseous PAHs was the use of an Amberlite XAD-2 resin cartridge (91.6%), followed by chromosorb-102 (4.6%), polyurethane



**Figure 4.** Comparison of the PyrT/BaP ratio variability within sectors at the process level GSD: geometric standard deviation, n: number of processes within a sector, m: number of activities within a sector.

foam (3.7%), and bottles with ethanol or impinger with toluene (0.03%). The fiber glass membrane filter was the most employed sampling technique to collect particulate PAHs (58.6%), followed by polytetrafluoroethylene (PTFE) or Teflon membrane filter (33.7%), quartz filter (5.2%), and acrylic copolymer membrane filter (2.6%). The detailed information regarding the sampling strategies (e.g., year, location, duration, flow rate, device, limit of quantification/detection...) and other relevant information (if the workers were wearing a mask, the presence or not of collective protective equipment, if biomonitoring was conducted, and if dermal monitoring was conducted) is available and freely downloadable from the table provided in the “data source” tab on the PAH HBM tool.

### PAH levels reported

In most of the published samples (96.3%), BaP levels were reported (Figure 4), while PyrT levels were noted in 72.4% of them, PyrP and PyrG levels in 26.4%, and PyrT/BaP ratio in 5.87%, respectively. PAH levels or PyrT/BaP ratios were reported most of the time as arithmetic means ( $n = 34$ , 48%), followed by single values (35%), medians (34%), GMs (18%), and minimum and maximum ranges (11%) (Figure 5). For most cases

(72%), only single PyrT/BaP values could be used. Indeed, it was possible to generate PyrT/BaP distributions for only 20 studies (28%), which accounted for more than one-third of the published samples ( $n = 1292$ , 36%). There were 15 studies (21.1%) that did not report the number of samples.

### Descriptive analysis of PyrT/BaP ratios

#### Levels of PyrT/BaP ratios

PyrT/BaP ratios are presented in Figure 2 and Table 1 for all sectors, while PyrT/BaP ratios for all occupational contexts (sector, process, and activity) are provided in Table S2. The estimated BGV using the recommendations of ACGIH is also presented in Tables S1 and S2. The highest PyrT/BaP ratios were noted in ink (61.3 [0.75; 149]). The median PyrT/BaP ratio observed in ink was 1.6, 2.5, 6.7, 6.7, and 8.4-fold higher than the ratio from tire and rubber production, use of tar, bitumen and road paving, creosote application, catering, and waste management, respectively. It was also 10.0, 11.7, 12.7, 23.6, 24.1, 26.7, and more than 30-fold higher than the ratios detected in foundries, the use of lubricating oils, engine exhaust emissions, aluminum production, combustion processes, and other metallurgy sectors (e.g., coke production),

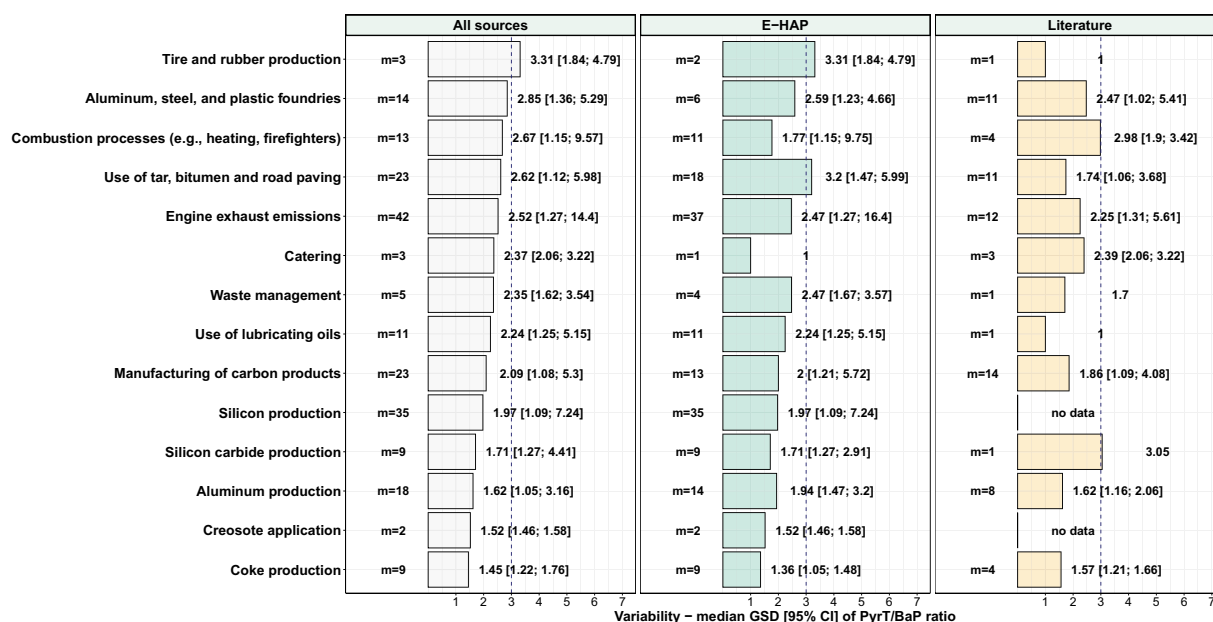


Figure 5. Comparison of the PyrT/BaP ratio variability within sectors at the activity level GSD: geometric standard deviation, m: number of activities within a sector.

Table 1. PyrT/BaP ratios for each sector.

| Sector   | Source      | Time period | Number of countries | n  | m  | Number of samples | Median [IQR] | min-max range | Estimated BGV (µg/L) |
|--|-------------|-------------|---------------------|----|----|-------------------|--------------|---------------|----------------------|
| Aluminum production                                | All sources | 1981–2016   | 5                   | 6  | 18 | 188               | 2.54 [2.56]  | [0.09; 40.8]  | 6.35 [0.23; 102]     |
|  | Literature  | 1981–2016   | 4                   | 4  | 8  | 64                | 5.50 [5.93]  | [0.98; 14.8]  | 13.8 [2.45; 37.0]    |
|  | E-HAP       | 2001–2010   | 1                   | 5  | 14 | 124               | 2.09 [1.66]  | [0.09; 40.8]  | 5.23 [0.23; 102]     |
| Aluminum, steel, and plastic foundries             | All sources | 1986–2021   | 5                   | 4  | 14 | 265               | 6.14 [16.2]  | [0.01; 418]   | 15.4 [0.03; 1045]    |
|  | Literature  | 1986–2012   | 4                   | 4  | 11 | 195               | 8.19 [22.7]  | [0.01; 418]   | 20.5 [0.03; 1045]    |
|  | E-HAP       | 2002–2021   | 1                   | 2  | 6  | 70                | 5.94 [8.42]  | [0.58; 276]   | 14.9 [1.45; 690]     |
| Catering   | All sources | 2003–2019   | 4                   | 3  | 3  | 44                | 9.09 [5.60]  | [0.53; 311]   | 22.7 [1.33; 778]     |
|  | Literature  | 2003–2019   | 3                   | 3  | 3  | 43                | 9.09 [6.53]  | [0.53; 311]   | 22.7 [1.33; 778]     |
| Coke production                                    | All sources | 1995–2020   | 8                   | 9  | 9  | 1144              | 0.87 [0.51]  | [0.39; 4.56]  | 2.18 [0.98; 11.4]    |
|  | Literature  | 1995–2020   | 7                   | 5  | 4  | 1099              | 0.85 [0.46]  | [0.39; 4.56]  | 2.13 [0.98; 11.4]    |
|  | E-HAP       | 2009        | 1                   | 8  | 9  | 45                | 1.10 [0.58]  | [0.51; 2.03]  | 2.75 [1.28; 5.08]    |
| Combustion processes (e.g., heating, firefighters) | All sources | 1992–2022   | 6                   | 8  | 13 | 206               | 2.31 [6.04]  | [0.005; 177]  | 5.78 [0.01; 443]     |
|  | Literature  | 1992–2022   | 5                   | 3  | 3  | 144               | 2.35 [8.74]  | [0.61; 177]   | 5.88 [1.53; 443]     |
|  | E-HAP       | 2003–2020   | 1                   | 6  | 11 | 62                | 2.16 [3.24]  | [0.005; 164]  | 5.40 [0.01; 410]     |
| Creosote application                               | All sources | 2018        | 1                   | 2  | 2  | 19                | 9.14 [5.91]  | [3.65; 25.5]  | 22.9 [9.13; 63.8]    |
|  | E-HAP       | 2018        | 1                   | 2  | 2  | 19                | 9.14 [5.91]  | [3.65; 25.5]  | 22.9 [9.13; 63.8]    |
| Engine exhaust emissions                           | All sources | 1997–2022   | 8                   | 11 | 42 | 1299              | 2.62 [5.61]  | [0.03; 1841]  | 6.55 [0.08; 4603]    |
|  | Literature  | 1997–2022   | 8                   | 6  | 12 | 868               | 1.42 [2.54]  | [0.03; 91.3]  | 3.55 [0.08; 228]     |
|  | E-HAP       | 2002–2021   | 1                   | 10 | 37 | 431               | 4.29 [13.8]  | [0.03; 1841]  | 10.7 [0.08; 4603]    |
| Manufacturing of carbon products                   | All sources | 1995–2021   | 6                   | 4  | 23 | 642               | 1.05 [2.56]  | [0.24; 359]   | 2.63 [0.60; 898]     |
|  | Literature  | 1995–2020   | 6                   | 4  | 14 | 503               | 0.74 [11.4]  | [0.24; 262]   | 1.85 [0.60; 157]     |
|  | E-HAP       | 2008–2021   | 1                   | 2  | 13 | 139               | 1.41 [1.57]  | [0.30; 359]   | 3.53 [0.75; 898]     |
| Silicon carbide production                         | All sources | 1987–2021   | 3                   | 2  | 9  | 72                | 1.30 [1.21]  | [0.23; 14.5]  | 3.25 [0.58; 36.3]    |
|  | E-HAP       | 2014–2021   | 2                   | 2  | 9  | 70                | 1.25 [1.20]  | [0.23; 5.73]  | 3.13 [0.58; 14.3]    |
| Silicon production                                 | All sources | 2005–2021   | 1                   | 9  | 35 | 629               | 2.04 [2.76]  | [0.09; 143]   | 5.10 [0.23; 358]     |
|  | E-HAP       | 2005–2021   | 1                   | 9  | 35 | 629               | 2.04 [2.76]  | [0.09; 143]   | 5.10 [0.23; 358]     |
| Tire and rubber production                         | All sources | 2016–2017   | 2                   | 2  | 3  | 7                 | 38.7 [98.7]  | [4.76; 117]   | 96.8 [11.9; 293]     |
|  | E-HAP       | 2017        | 1                   | 1  | 2  | 6                 | 71.8 [90.3]  | [4.76; 117]   | 96.8 [11.9; 293]     |
| Use of lubricating oils                            | All sources | 2003–2021   | 2                   | 6  | 11 | 130               | 5.24 [8.71]  | [0.69; 265]   | 13.1 [1.73; 663]     |
|  | E-HAP       | 2003–2021   | 1                   | 6  | 11 | 129               | 5.19 [8.90]  | [0.69; 265]   | 13.1 [1.73; 663]     |
| Use of tar, bitumen and road paving                | All sources | 1989–2022   | 10                  | 9  | 23 | 1216              | 24.7 [26.4]  | [0.35; 2439]  | 61.8 [0.88; 6098]    |
|  | Literature  | 1989–2022   | 9                   | 5  | 11 | 779               | 26.6 [11.9]  | [1.00; 964]   | 66.5 [2.50; 2410]    |
|  | E-HAP       | 2004–2021   | 1                   | 9  | 18 | 437               | 14.2 [35.3]  | [0.35; 2439]  | 35.5 [0.88; 6098]    |
| Waste management                                   | All sources | 2001–2017   | 1                   | 2  | 5  | 78                | 7.26 [9.44]  | [1.18; 39.5]  | 18.2 [2.95; 98.8]    |
|  | Literature  | 2001        | 1                   | 1  | 1  | 31                | 9.68 [7.27]  | [3.47; 32.0]  | 24.2 [8.68; 80.0]    |
|  | E-HAP       | 2017        | 1                   | 1  | 4  | 47                | 6.35 [10.4]  | [1.18; 39.5]  | 15.9 [2.95; 98.8]    |

BGV: biological guidance value, IQR: interquartile range, n: number of processes within the considered sectors, m: number of activities within the considered sector.

respectively. Median PyrT/BaP ratios cited in the literature were similar to those of E-HAP, being respectively only 2.6, 1.9, 1.5, 1.4, and 1.2-fold higher than the median ratio of E-HAP for aluminum production, use of tar, bitumen and road paving, waste management, foundries, and combustion processes, respectively (Table 1). In contrast, the median PyrT/BaP ratios found in the literature were 1.3, 1.9, and 3-fold lower than those of E-HAP for coke production, manufacturing of carbon products, and engine exhaust emissions, respectively. In several sectors (coke production, manufacturing of carbon products, engine exhaust emissions), PyrT/BaP ratios appeared to have increased over time (Figure 2).

Most PyrT/BaP ratios were not within the 1.5–4.5 range (Figure.S6–S8), including aluminum production (51.2% of the samples within the 1.5–4.5 range), silicon production (43.1%), and silicon carbide production (37%). In contrast, sectors with less than 20% samples within the 1.5–4.5 range were manufacturing of carbon products (17.9%), foundries (14.8%), use of tar, bitumen and road paving (12.9%), creosote application (5.3%), coke production (5.1%), catering (4.2%), ink, and tire and rubber production (not detected).

### Variability of PyrT/BaP ratios

The variability of PyrT/BaP ratios was dependent upon the sector, with a geometric standard deviation (GSD) ranging from 1.5 for coke production to 6.17 for aluminum, steel and plastic foundries (Figure 3). Sector variability was usually higher for data from E-HAP compared to published data, with the exception of manufacturing of carbon products, foundries, and coke production.

Regarding the processes (second level of description of the occupational context) within each sector (Table S2), the PyrT/BaP ratios were less variable than at the sector scale, with median GSDs ranging from 1.52 for creosote application to 3.83 for foundries (Figure 4). PyrT/BaP ratios were more variable for E-HAP than in the literature, with the exception of coke production and combustion processes. For E-HAP, there were 21 processes (32.3%) with a GSD > 3, and 3 (4.6%) with a GSD ≥ 6. Processes with the highest PyrT/BaP ratio variability were aluminum oxide production in the combustion processes (GSD = 11.1), followed by engine

exhaust emissions from highways (GSD = 8.34), grease welding during the use of lubricating oils (GSD = 5.36), vehicle drivers (GSD = 4.95), and application of hot bitumen on roads (GSD = 4.8). For data from the literature, there were 7 processes (17.9%) with a GSD > 3, and 1 (2.6%) with a GSD ≥ 6. The processes with the highest PyrT/BaP ratio variability were miscellaneous foundries (GSD = 6.98), followed by plastics processes (GSD = 3.71), manufacturing of fiber tubes (GSD = 3.51), firefighters (GSD = 3.44), miscellaneous catering (GSD = 3.27), and steelworks (GSD = 3.14).

Regarding the activities (third and most descriptive level of the occupational context) within each sector (Table S2), the PyrT/BaP ratios were clearly found to be less variable than at the sector and process description level scales, with median GSDs ranging from 1.39 for ink to 3.31 for tire and rubber production (Figure 5). PyrT/BaP ratios were more variable for E-HAP than in the literature, with the exception of coke production. For E-HAP, there were 42 activities (24.1%) with a GSD > 3, and 7 (4%) with a GSD ≥ 6. The activities with the highest PyrT/BaP ratio variability were garbage collector drivers (GSD = 20.1), highway administrative personnel (GSD = 15.8), highway services and technicians (GSD = 7.02), mechanics working on light vehicles with diesel engines (GSD = 7.25), heat attendant masons fixing burners in the silicon production (GSD = 14.2), and furnace reconstruction in the aluminum oxide production (GSD = 11.1). For data from the literature, there were 8 activities (11.1%) with a GSD > 3, and 1 (1.4%) with a GSD ≥ 6. The activities with the highest PyrT/BaP ratio variability were building site machinery drivers (GSD = 6.14), press activities in the plastics processes (GSD = 4.43), miscellaneous activities during the firebrick production (GSD = 4.28), tar applications during road paving (GSD = 4.00), and outside interventions or exercise activities for firefighters (GSD = 3.44).

### Discussion

This review provides a detailed picture of the PAH industrial landscape and emission profiles over the last 40 years. Having a track record of PyrT/BaP ratios is paramount for occupational physicians, industrial

hygienists, and decision-makers because the composition of the mixture influences its toxicity. To the best of our knowledge, there is currently no available review providing a comprehensive compilation of existing PyrT/BaP ratios in occupational settings, consolidated in a single resource that might support PAH biomonitoring and risk assessment. In addition, only 7 of the published papers provided PyrT/BaP ratios, which emphasizes the usefulness of this work.

### **Remarks regarding retrieved data**

Published data were found to be heterogeneous in nature. The study designs, sampling strategies, statistics, and information reported were not harmonized between investigations. For instance, 39% of published papers did not report PyrG levels, although urinary 1-OHP is highly influenced by and correlated with PyrG (Barbeau et al. 2015). The Pyr nature (gaseous, particulate, or total) was rarely provided and had to be deduced from the sampling strategies. However, occasionally the sampling strategies were not sufficiently descriptive to determine the Pyr nature. To lessen this bias, sampling strategies that may not be directly comparable were not included in the data analysis.

One of the major shortcomings of the literature data was that from one paper to another, the statistics used (e.g., GSD, arithmetic mean) to report PAH levels and ratios were different. In addition, for many published papers, the number of samples, the number of missing data, and the limit of quantification were not provided. When the sample size was not provided, we assumed that it was a single value, which might not always be the case. Because of the heterogeneity of available data, different statistics were used to analyze the published data, which is not ideal. Therefore, data from published literature should be carefully considered. Regarding E-HAP, there was no problem with the data since the authors own E-HAP and because the sampling strategies of E-HAP have been the same since its inception (Maitre et al. 2018; Petit et al. 2017).

The occupational context reported in published papers was heterogeneous and predominantly not based upon international classifications. Defining the occupational context in terms of SEGs is critical for inferential analysis and essential to understanding

exposure variability (Lippmann, Gomez, and Rawls 1996; Loomis and Kromhout 2004). However, the construction of SEGs for a given pollutant might turn out to be rather challenging because of the multifactorial variability of exposures either between or within industries (Petit et al. 2017). Coding systems are essential to store and classify data, especially in databases where existing structures and broad characteristics of the workplace (job title, work location, process, or engineering controls) are generally used to code exposure and more specifically SEGs (Burdorf and van Tongeren 2003; Symanski, Maberti, and Chan 2006). Standard coding systems, such as ISCO (International Standard Classification of Occupations), NAICS (North American Industry Classification System), or NACE (Statistical Classification of Economic Activities in the European Community) (Mannetje and Kromhout 2003), are based upon general categories such as job titles and are therefore too generic and not directly related to both the worker's tasks and emission sources (Marquart et al. 2011; Petit et al. 2017). Marquart et al. (2011) proposed a classification based upon determinants of emission, while others employed different grouping strategies, such as combining sources of information like job titles, occupation, and factory (Koh et al. 2015; Lee et al. 2015). However, information recorded regarding workers and workplaces might not always be compatible with such coding systems (Koeman et al. 2013). In addition, when using clerical coding, it is rather complicated and time-consuming to use the information recorded to find the most relevant or best-corresponding occupation and industry described in the standard coding systems (Patel et al. 2012; Russ et al. 2014). It was decided to select harmonization in the occupational context based upon classification used for E-HAP to facilitate comparison and be more accurate. To lessen a potential classification bias, the individual in charge of the coding of E-HAP (AM) translated the occupational context into E-HAP codes of three levels of description (sector, process, and activity). In addition, this three-level coding system was found to offer a high degree of accuracy in a previous study (Petit et al. 2017). Nonetheless, the original terms employed in the published papers were kept and are available on the PAH HBM tool.

## Results interpretation

The results of this review reflect PAH emissions from many sectors in 19 countries over more than 40 years, making these data unique and valuable. These large industrial processes and temporal periods examined might explain the large variability of PyrT/BaP ratios encountered. Indeed, there are many factors that might differ between countries and over time, such as industrial hygiene measures and/or the use of different and evolving processes and practices. For example, in French aluminum production, there was a change of process in the 1990's in France with the use of prebaked electrodes instead of Soderberg electrodes (Hopf, Carreón, and Talaska 2009; Maître et al. 2018). Since 2015, seals used during the electrolysis furnace repairs do not contain PAHs anymore, which led to the cessation of PAH occupational exposure surveillance in the French aluminum production (Allard, Tawfik, and Kumar 2016). In road paving, changes in raw material composition (no more coal tar) and temperature of application (decrease) have also occurred (Cavallari et al. 2012; Germin-Aizac et al. 2023), while vehicle engines and vehicle fuel also evolved. The introduction of new standards, legislation and/or reductions in emissions sources might also lead to decreasing exposures and changes in PAH mixture composition (Creely et al. 2007). In addition, the diversity of activities, processes, and jobs by sector is high, with, for instance, the combustion process sector including firefighters, incinerators, heating system maintenance, electrocautery surgery, and chimney sweepers. This might explain why the variability of PyrT/BaP ratios was often higher in E-HAP than those from published data because the number of occupational contexts within each sector and process is higher in E-HAP than in published data. It should be noted that the variability of published data is smaller than it should be in reality (underestimation) because for most studies ( $n = 51$ , 72%) only single values (e.g., mean, median) were used. Indeed, because of missing information (e.g., type of distribution, distribution parameters, number of samples), it was most of the time not possible to generate/recreate the distribution reported in order to reflect as accurately as possible the true variability of published results. The magnitude of

this underestimation is, however, impossible to determine. This might explain why the variability of PyrT/BaP ratios was most of the time smaller in the literature than for E-HAP, even though published data was more heterogeneous in nature with results from various countries, time periods, or sampling strategies. Results from literature data need to therefore be interpreted carefully.

Only long-term sampling for PyrT/BaP ratios needs to be used to assess chronic health risks because urinary 1-OHP is correlated with averaged airborne PAH levels (Barbeau et al. 2015). As previously shown, PyrT/BaP ratios were highly variable in many occupational groups (Jongeneelen 2014; Valière et al. 2022). This variability arises predominantly from the aforementioned statements and the fact that the composition of PAH mixtures varies considerably across different occupational contexts. Only 6 sectors out of 15 had a GSD < 3. Hence, it is better to focus on the most descriptive level of description available. All sectors utilizing products derived from petroleum had a PyrT/BaP ratio that was most usually above the value of 2.5 proposed by ACGIH (2020), with the exception of combustion processes and silicon carbide production. Regarding sectors using products derived from coal, these were usually under the value of 2.5 proposed by ACGIH, with the exception of creosote application, foundries, and the use of tar, bitumen and road paving. Jongeneelen (2014) recommended adjusting urinary 1-OHP levels when the PyrT/BaP ratio lies in the 1.5–4.5 range and not adjusting otherwise. All sectors were noted to exhibit values outside this range, with between 0 and 55% of the ratios within this range. In contrast to what Jongeneelen (2014) recommended, it is postulated that urinary 1-OHP levels needs to be adjusted, regardless of the PyrT/BaP ratio, as long as BaP levels are detectable (>limit of quantification) for accurate calculation.

Given the variability of PyrT/BaP ratios, a single PyrT/BaP value cannot apply to all workplaces. It also raises the question of the relevance of defining an indicative BGV for 1-OHP in sectors where the PyrT/BaP ratio variability is high. It may be possible for creosote application, coke production, silicon carbide production,

aluminum production, and waste management since the PyrT/BaP ratio variability was relatively low (GSD <3). It seems better to focus on the most descriptive occupational context possible since the variability of PyrT/BaP ratios was the smallest for activities. However, for some sectors, the use of additional levels of description of the occupational context might be necessary because the variability of the PyrT/BaP ratio remained high, in particular for specific activities involved in combustion processes, engine exhaust emissions, and the manufacturing of carbon products. These additional levels of description might be based upon the country, time period, presence or absence of collective protection measures, or on a more accurate description (subdivision) of the working tasks (Petit et al. 2017).

Alternatively, the use of BaP biomonitoring data may also be relevant to precisely assess internal exposures to carcinogenic BaP and related adverse health risks. However, the main BaP metabolite (3-OHBaP) is generally found at low concentrations in urine (below 1 ng/L), making it challenging to accurately measure it (Barbeau, Maître, and Marques 2011, 2015). Barbeau et al (2018). also identified another promising biomarker, namely trans-anti-7,8,9,10-tetrahydroxy-7,8,9,10-tetrahydrobenzo[a]pyrene (TetraolBaP), reflecting the carcinogenic pathway of BaP metabolism. Both biomarkers request either sophisticated pre-analytical (automated solid-phase extraction) or analytical methods (mass tandem spectrometry), precluding their systematic use in occupational settings.

Recently, several investigators questioned the relevance of 1-OHP for PAH HBM and suggested using a combination of several metabolites instead of 1-OHP alone for more comprehensively assessing PAH exposure across multiple sources (Barros, Oliveira, and Morais 2023; Oliveira et al. 2016; Paiva et al. 2024). However, there is not yet a consensus regarding which PAH metabolites to include for this new proposed strategy, which also does not take into account any BaP metabolites resulting from the toxification pathway of BaP metabolism, such as TetraolBaP. In addition, to our knowledge, no guidelines exist for interpreting this new strategy, and there is no BGV based upon the combination of multiple PAH metabolites to

date. Consequently, it is advocated for continuous use of urinary 1-OHP adjusted by airborne PyrT/BaP for PAH HBM until a more reliable biomarker that better captures and reflects carcinogenic exposure to PAHs is found. Using dedicated 1-OHP BGVs based upon specific PyrT/BaP ratios may indirectly help to identify exposures that may result in genotoxic effects and thus help to prevent cancer risks.

### **Limitations of this work**

While a comprehensive literature search was conducted, the search was not exhaustive or completely systematic. Indeed, the literature search was conducted using only one source (PubMed). To conduct a more comprehensive and systematic work, other bibliographic databases such as Web of Science, Scopus, Google Scholar or Dimensions may have been used.

Because the analyzed data were heterogeneous, an empirical approach needed to be applied to select PyrT/BaP ratios using different statistics, which is far from optimal and limits the comparability of PyrT/BaP ratios. Ideally, it would have been best to randomly generate ratios using distribution parameters, which it was possible to do for only 37% of published samples. Findings therefore need to be considered with caution.

### **PAH HBM tool**

The created PAH HBM tool may be used as a job exposure matrix for PyrT/BaP ratios. It is not a classical job exposure matrix because it describes activities within processes and sectors instead of job titles. Hence, it is more of a task- or activity-specific exposure matrix. This tool also enables the user to calculate an indicative BGV based upon the recommendations of ACGIH and a defined exposure scenario, as well as the probability of exceeding this BGV. Hence, the PAH HBM tool might provide consistency and support direct comparisons between studies and countries to help in the establishment of appropriate safe PAH guidelines. Because of a lack of knowledge from occupational physicians regarding HBM in occupational settings due to the absence of BLV (Fréry and El Yamani

2020), the PAH HBM tool may be useful for educational and empowerment purposes (e.g., training courses for occupational physicians) and for promoting HBM regarding occupational exposure to PAHs.

### **Practical recommendations**

#### **Data reporting**

This review highlights the need for harmonized data to ensure both comparability and reproducibility.

Hence, it is advocated for standardization of investigations to make published data more homogeneous in the future. To that end, the following recommendations are proposed for future PAH exposure studies:

- A full description of the occupational context, with a detailed description of the tasks performed, duration of the tasks, the exposure routes, and the RPE worn.
- A detailed description of the exposure/emission sources.
- A detailed description of the chemicals analyzed along with their physical nature (e.g., particulate, gaseous form) and their names according to international nomenclatures (e.g., CAS number).
- A full description of the sampling strategy, with a detailed description of the sampling technique (e.g., Teflon membrane filter for particulate PAHs), sampling time, sampling volume, and sampling flow rate.
- A detailed description of the analytical technique(s) used to detect and quantify the chemicals (e.g., high-pressure liquid chromatography coupled with fluorescence detection following solvent extraction), along with the limits of detection/quantification.
- The reporting of the number of samples along with the number of missing values and, if relevant, the technique used to account for missing data.
- The reporting of quantitative data using the International System of Quantities.
- The reporting of concentrations of all pollutants using the same statistics (e.g., geometric mean).

- The reporting of all distribution parameters, with for instance both arithmetic mean and arithmetic standard deviation for normal distribution, GM and GSD for lognormal distribution, or lambda for Poisson distribution.

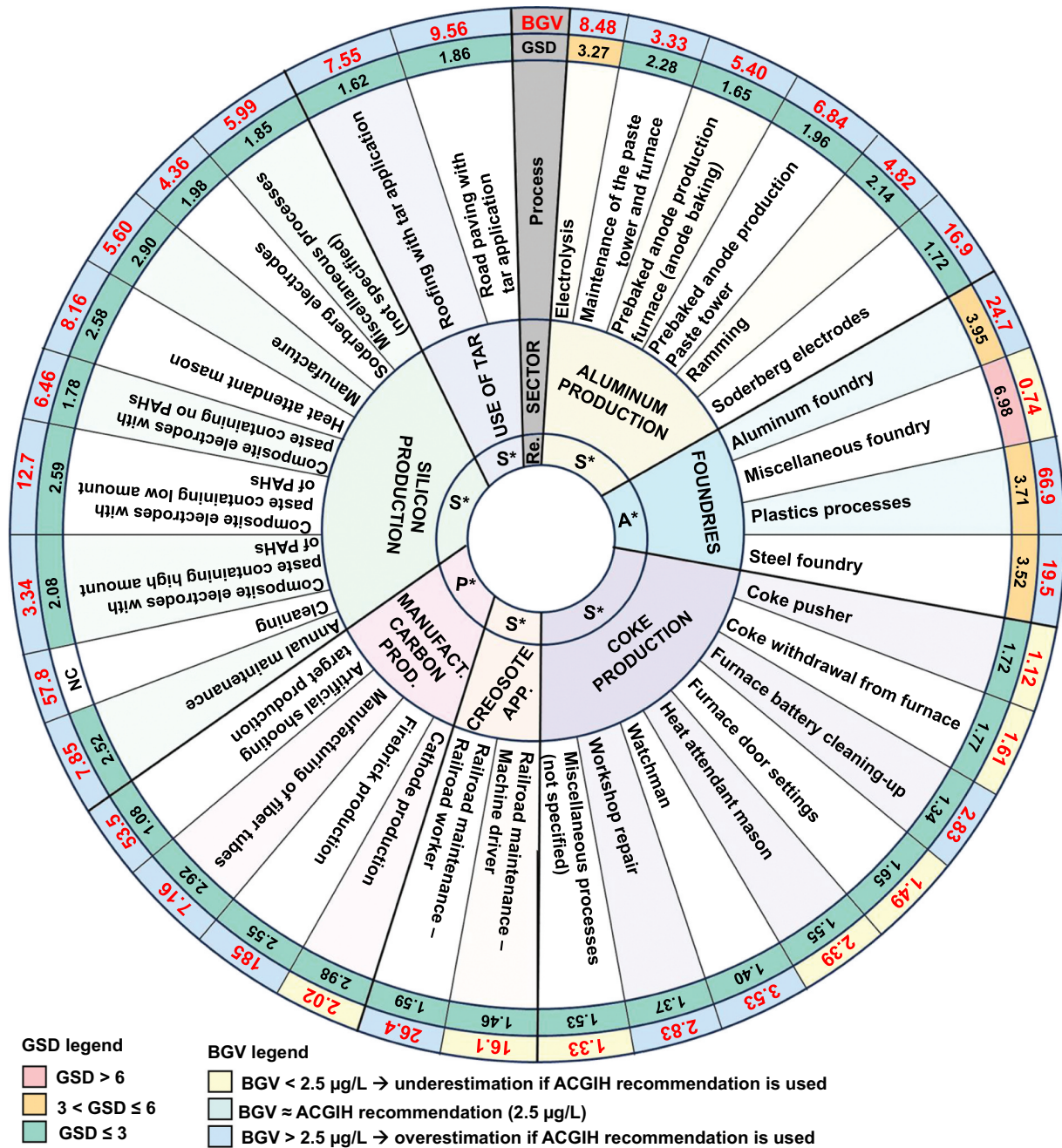
These data should also be accompanied by ancillary information that is relevant for an accurate exposure and risk assessment. These recommendations are not only valid for PAHs but can be applied to any pollutants when reporting data, regardless of the media considered.

#### **Interpretation of 1-OHP urinary levels**

Improving the interpretation of 1-OHP is of critical importance to better quantify PAH exposure and take into account the variability of PAH mixtures. By more accurately interpreting 1-OHP levels, high-risk groups with elevated PAH exposure, such as specific occupational groups (e.g., coke oven workers, firefighters), might be identified. The effectiveness of exposure reduction strategies (e.g., emission controls) might also be more precisely assessed over time. This would potentially enable targeted interventions and exposure reduction measures for these vulnerable groups. Improved 1-OHP interpretation might also facilitate early detection and prevention of PAH-related adverse health effects (e.g., genotoxic effects resulting from PAH exposure such as sister chromatid exchange, micronucleus aberrations, or chromosomal aberrations), ultimately contributing to a decrease in the incidence of these adverse health effects.

It is recommended using the PyrT/BaP ratio (and its associated 95% confidence interval) in the closest and most descriptive occupational context available (Table S2). However, for the sake of simplification, one might use only the median of the PyrT/BaP ratio instead of the distribution. To this end and in order to help 1-OHP interpretation, the following frame is proposed based upon the GSD of the PyrT/BaP ratio and industrial sector (see [Figures 6 and 7](#) for sectors using products derived from coal tar pitch and petroleum, respectively). For sectors using products resulting from coal tar pitch, the recommended BGV might be employed at the sector level owing to the small variability of PyrT/BaP ratios, except for “manufacturing of carbon products,” for which it is recommended using

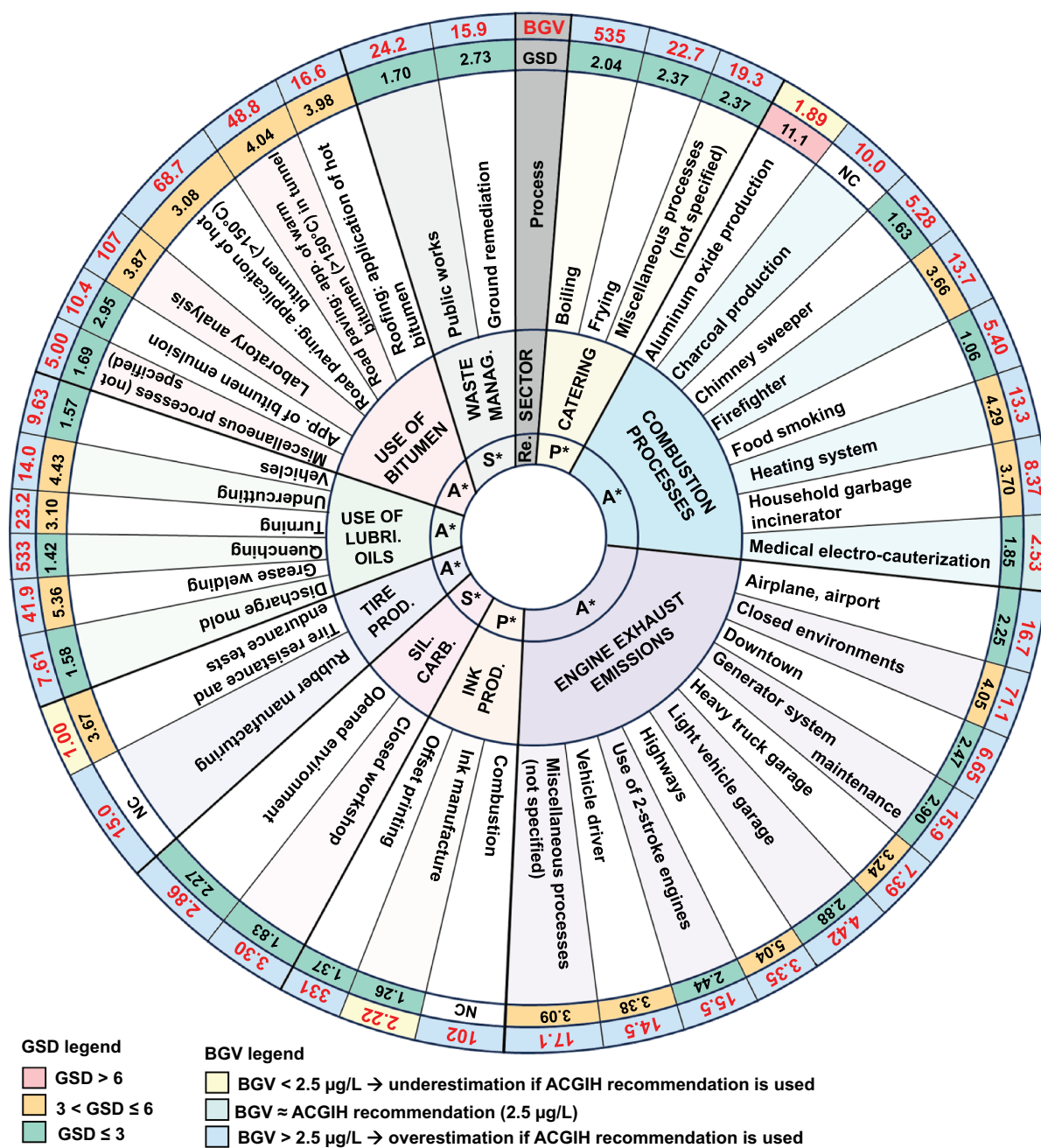




**Figure 6.** BGV recommendation for sectors using products derived from coal. **A\***: recommendation to use the BGV at the activity scale, app.: application, BGV: median biological guidance value expressed in µg/L, GSD: geometric standard deviation of the PyrT/BaP ratio, manufact.: manufacturing, NC: not calculated, P\*: we recommend to use the BGV at the process scale, prod.: production, Re.: recommendation, S\*: we recommend to use the BGV at the sector scale.

the BGV at the process scale, and “foundries” at the activity scale. In industrial sectors using products derived from petroleum or petroleum coke, the recommended BGV need to be used at the activity scale owing to the much larger variability of PyrT/BaP ratios, with the exception of “waste management” and “silicon carbide production” (sector scale), “ink production,” “printing companies,”

and “catering” (process scale). This study may help apply the ACGIH 1-OHP-adjusted BGV that has been so challenging to comply with until now, owing to the regular absence of available PyrT/BaP ratios in field studies. The PAH HBM tool could facilitate the systematic use of PyrT/BaP ratios in occupational settings by automatically calculating the BGV according to the occupational context and



**Figure 7.** BGV recommendation for sectors using products derived from petroleum. **A\***: we recommend to use the BGV at the activity scale, app.: application, BGV: median biological guidance value expressed in µg/L, GSD: geometric standard deviation of the PyrT/BaP ratio, lubri.: lubricating, manag.: management, NC: not calculated, P\*: we recommend to use the BGV at the process scale, Re.: recommendation, S\*: we recommend to use the BGV at the sector scale, Sil. Carb.: silicon carbide production.

other parameters/information specified by the user.

### Future perspectives

BaP may not be the only appropriate indicator of exposure to PAHs (Aquilina and Harrison 2023; Louro et al. 2022), even though it is often used as

a marker for airborne PAH exposure, in particular for cancer risk assessment (Aquilina and Harrison 2023; Louro et al. 2022). The BaP toxic equivalent concentration (BaP<sub>eq</sub>) is also used to try to take into account total carcinogenic potency arising from the whole PAH mixture (Aquilina and Harrison 2023). In this approach, the concentration of a given carcinogenic congener is expressed

as a BaP equivalent concentration using a toxic equivalent factor (TEF) that utilizes BaP as a reference compound to adjust its original concentration depending upon toxicity differences between both congeners (Haber et al. 2022). BaP<sub>eq</sub> corresponds to the sum of the BaP level and of all congener BaP equivalent concentrations. One possible perspective from this investigation might be to collect BaP<sub>eq</sub> from published literature and calculate PyrT/BaP<sub>eq</sub> ratios. However, depending upon the study, the TEFs and PAHs used for the calculation of BaP<sub>eq</sub> vary highly (Aquilina and Harrison 2023; Dreij et al. 2017; Jarvis et al. 2014; Maître et al. 2018; Samburova, Zielinska, and Khlystov 2017). In addition, the use of TEFs is highly debated (Aquilina and Harrison 2023; Haber et al. 2022), and utilization of BaP<sub>eq</sub> which assumes additivity of PAH congener toxicities is seldom reported in experimental studies (El Hajjar et al. 2023; Genies et al. 2016; Jarvis et al. 2014). Alternative solutions might be considered, such as the use of mixture exposure functions (Aquilina and Harrison 2023).

Urinary 1-OHP is hardly influenced by confounding factors, such as smoking and other environmental sources (Persoons et al. 2020). Biomonitoring results are correlated with airborne levels of parent PAHs when no respiratory protection (RPE) is worn by workers (Louro et al. 2022; Unwin et al. 2006). RPE efficiency is highly variable and depends mostly upon how these are used, stored, and replaced by the workers (Chen, Yang, and Lin 2012). To take into account the efficiency of RPE worn by workers, airborne PAH levels used to calculate PyrT/BaP ratios may be weighted by an assigned protection factor (Crawford et al. 2014; Unwin et al. 2006; Valière et al. 2022). The possibility of taking RPE into account has been implemented in the PAH HBM tool, with a table listing the assigned protection factors of 80 RPEs found in the literature for several countries.

In some occupational settings, PAHs may be absorbed through the skin (Louro et al. 2022; Valière et al. 2022). When skin exposure occurs, the use of airborne PyrT/BaP ratios may not be relevant or enough to properly interpret urinary 1-OHP levels (Valière et al. 2022). Thus, alternative solutions are required, such as the use of dermal PyrT/BaP ratios or a combination of both airborne

and dermal PyrT/BaP ratios, as well as regular use of biomonitoring.

With the growing use of job exposure matrices for the assessment of occupational exposures, the ability to translate a set of coded occupations and industries into other systems becomes critical (Rémen et al. 2018). Therefore, a perspective from this investigation might be to add international coding systems to the PAH HBM tool to facilitate its use.

## Conclusion

Given the complexity of industrial emissions and high variability of PAHs content, the inventory of PyrT/BaP ratios according to industrial activities is assumed to be a useful resource for occupational physicians and industrial hygienists to help their interpretation of PAH biomonitoring studies based upon urinary 1-OHP. The current investigation summarizes 40 years of data from almost 20 countries and presents the diversity and evolution of PAH emissions. A user-friendly frame for 1-OHP BGV was proposed as well as a HBM interpretation tool. The inventory and its website remain open for new entries, and a more global coverage might certainly be preferable to support the broader objectives to support PAH human health risk assessment, which might help promote collaborative and harmonized research in this area. Our presented review offers a practical approach for systematic PAH exposure and risk assessment, with a simple frame to follow based upon occupational context and the most frequently used biomonitoring approach (1-OHP monitoring).

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## Data availability statement

The data that supports the findings of this study is openly available on the PAH HBM tool at <https://exporisk-timc.imag.fr/PAH/>. Further information is available from the corresponding author upon request.

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## Supplemental information

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
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19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30

### Title

Review of environmental airborne Pyrene/Benzo[a]pyrene levels from industrial emissions for the improvement of 1-hydroxypyrene biomonitoring interpretation

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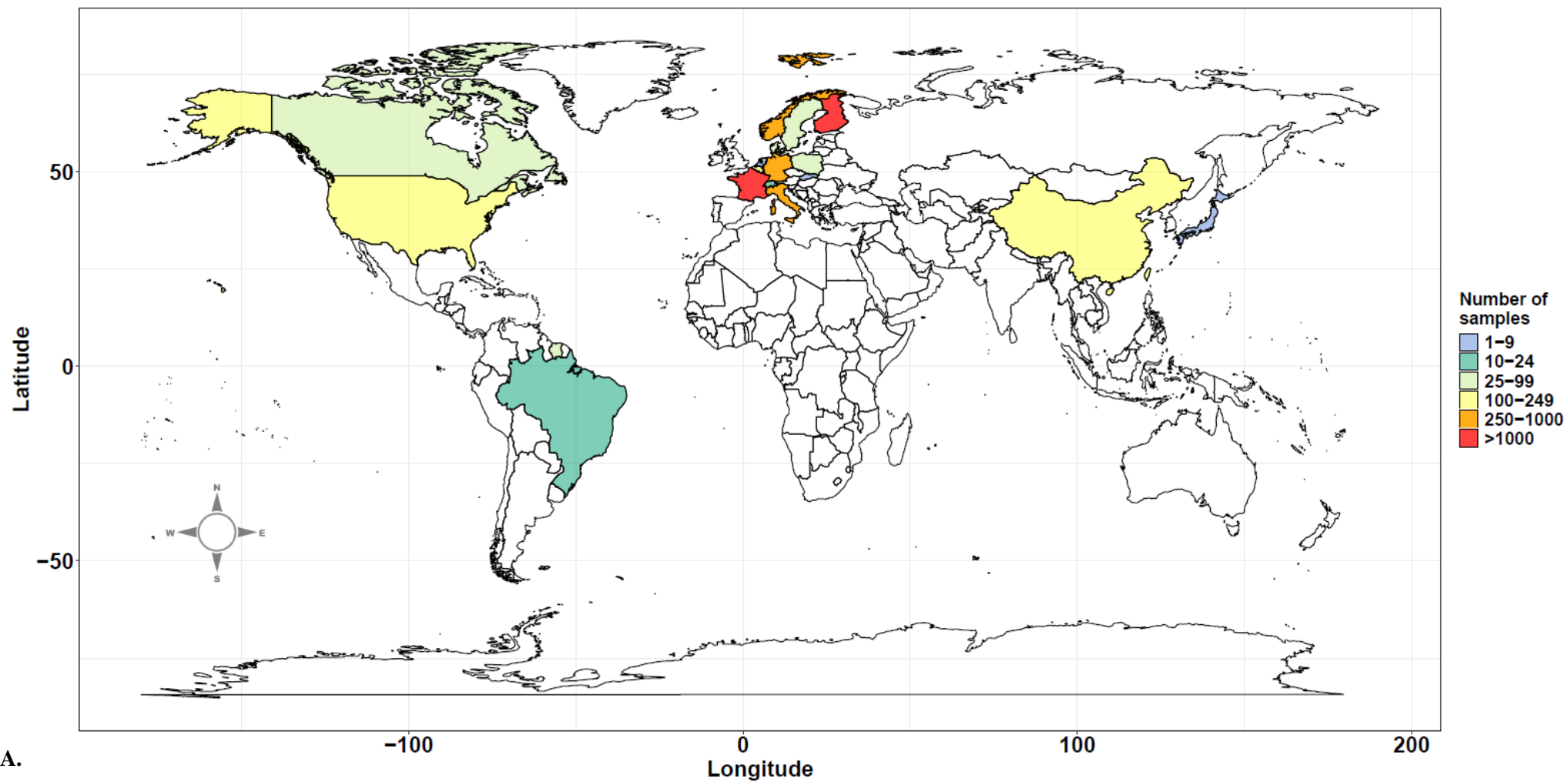
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### Table of content

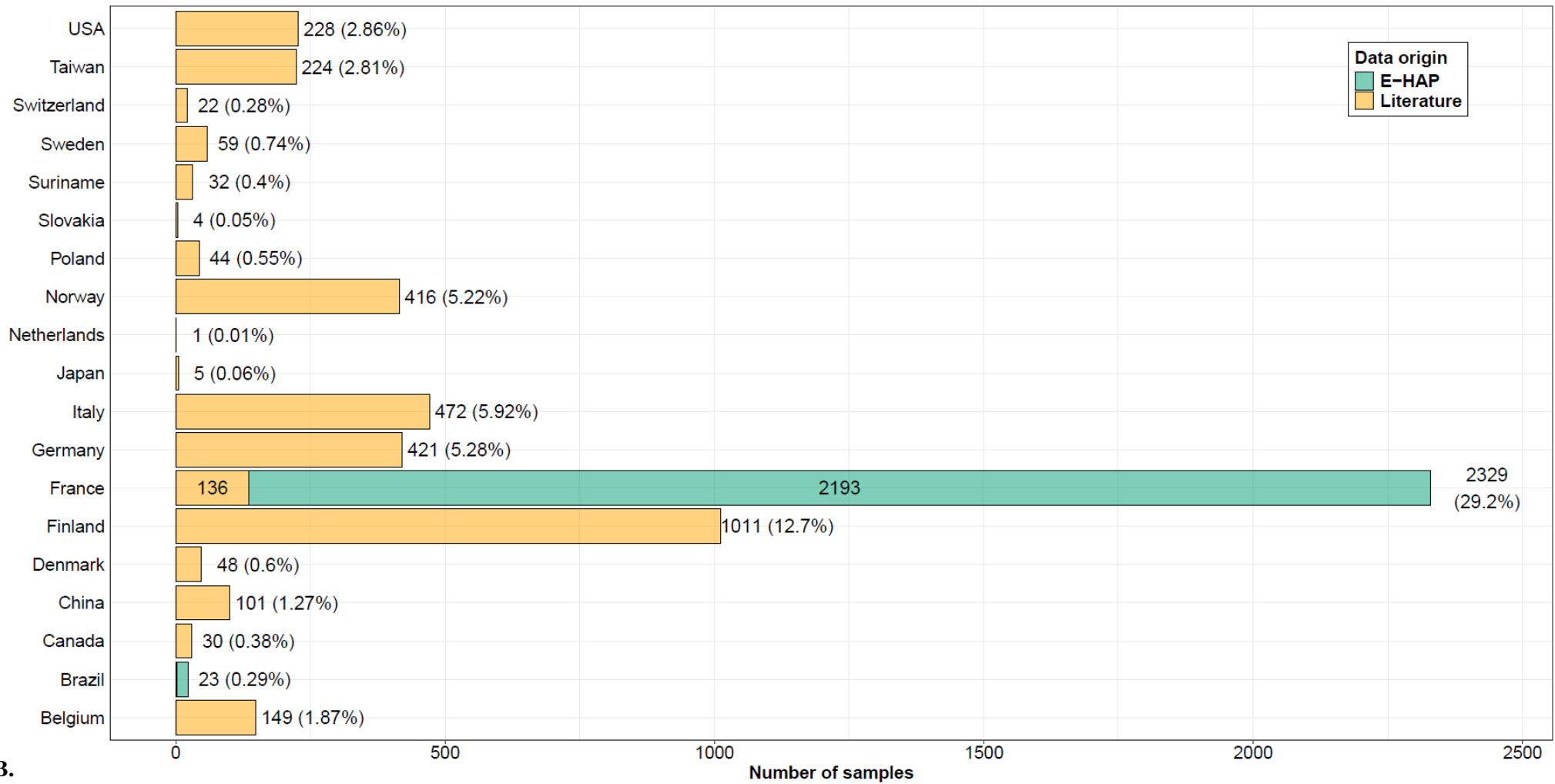
|   |    |
|---|----|
| <b>Fig.S1</b> Number of samples per country.....  | 4  |
| <b>Fig.S2</b> Number of studies and samples per 5-year period.....  | 6  |
| <b>Fig.S3</b> Characteristics of the occupational context .....   | 7  |
| <b>Fig.S4</b> Characteristics of the sampling strategies and PAHs reported in the literature.....             | 8  |
| <b>Fig.S5</b> Characteristics of the statistics used for reporting PAH levels in the literature .....         | 9  |
| <b>Fig.S6</b> Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the sector level  | 10 |
| <b>Fig.S7</b> Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the process level | 11 |



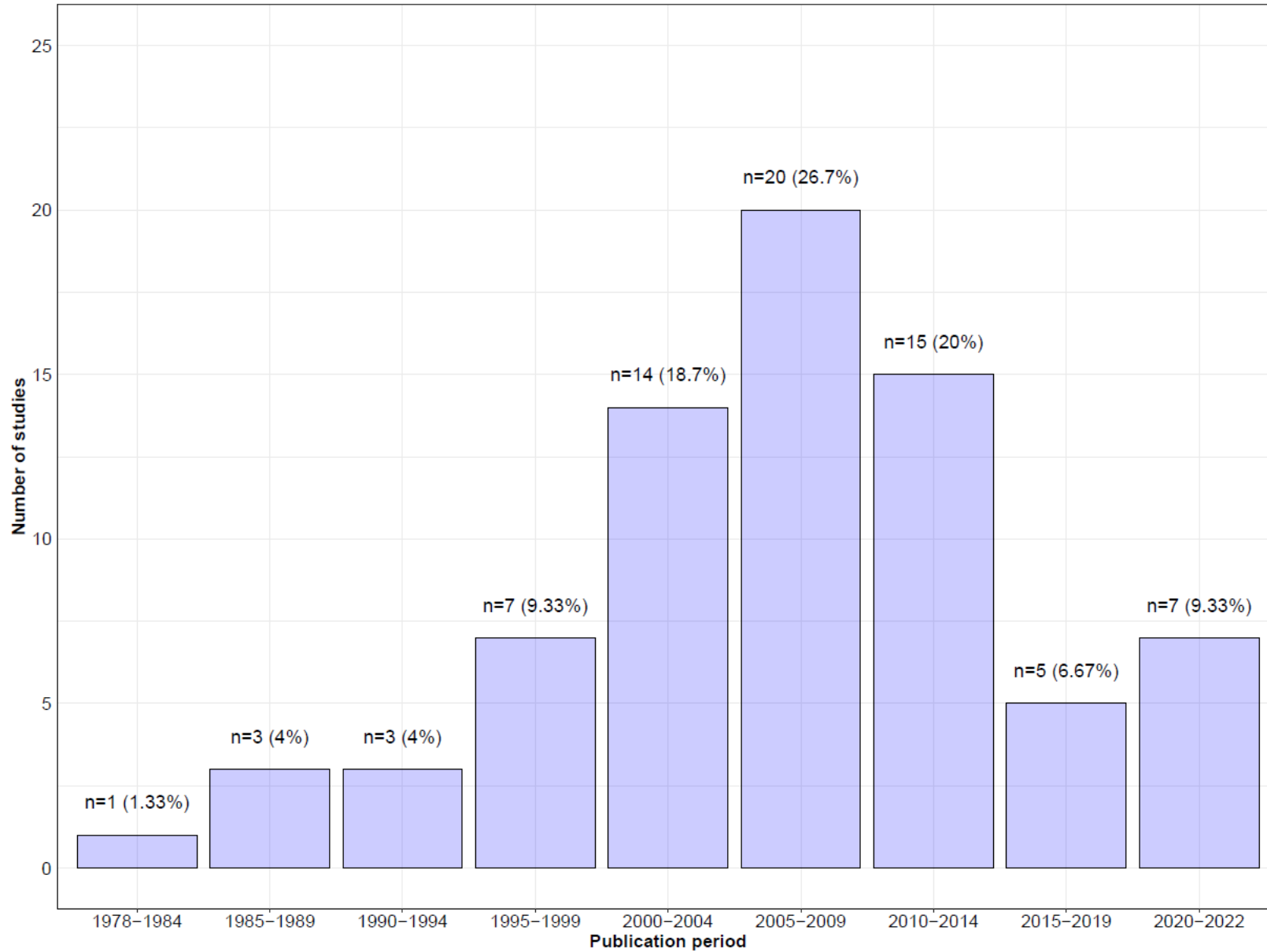
31 **Fig.S8** Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the activity level  
32 ..... 12  
33 **Search query on PubMed** ..... 13  
34 **Table S1** - Criteria used for the paper selection..... 15  
35 **Table S2** – Inventory of PyrT/BaP ratios and estimated BGV for each occupational context ..... 15  
36 **The PAH HBM tool**..... 16  
37 **Fig.S9** Screenshot of the PAH HBM tool ..... 19  
38 **References** ..... 20  
39



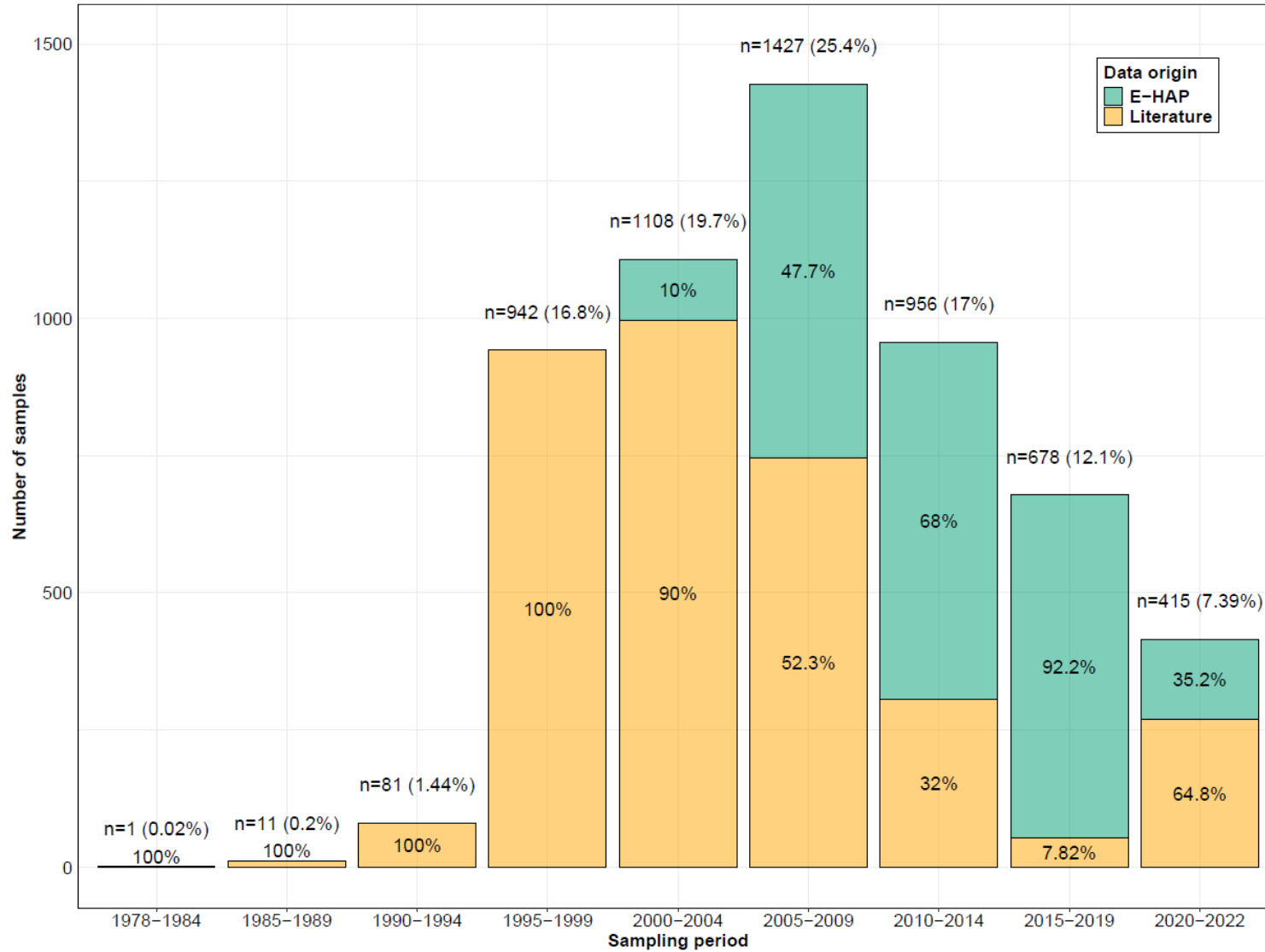
40



41 **B.**  
 42  
 43 **Fig.S1** Number of samples per country  
 44  
 45 A. Worldmap of the number of samples per country  
 46 B. Bar chart of the number of samples per country for each data source



A.



B.

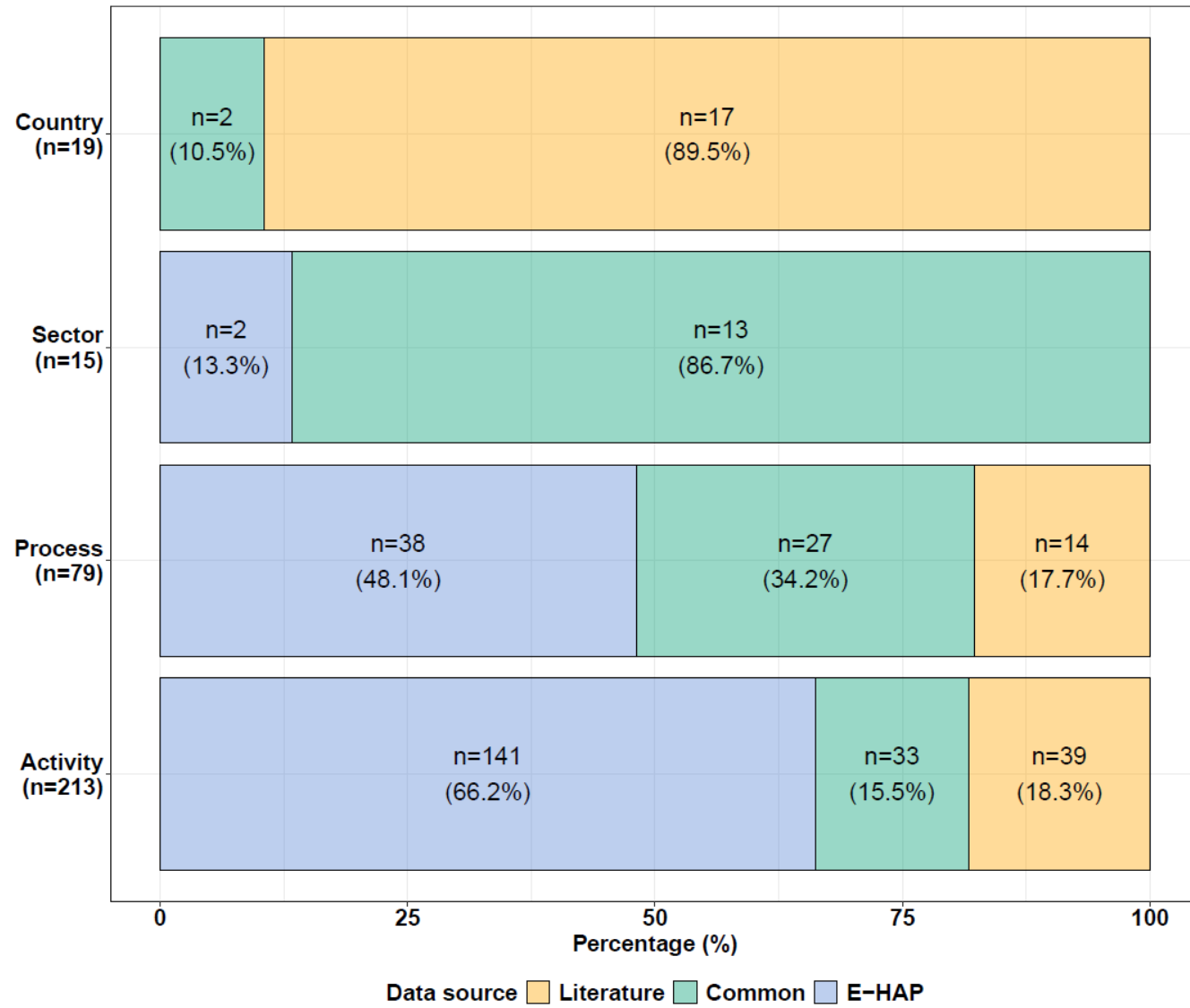
**Fig.S2** Number of studies and samples per 5-year period

48

49

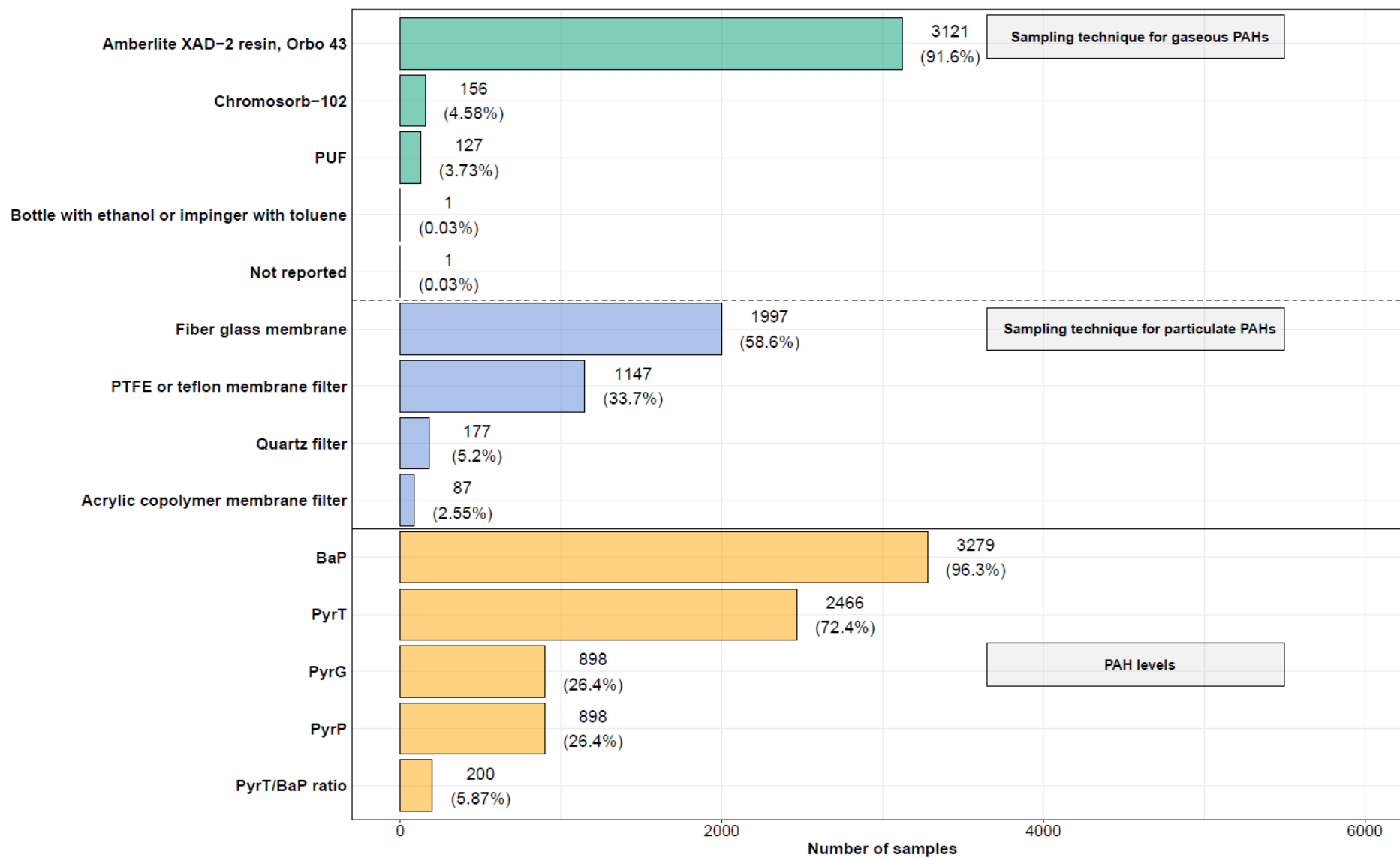
50 A. Number of studies from the literature per 5-year period

51 B. Number of samples per 5-year period and data origin

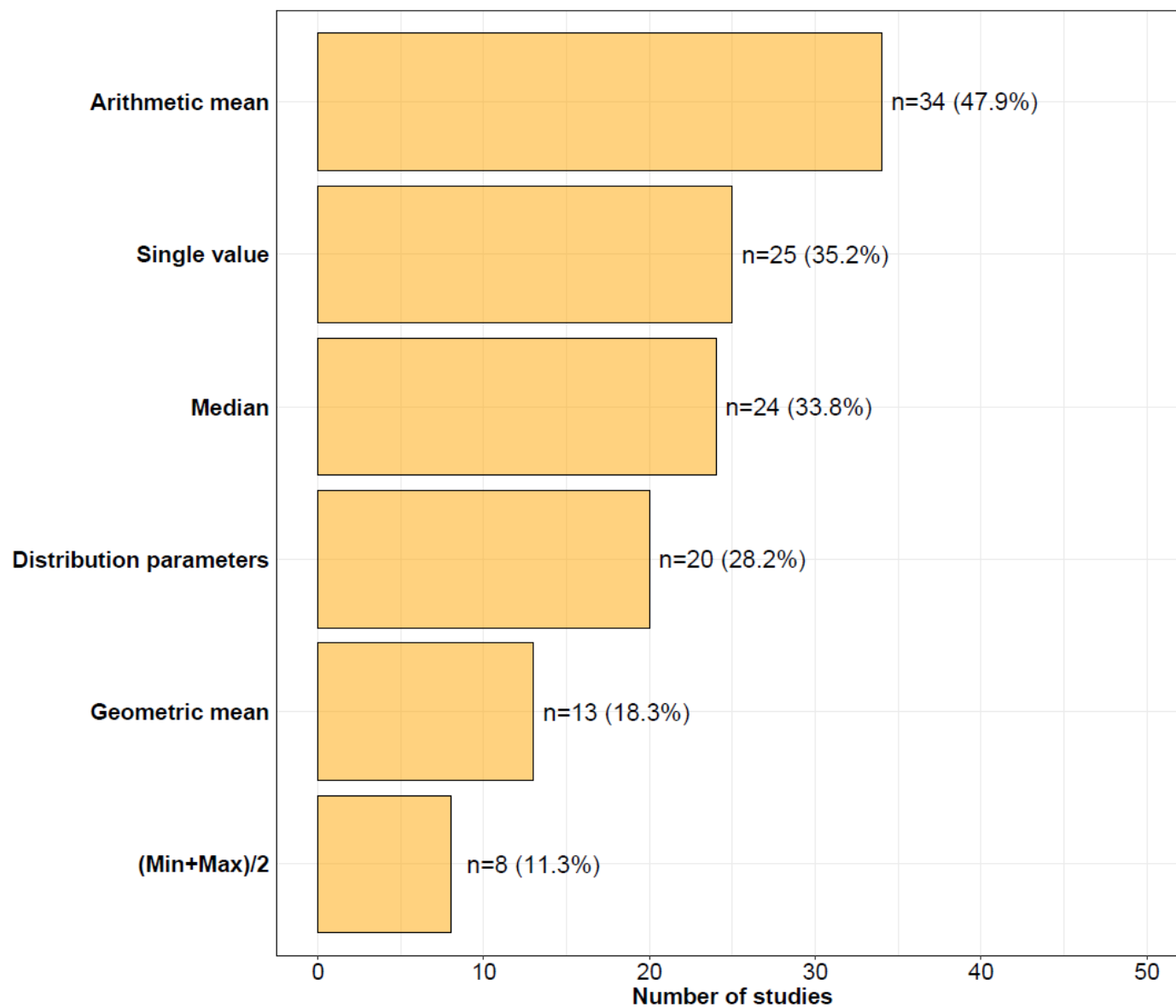


52

53 **Fig.S3** Characteristics of the occupational context



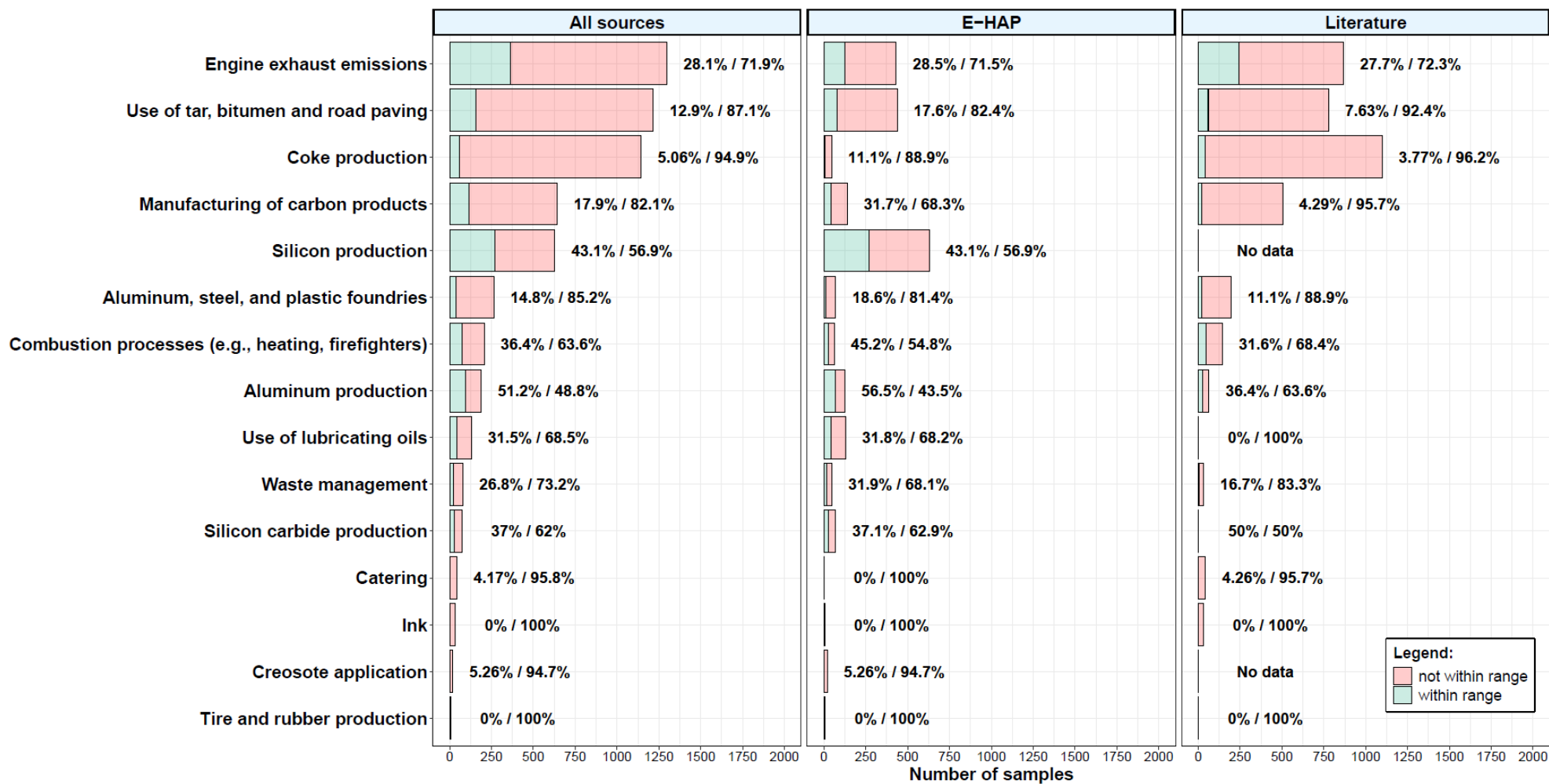
54  
 55 **Fig.S4** Characteristics of the sampling strategies and PAHs reported in the literature  
 56 BaP: benzo[a]pyrene, PUF: polyurethane foam, PyrG: gaseous Pyr, PyrP: particulate pyrene, PyrT: total pyrene



57  
58

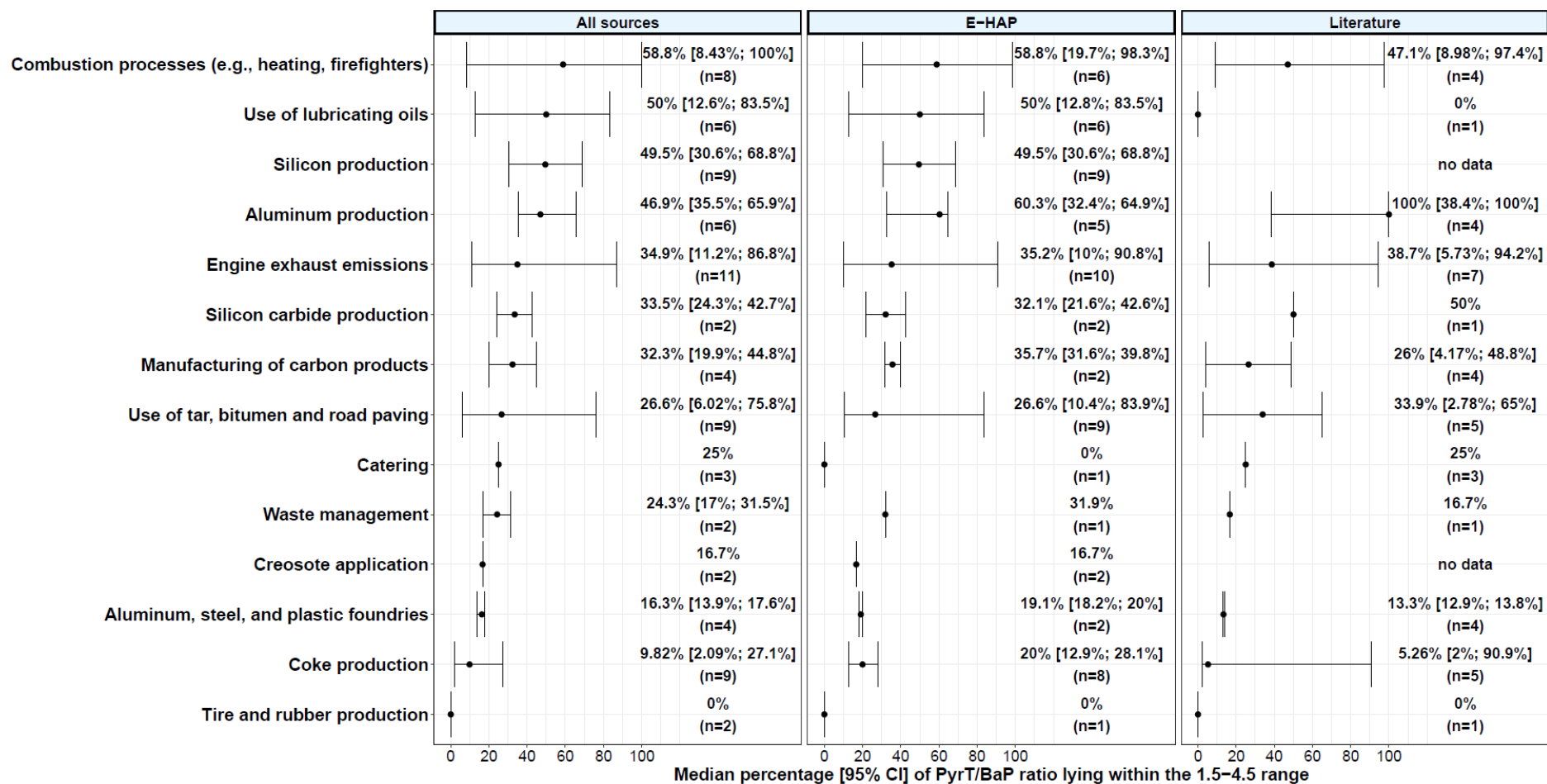
**Fig.S5** Characteristics of the statistics used for reporting PAH levels in the literature





59

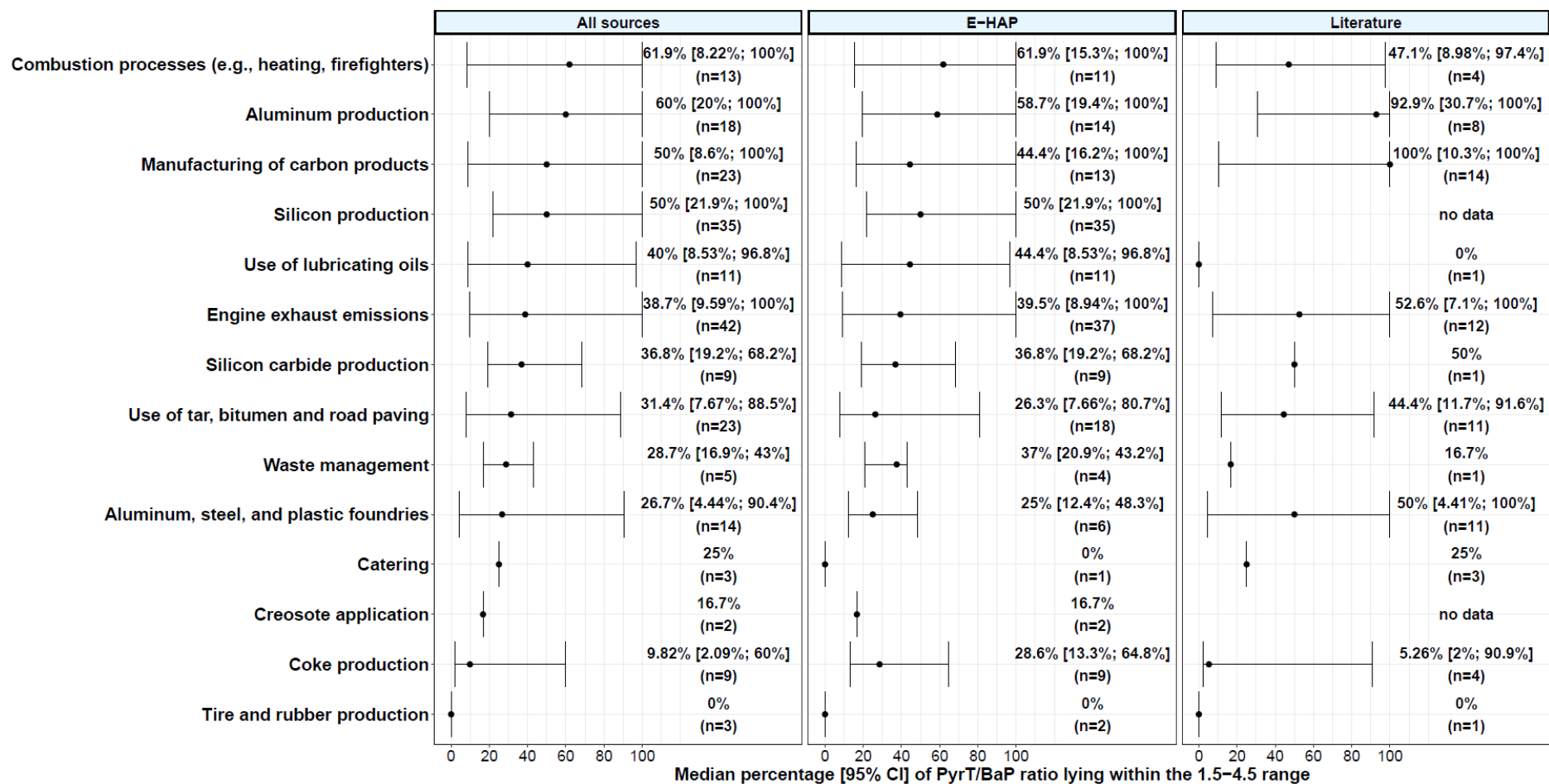
60 **Fig.S6** Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the sector level



61

62 **Fig.S7** Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the process level

63 n: total number of processes within a sector



64

65 **Fig.S8** Percentage of the PyrT/BaP ratio sample that lies within the 1.5-4.5 range at the activity level

66 n: total number of activities within a sector

67 **Search query on PubMed**

68 (((((((((((("polycyclic aromatic hydrocarbons"[MeSH Terms] OR "polycyclic aromatic  
69 hydrocarbon"[All Fields] OR "polycyclic aromatic hydrocarbons"[All Fields] OR "polycyclic aromatic  
70 compound"[All Fields] OR "polycyclic aromatic compounds"[All Fields] OR "polyaromatic  
71 hydrocarbon"[All Fields] OR "polyaromatic hydrocarbons"[All Fields] OR "polynuclear aromatic  
72 hydrocarbon"[All Fields] OR "polynuclear aromatic hydrocarbons"[All Fields] OR "polynuclear  
73 aromatic compound"[All Fields] OR "polynuclear aromatic compounds"[All Fields] OR "polycyclic  
74 compounds"[MeSH Terms] OR "polycyclic compound"[All Fields] OR "polycyclic compounds"[All  
75 Fields] OR "pah"[All Fields] OR "pahs"[All Fields] OR "benzo(a)pyrene"[MeSH Terms] OR  
76 "benzo(a)pyrene"[All Fields] OR "B[a]P"[All Fields] OR "benz(a)pyrene"[All Fields] OR "3,4-  
77 Benzpyrene"[All Fields] OR "3,4-Benzopyrene"[All Fields] OR "50-32-8"[All Fields] OR  
78 "pyrenes"[MeSH Terms] OR "pyrenes"[All Fields] OR "pyrene"[All Fields] OR "129-00-0"[All  
79 Fields]) AND ("occupations"[MeSH Terms] OR "occupations"[All Fields] OR "occupation"[All Fields]  
80 OR "occupational"[All Fields] OR "occupational exposure"[MeSH Terms] OR "occupational  
81 exposure"[All Fields] OR "worker"[All Fields] OR "workers"[All Fields] OR "workplace"[MeSH  
82 Terms] OR "workplace"[All Fields] OR "professionnal"[All Fields] OR "professionnals"[All Fields]  
83 OR "profession"[All Fields] OR "professions"[All Fields] OR "task"[All Fields] OR "tasks"[All Fields]  
84 OR "job"[All Fields] OR "jobs"[All Fields] OR "industrials"[All Fields] OR "industry"[MeSH Terms]  
85 OR "industry"[All Fields] OR "industrial"[All Fields] OR "industries"[All Fields] OR "companies"[All  
86 Fields] OR "company"[All Fields] OR "factories"[All Fields] OR "factory"[All Fields]) AND  
87 ("english"[Language] OR "french"[Language]) AND ("air pollutants"[MeSH Terms] OR "air  
88 pollutants"[All Fields] OR "occupational air pollutants"[All Fields] OR "air pollutants,  
89 occupational"[MeSH Terms] OR "air pollutants, occupational"[All Fields] OR "airborne"[All Fields]  
90 OR "atmospheric"[All Fields] OR "inhalation exposure"[MeSH Terms] OR "inhalation"[All Fields])  
91 AND ("level"[All Fields] OR "levels"[All Fields] OR "concentration"[All Fields] OR  
92 "concentrations"[All Fields] OR "monitoring"[All Fields] OR "profile"[All Fields] OR "profiles"[All  
93 Fields] OR "sampling"[All Fields] OR "analysis"[All Fields]) NOT "children"[Title]) NOT  
94 "child"[Title]) NOT "animal"[Title]) NOT "animals"[Title]) NOT "mice"[Title]) NOT "rats"[Title])

95 NOT "food"[Title]) NOT "diet"[Title]) NOT "dietary"[Title]) NOT "feed"[Title]) NOT "home"[Title])

96 NOT "house"[Title]) NOT "residences"[Title]) NOT "urban"[Title])

97

98 *Note:* terms related to PAHs are written in green fonts, terms related to **occupation** in red fonts, terms

99 related to **atmospheric exposure** in blue fonts, terms related to **exposure monitoring** in orange fonts,

100 **language** criteria in purple fonts, and terms excluded in black fonts.

101 The search was conducted on February 10, 2022, and repeated on October 24, 2023, to include

102 publications from 2022.

103 **Table S1** - Criteria used for the paper selection

| Question  | Description   | Answer |                |
|---|---|--------|----------------|
|   |   | no     | yes/can't tell |
| <b>Stage 1: Paper language</b>  |   |        |                |
| Q <sub>11</sub>   | Is the paper written in English or French?  | 0      | 1              |
| <i>S<sub>1</sub> = Q<sub>11</sub>; Paper eligible for stage 2 if S<sub>1</sub> &gt; 0</i>   |   |        |                |
| <b>Stage 2: Screening paper title</b>   |   |        |                |
| Q <sub>21</sub>   | Does the title mention terms related to PAHs?   | 0      | 1              |
| Q <sub>22</sub>   | Does the title mention terms related to occupation/work?  | 0      | 1              |
| <i>S<sub>2</sub> = Q<sub>21</sub> × Q<sub>22</sub>; Paper eligible for stage 3 if S<sub>2</sub> = 1</i>                                       |   |        |                |
| <b>Stage 3: Screening paper abstract</b>  |   |        |                |
| Q <sub>31</sub>   | Does the abstract describe an analysis related to PAHs?   | 0      | 1              |
| Q <sub>32</sub>   | Does the abstract describe an analysis related to an occupation/work task/industry/sector?  | 0      | 1              |
| Q <sub>33</sub>   | Does the abstract describe an analysis related to an airborne exposure monitoring?  | 0      | 1              |
| Q <sub>34</sub>   | Does the abstract describe an analysis related to airborne levels?  | 0      | 1              |
| <i>S<sub>3</sub> = Q<sub>31</sub> × Q<sub>32</sub> × Q<sub>33</sub> × Q<sub>34</sub>; Paper eligible for stage 4 if S<sub>3</sub> = 1</i>     |   |        |                |
| <b>Stage 4: Screening paper content</b>   |   |        |                |
| Q <sub>41</sub>   | Does the article reports airborne concentrations (quantitative) of both BaP and PyrT, or both PyrG and PyrP as well as BaP?             | 0      | 1              |
| Q <sub>42</sub>   | Does the article reports airborne PyrT/BaP ratio?   | 0      | 1              |
| Q <sub>43</sub>   | Does the article reports exposure representative/typical of the work/activity studied? (not worst-case scenario, nor accident/incident) | 0      | 1              |
| Q <sub>44</sub>   | Does the article reports long-term sampling?  | 0      | 1              |
| <i>S<sub>4</sub> = (Q<sub>41</sub> + Q<sub>42</sub>) × Q<sub>43</sub> × Q<sub>44</sub>; Paper eligible for inclusion if S<sub>4</sub> ≥ 1</i> |   |        |                |
| <b>Score = S<sub>1</sub> × S<sub>2</sub> × S<sub>3</sub> × S<sub>4</sub>; Paper selected for review/analysis if score ≥ 1</b>                 |   |        |                |

104 *Note:* BaP: benzo[a]pyrene, PyrG: gaseous pyrene, PyrP: particulate pyrene, PyrT: total pyrene, Q:  
 105 question, S: score.

106

107

108 **Table S2** – Inventory of PyrT/BaP ratios and estimated BGV for each occupational context

109 Please refer to the MS Excel file entitled Table S2.

## 110 **The PAH HBM tool**

111 The results of the inventory of PyrT/BaP ratios were implemented online on the PAH HBM tool. The  
112 PAH HBM tool can be accessed on any device with an internet browser and requires no programming  
113 knowledge to use. The PAH HBM tool is freely available to anyone who wants to use it and is available  
114 at: <https://exporisk-timc.imag.fr/PAH/>. The goal of the PAH HBM tool is to support/help in the  
115 interpretation and decision-making regarding 1-OHP concentrations by providing useful and relevant  
116 information. Indeed, this tool allows the user to calculate an indicative BGV and the probability of  
117 exceeding this BGV based on the recommendations of ACGIH and for defined exposure scenarios.

118 The PAH HBM tool incorporates a variety of features to make it easy to use. Beyond making the  
119 interpretation of 1-OHP urinary levels easier, this tool offers the chance to have an immediate glimpse  
120 into the results and to see how the results change according to different setting configurations. In  
121 addition to making information more readily understood and retained in a quicker time, the visual aids  
122 and representations provided by the PAH HBM tool could be useful for improving results  
123 communication and promoting transparency among studies when interpreting 1-OHP urinary levels.  
124 Periodic updates of the PAH HBM tool will allow for the integration of updated and new data as well  
125 as new functionalities. Help buttons are displayed throughout the entire tool to provide help and insights  
126 for using or setting parameters, reading graphs, and interacting with graphs and tables. The results  
127 generated with the PAH HBM tool are only valid for the exposure scenario and parameters defined by  
128 the user within the limits and uncertainties associated with the data (e.g., data from the literature) and  
129 methods used. The choice of the most relevant PyrT/BaP ratio, parameters, and exposure scenario to use  
130 falls under the responsibility of the PAH HBM tool user. While available information is updated  
131 regularly in the PAH HBM tool, it might not be complete or up-to-date at the time of use. In addition,  
132 the PAH HBM provides no interpretation. Therefore, it falls on the user to interpret the results provided  
133 by the PAH HBM accordingly. The PAH HBM tool is intended for occupational physicians, researchers,  
134 risk managers, practitioners, authoritative bodies, decision-makers, or anyone who wishes to interpret  
135 1-OHP urinary levels.

136 Fig.S9 presents a screenshot of the PAH HBM tool. On top of the web page (on the left), there are eight  
137 tabs, written in blue fonts, that can be clicked on. The active tab has a dark blue background and a bold

138 black font. The first tab (starting from the left), named “*Airborne PAH ratio & BLV*”, displays the  
139 estimated BGV based on the recommendation of ACGIH and a defined exposure scenario, the  
140 distribution of 1-OHP concentrations adjusted by the PyrT/BaP ratio, as well as the probability of  
141 exceeding the estimated BGV. The “*Data source*” tab provides the inventory of PyrT/BaP ratios from  
142 this work. The “*Respiratory assigned protection factors*” tab provides a table listing all of the respiratory  
143 assigned protection factors found in the literature. The “*Exposure limits values*” tab provides a table  
144 listing all of the airborne BaP and urinary 1-OHP limit values found in the literature. The “*News &*  
145 *Articles*” tab will report articles describing, using, or citing the *PAH HBM tool*. The “*Help/Info*” tab  
146 provides general information regarding the *PAH HBM tool*, such as the goal, strengths, and limitations  
147 of the tool, as well as information regarding table and figure interactivity, information pertaining to the  
148 condition of use, data privacy, data protection, and legal mentions, and how to report bugs or mistakes.  
149 The “*Contact*” tab provides contact information details, while the “*Mentions légales*” tab stipulates the  
150 legal mentions in French.

151 The blue box on the left of the tool allows the user to define an exposure scenario. The user can define  
152 an occupational context by choosing a country and specifying the SEG (sector, process/post, and  
153 activity). For the PyrT/BaP ratio, it is possible to use data from this literature review to make a simulation  
154 or to upload files that are not stored or kept to ensure the safety and anonymity of the data. It is possible  
155 to account for respiratory protection, such as in a recent study (Valière et al. 2022). If the user wants to  
156 estimate the probability of exceeding the estimated indicative BGV, it is possible to either make a  
157 simulation regarding 1-OHP concentrations or upload a file. The user can also set a BLV instead of  
158 using the one that was estimated. Once the exposure scenario has been defined, the user must click on  
159 the “*run new analysis*” button on top of the box to execute the calculations. It can take from a few  
160 seconds to a few minutes to generate all the graphs and tables, depending on the number of simulation  
161 runs chosen, the user internet connection, and the user computer power. Help buttons are available for  
162 every choice to make, with, for instance, instructions on how a file should be structured before being  
163 uploaded.

164 All of the tables and figures available on the PAH HBM tool are interactive. There is a help button below  
165 each table, named “*How to interact with this table?*” which explains how to interact with all the tables.



166 On top of each table (on the left), there are seven action buttons. The “*Copy*” button allows the user to  
167 copy the table to a clipboard. The “*CSV*”, “*Excel*” and “*PDF*” buttons enable the user to export the table  
168 to CSV, XLS, or PDF format, respectively. The “*Print*” button allows the user to print the table. The  
169 user can choose which columns to visualize using the “*Column visibility*” button. The last button, “*Show*  
170 *10 rows*”, allows the user to choose the number of rows to display. When the former button is not set on  
171 the “*Show all rows*” option, the user will have to click on the buttons under the table (on the right) to  
172 navigate through the table. Beware, for exporting or printing the entire table, the user needs to first click  
173 on the number of rows to display button (named “*Show 10 rows*” by default), then choose the “*Show all*  
174 *rows*” option, and finally click on one of the three export/download buttons. The interactive tables allow  
175 the user to perform queries, either on a specific column or on the entire table. The global search is  
176 performed across all searchable columns and starts when typing text on the “*Search*” rectangle/bar  
177 located on top of the table (on the right). Searching on individual columns can be performed by typing  
178 text on the white rectangle/bar below each column header. Queries are not case-sensitive and provide  
179 on-the-fly filtering with immediate feedback to the user. For the global search, the order of the words in  
180 the query does not matter. Clicking on the cross symbol that appears on the right of the query will cancel  
181 the search. Clicking on the arrowhead facing the top of the web page will sort the chosen column either  
182 alphabetically or in ascending numerical order, depending on the type of data the column contains  
183 (numerical values or texts). It is also possible to change the order of the columns in a table by clicking  
184 and dragging the column header to the left or to the right. References and access links are underlined  
185 and written in blue font and can be clicked on to open the website where the paper/record can be  
186 viewed/obtained. Note that empty cells correspond to non-reported values.

**PAH HBM tool - Polycyclic Aromatic Hydrocarbon Human Biomonitoring tool**

**Box for setting the exposure scenario**

**Analysis**  
[Run new analysis](#) **Action button for running the calculations** [Help](#)

**Occupational context**

Country: All **country** [Help](#)

Sector - Characteristics of products/raw materials: All **sector** [Help](#)

Post - Location and/or operation with different emission sources: All **process** [Help](#)

Activity - Task or a series of tasks: All **activity** [Help](#)

**Airborne PAH concentration**

Upload a concentration file?  Yes  No [Help](#)

Use data from literature?  Yes  No [Help](#)

Sampling time to consider:  Both  LT  ST [Help](#)

**Respiratory protection**

Account for respiratory protection?  Yes  No [Help](#)

**Urinary 1-hydroxypyrene concentration**

Upload a concentration file?  Yes  No [Help](#)

Make a simulation?  Yes  No [Help](#)

Distribution type: Log-normal [Help](#)

1-hydroxypyrene - Geometric mean ( $\geq 1$ ): 1 Unit:  $\mu\text{g/L}$  [Help](#)

**Airborne PAH ratio & BLV** [Data source](#) [Respiratory assigned protection factors](#) [Exposure limit values](#) [News & Articles](#) [Help/Info](#) [Contact](#) [Mentions légales](#) **Tabs**

**Table 1: Airborne PAH ratios and estimated BLV using recommendations from ACGIH**

[Copy](#) [CSV](#) [Excel](#) [PDF](#) [Print](#) [Column visibility](#) [Show 10 rows](#) **Action buttons** Search: **Global search**

| Country | Sector | Post | Activity | PyT/BaP ratio (GM [95% CI]) | BaP/PyT ratio (GM [95% CI]) | Estimated BLV (GM [95% CI]) ( $\mu\text{g/L}$ ) |
|---------|--------|------|----------|-----------------------------|-----------------------------|---|
| All     | All    | All  | All      | 2.33 [0.475 - 143]          | 0.43 [0.00697 - 2.1]        | <b>5.82 [1.19 - 359]</b>                        |

**Estimated BGV**

Note: 95% CI: 95% confidence interval, BaP: benzo[a]pyrene, BLV: biological limit value, GM: geometric mean, PyT: total pyrene.  
 The BLV was estimated using the following equation from ACGIH (2020):  $2.5 \times \text{PyT}/\text{BaP}$ .  
 If respiratory protection factors are assigned, they are taken into account for the calculation of the PyT/BaP ratio.  
 ACGIH, 2020. Polycyclic aromatic hydrocarbons (PAHs). Update 2017. In: Documentation of the TLVs and BEIs with Worldwide Occupational Exposure Values, seventh ed. ACGIH, Cincinnati (USA).

Showing 1 to 1 of 1 entries [How to interact with this table?](#) [Previous](#) 1 [Next](#)

**Results**

**Context**

**1-hydroxypyrene concentration ( $\mu\text{g/L}$ ) adjusted by BaP/PyT**

0.346 [0.00585 - 5.73]

**BLV = 1  $\mu\text{g/L}$**

[How to read this graph?](#)

**Fig.1: Distribution of 1-hydroxypyrene concentrations adjusted by the BaP/PyT ratio**

187  
188

**Fig.S9** Screenshot of the PAH HBM tool

189 **References**

- 190 Valière M, Petit P, Persoons R et al (2022). Consistency between air and biological monitoring for  
191 assessing polycyclic aromatic hydrocarbon exposure and cancer risk of workers. *Environ Res*  
192 207:112268. <https://doi.org/10.1016/j.envres.2021.112268>.