Polycyclic Aromatic Hydrocarbons from Vegetation Burning and Health Effects

Kazuichi HAYAKAWA

Institute of Nature and Environmental Technology, Kanazawa University
Kakuma-machi, Kanazawa, Ishikawa, 920-1192, Japan
E-mail: hayakawa@p.kanazawa-u.ac.jp

Abstract

Air pollution now causes several million deaths each year. Among air pollutants, polycyclic aromatic hydrocarbons (PAHs) and their derivatives, such as nitro-, hydroxy- and quinoid PAHs attract much attention. These pollutants are emitted through burning processes of fossil fuels and vegetation, and exist in gas and particle phases in the air. Despite their strong adverse health effects, including lung cancer, asthma and endocrine disruption, their outdoor and indoor air pollution levels have not been reduced quickly worldwide. Recently, biomass has become popular as a renewable energy source that does not increase the atmospheric concentration of global carbon dioxide, a greenhouse gas implicated in global warming. On the other hand, there are still many areas in developing countries where slash-and-burn farming is practiced, and forest fires have been increasing rapidly worldwide. Therefore, sufficient attention is needed to the health effects of PAHs and related compounds generated from these sources. The aim of this report is to describe the emission and distribution of PAHs and their derivatives in outdoor and indoor air and their health effects, focusing on vegetation fires.

Key words: health effect, nitropolycyclic aromatic hydrocarbon, oxygenated polycyclic aromatic hydrocarbon, polycyclic aromatic hydrocarbon, vegetation burning

1. Introduction

Air pollution increases mortality and morbidity. The World Health Organization (WHO) has reported that the combined effects of ambient air pollution and household air pollution are associated with 6.7 million premature deaths annually (WHO, 2018). World coal and oil consumption has steadily increased since the industrial revolution. The WHO has reported recently that air pollution is very serious in the Western Pacific region (WHO, 2023). Fossil fuels such as coal and petroleum account for a large proportion of the world's primary energy consumption. In this region, biomass is also an important fuel both indoors and outdoors. Moreover, slash-and-burn farming, forest fires, habits such as smoking, and incense burning also increase personal exposure to air pollutants.

Among air pollutants, polycyclic aromatic hydrocarbons (PAHs) and their derivatives, such as nitrated PAHs (NPAHs) and oxygenated PAHs (OPAHs), are known to be generated by incomplete combustion of organic substances and to induce various adverse health effects, including carcinogenicity and mutagenicity. PAHs contain two or more 4- to 6-carbon fused rings, of which the benzene-ring structure is the most common. This report focuses on PAHs and their derivatives emitted from vegetation fires and describes adverse health effects resulting from human exposure.

2. PAHs and Their Derivatives

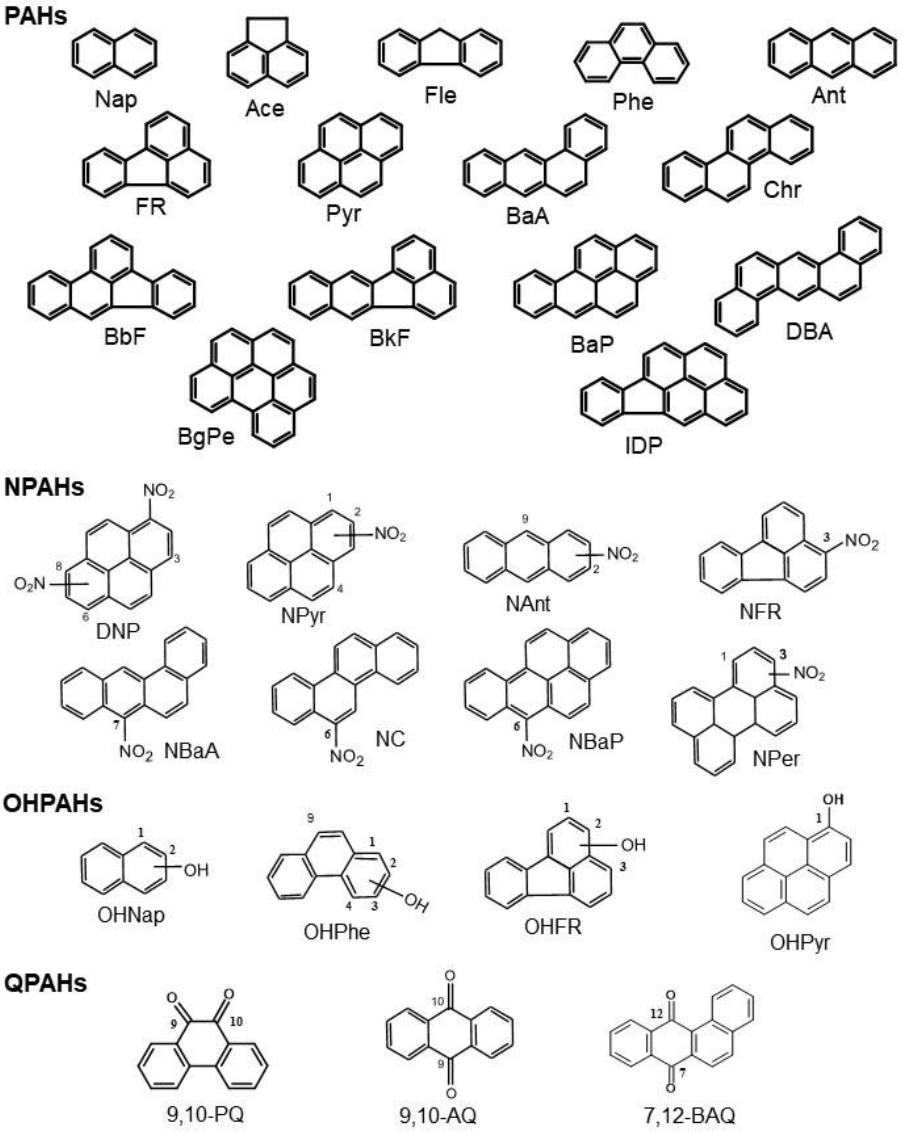
2.1 PAHs, NPAHs, QPAHs and OHPAHs

Many kinds of PAHs and their derivatives, such as NPAHs, hydroxylated PAHs (OHPAHs), quinoid PAHs (QPAHs) and halogenated PAHs (XPAHs), are produced through incomplete combustion of organic materials and secondary atmospheric reactions. In this report, the OHPAHs and QPAHs are classed among the oxy-PAHs (OPAHs). During combustion processes, particulate matter (PM), i.e., soot, is also formed. In the air, two- and three-aromatic ring PAHs occur mainly in the gas phase, five- and higher-ring PAHs are bound to particles (particle phase), and four-ring PAHs are found in both phases. PAH derivatives also exist in both phases in a similar manner to

that of PAHs depending on ring numbers. In this report, abbreviations are used for major PAHs and their derivatives. Please refer to the list of abbreviations at the end of this report. Their chemical structures are shown in Fig. 1.

2.2 Distribution in Ambient Air

PAHs and their derivatives are ubiquitous in both indoor and outdoor air. As described above, lower-molecular-weight PAHs exist in gaseous form. Likewise, higher-molecular-weight PAHs exist mainly as fine PM with an aerodynamic diameter of less than or equal to a nominal 2.5 μm ($PM_{2.5}$). The distribution of their derivatives has similar tendencies. Fig. 2 shows concentrations of major $PM_{2.5}$-bound PAHs, NPAHs, OHPAHs and QPAHs measured in urban air in Kanazawa, Japan. Although the concentration levels of the derivative groups differ greatly, the concentration order shows the same trend between urban and suburban air and between vehicular and other combustion emissions (Hayakawa *et al*., 2020]. As can be seen in Fig. 2, the concentrations of total PAHs (ΣPAH), NPAHs (ΣNPAH), OHPAHs (ΣOHPAH), and QPAHs (ΣNOPAH) in Kanazawa City were 1000 pg m^{-3}, 9.6 pg m^{-3}, 75 pg m^{-3} and 420 pg m^{-3}, respectively, with [ΣPAH] > [ΣQPAH] > [ΣOHPAH] > [ΣNPAH] in decreasing order. Among these compounds, pyrene (Pyr), benz[*a*]anthracene (BaA) and benz[*a*]pyrene (BaP) are the PAHs whose derivatives were commonly detected in the NPAHs, OHPAHs and QPAHs. For example, three isomers were respectively detected as pyrene-quinones (PyrQs). The concentration order of Pyr derivatives, quinoid pyrenes (QPyrs), hydroxypyrenes (OHPyrs) and nitropyrenes (NPs), were [Pyr] > [QPyrs] > [OHPyrs] > [NPs]. The derivatives of BaA and BaP also showed the same decreasing order described above. These results suggest that the order of concentrations of PAHs and their derivatives mainly depends on how easily the PAHs are derived in the combustion of organic matter.



Abbreviations, see list of abbreviation.

Fig. 1 Chemical structures of PAHs, NPAHs, OHPAHs and QPAHs.

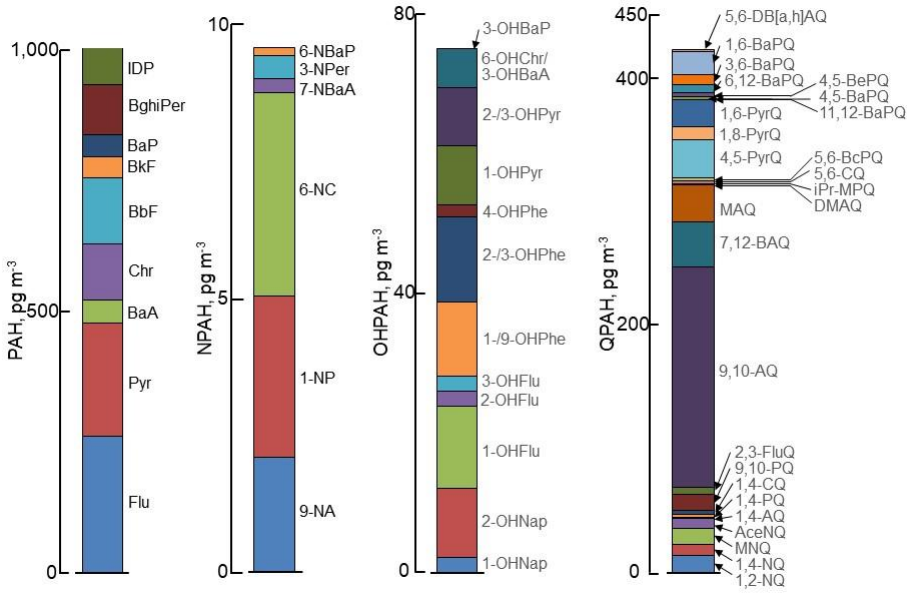


Fig. 2 Atmospheric PM2.5-bound PAHs, NPAHs, OHPAHs and QPAHs. $PM_{2.5}$ samples were collected for one week in the winter of 2018.

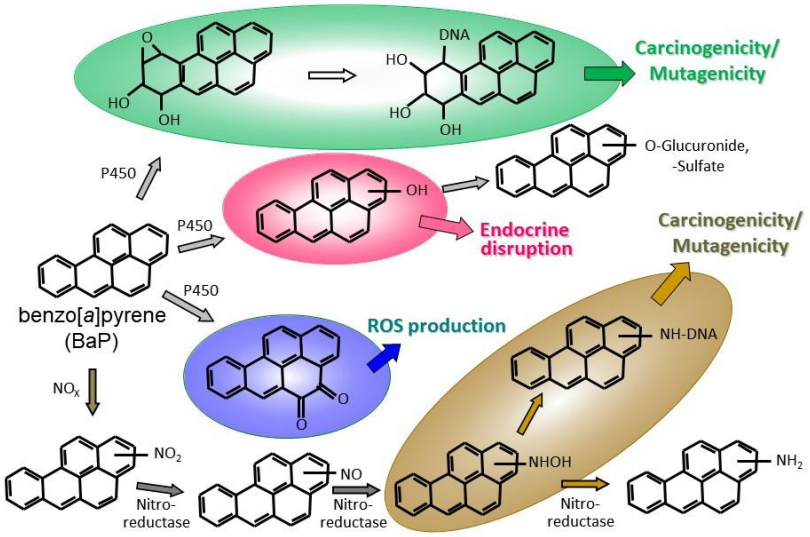


Fig. 3 Metabolic activation of BaP.

3. Metabolism of PAHs and Health Effects

3.1 Metabolic Activation

In accordance with the most accepted metabolic activation of PAHs (Straif *et al*., 2013), Fig. 3 gives an overview of the metabolic activation of PAHs in animals and microorganisms, using benzo[*a*]pyrene (BaP) as a representative PAH (Hayakawa, 2016). BaP can bind to the aryl hydrocarbon receptor (AhR) that induces the cytochrome P450 (CYP) family (e.g., CYP1A1, CYP1A2, CYP1B1), which forms epoxides, quinones and phenols of BaP. The first metabolic activation pathway involves the formation of BaP-7,8-diol-,9,10-epoxide, which leads to DNA adduct formation, exhibiting carcinogenicity (green route). The second metabolic pathway involves the formation of OHPAHs in the presence of CYP. Several OHPAHs have been found to bind to estrogen receptors (ERs) or inhibit estrogens from binding to ERs. A chemical structure-biological activity relationship is considered the mechanism (red route) (Hayakawa *et al*., 2007). As a result, the number of papers on the relationship between PAHs and endocrine disruption has been increasing (Cathey *et al*., 2020). The third metabolic pathway involves the formation of QPAHs. Several QPAHs, such as 9,10-phenanthrenequinone (9,10-PQ), overproduce reactive oxygen species (ROS) through a redox cycle (blue route). On the other hand, PAHs are nitrated to NPAHs during combustion processes and via secondary atmospheric reactions. In microorganisms, NPAHs are metabolized to nitroso-, hydroxyamino-, and finally, amino-derivatives of PAHs. In this pathway, hydroxyamino PAHs cause DNA adduct formation. This is known to be an indirect-acting mutagenic pathway of NPAHs (brown route) (Hayakawa, 2016).

3.2 Carcinogenicity and Adverse Health Effects

Epidemiological and animal experimental evidence on the health effects of air pollution has been growing and evolving. The International Agency for research on Cancer (IARC) has classified more than sixty PAHs and related compounds into four classes, *carcinogenic to humans* (Group 1), *probably carcinogenic to humans* (Group 2A), *possibly carcinogenic to humans* (Group 2B) and *not classifiable as to their carcinogenicity to humans* (Group 3). Among them, BaP is in Group 1. It is important that this classification is based on the evidence of carcinogenicity to humans, but does not depend on the strength of the carcinogenicity. Four PAHs, cyclopenta[*cd*]pyrene, dibenz[*a,h*]anthracene, dibenzo[*a,l*]pyrene, dibenz[*a,j*]acridine and one NPAH, 1-NP, are in Group 2A. Fifteen PAHs and hetero derivatives, such as Nap, benz[*j*]aceanthrylene, BaA, BbF, benzo[*j*]fluoranthene, BkF, benzo[*c*]phenanthrene, Chr, 5-methylchrysene, dibenzo[*a,h*]pyrene, dibenzo[*a,i*]pyrene, IDP, benzofuran, dibenz[*c,h*]acridine and dibenz[*a,h*]acridine and five NPAHs, such as 5-NAc, 2-NF, 4-NP, 1,6- and 1,8-DNPs are in Group 2B. The other PAHs and NPAHs such as Fle, Pyr, 2-NP and 6-NBaP, are in Group 3, because of their limited or inadequate experimental evidence (Table 1). The IARC also classified PAH-containing materials, such as shale oils, coal-tar distillates, coal-tar pitch, coke, coal gasification products, indoor emissions from household combustion of coal, iron and steel founding products (occupational exposure), engine exhaust, diesel, outdoor air pollution, PM in outdoor pollution, soot (as found in occupational exposure of chimney sweeps), tobacco smoke and second-hand tobacco smoke in Group 1 (IARC, 2021). It is thought that PAHs, NPAHs or OPAHs, which are contained in those materials, might contribute as causative agents to oxidative DNA damage. Epidemiological studies on adverse effects of these pollutants on lung function have been reported (Brucker *et al*., 2014; Mordukhovichi *et al*., 2016; Wang *et al*, 2016).

PAHs are oxidized by ozone or nitrogen dioxide to produce QPAHs, OHPAHs or NPAHs in the atmosphere. They are adsorbed in the bronchi and alveoli to induce the production of ROS by the above metabolic pathway (Pitts *et al*., 1980; Pitts, 1983; Yoshikawa *et al*., 1985; Kumagai *et al*., 1997 and 2012; Hayakawa *et al*., 2007). Among PAHQs, *ortho*-QPAHs overproduce ROS and thereby significantly decrease cell viability, whereas *para*-QPAHs do not (Motoyama *et al*., 2009). ROS causes airway inflammation and exacerbation of asthma and allergies (Al-Daghri *et. al*., 2013; Anyenda *et al*., 2016; Zhao, 2022; Hara *et al*., 2022). Recently, the number of reports on non-genotoxic effects of OPAHs has been increasing: QPAHs and/or OHPAHs activate the aryl hydrocarbon receptor, additional nuclear receptors and intracellular signaling pathways. These facts suggest the possibility that OPAHs play an adverse role in the development, metabolism and growth of humans and animals and that more attention needs to be paid to the toxicities of PAH metabolites (Vondráček and Machala, 2021).

Table 1 Carcinogenicity classification of PAHs and their derivatives.

Class	Compound
Group 1 (carcinogenic to humans)	benzo[*a*]pyrene
Group 2A (probably carcinogenic to humans)	cyclopenta[*cd*]pyrene, dibenz[*a,h*]anthracene, dibenzo[*a,l*]pyrene, dibenz[*a,j*]acridine, 1-nitropyrene
Group 2B (possibly carcinogenic to humans)	naphthalene, benz[*j*]aceanthrylene, benz[*a*]anthracene, benzo[*b*]fluoranthene, benzo[*j*]fluoranthene, benzo[*k*]fluoranthene, benzo[*c*]phenanthrene, chrysene, 5-methylchrysene, dibenzo[*a,h*]pyrene, dibenzo[*a,i*]pyrene, indeno[1,2,3-*cd*]pyrene, benzofuran, dibenz[*c,h*]acridine, dibenz[*a,*h]acridine, 5-nitroacenaphthene, 2-nitrofluorene, 4-nitropyrene, 1,6-dinitropyrene, 1,8-dinitropyrene
Group 3 (not classifiable as to their carcinogenicity to humans, because of limited or inadequate experimental evidence)	acenaphthene, acepyrene (3,4-dihydrocyclopenta[*cd*]pyrene), anthanthrene, anthracene, 11H-benz[*bc*]aceanthrylene, benz[*l*]aceanthrylene, benzo[*b*]chrysene, benzo[*g*]chrysene, benzo[*a*]fluoranthene, benzo[*ghi*]fluoranthene, benzo[*a*]fluorene, benzo[*b*]fluorene, benzo[*c*]fluorene, benzo[*ghi*]perylene, benzo[*e*]pyrene, coronene, 4H-cyclopenta[*def*]chrysene, 5,6-cyclopenteno-1,2-benzanthracene, dibenz[*a,c*]anthracene, dibenz[*a,j*]anthracene, dibenzo[*a,e*]fluoranthene, 13H-dibenzo[*a,g*]fluorene, dibenzo[*h,rst*]pentaphene, dibenzo[*a,e*]pyrene, dibenzo[*e,l*]pyrene, 1,2-dihydroaceanthrylene, 1,4-dimethylphenanthrene, fluoranthene, fluorene, 1-methylchrysene, 2-methylchrysene, 3-methylchrysene, 4-methylchrysene, 6-methylchrysene, 2-methylfluoranthene, 3-methylfluoranthene, methylphenanthrene, naphtho[1,2-*b*]fluoranthene, naphtho[2,1-*a*]fluoranthene, naphtho[2,3-*e*]pyrene, perylene, phenanthrene, picene, pyrene, triphenylene, 13H-dibenzo[*a,g*]fluorene, benzo[*a*]fluorene, benzo[*b*]fluorene, 1-methylphenanthrene, phenanthrene, benz[*a*]acridine, benz[*c*]acridine, 7-nitrobenz[*a*]anthracene, 3-nitroperylene, 3,9-dinitrofluoranthene, 2-nitronaphthalene, 9-nitroanthracene, 6-nitrobenzo[*a*]pyrene, 2-nitropyrene, 1-nitronaphthalene

4. Emission Sources

4.1 Sources of PAHs and NPAHs

There are many kinds of emission sources for PAHs and their derivatives: vehicles, ships, aircraft, coke production, industries such as iron-steel, aluminum and others, and agricultural machines that use fossil fuels. Petroleum cracking plants, gas stations, forest fires (wildfires) and open burning of crop residues constitute major outdoor sources. On the other hand, the combustion of coal, oil and gas, and the use of firewood and other vegetation fires in heating and cooking constitute indoor sources. Smoking is also a source, especially indoors. Of these sources, the contributions of residential/commercial biomass burning and open-field vegetation fires (agricultural waste burning, deforestation and wildfires) accounted for 60.5% and 13.6%, respectively, of the 16 global atmospheric PAHs in 2007, which were much larger than that of vehicles (12.8%) (Shen *et. al*., 2013). However, a survey of rural areas in China reported that the contribution of vegetation fires (15.9%) was smaller than the contribution of vehicles (32.7%) in 2020 (Li *et. al*., 2023). Thus, there have been large differences between reports in the contribution of vegetation fires to atmospheric PAHs.

4.2 Chemical Characteristics of Vegetation Fires

Several review reports have been published for PAHs emitted from biomass burning (Vicente and Alves, 2018; Zhang *et al*., 2022). The compositions of the PAHs and their derivatives were not very strongly affected by fuel type (Zhang *et al*., 2022), but with increasing combustion temperature, the fraction of higher molecular PAHs became larger than that of lower molecular PAHs (McGrath *et al*., 2003; Iinuma *et al*., 2007). On the other hand, the amounts of NPAHs emitted differed greatly depending on combustion temperature. Combustion temperatures in vehicle engines, coal stoves and wood stoves were 2,700 − 3,000°C, 1,100 − 1,200°C and 500 − 600°C, respectively (Hayakawa, 2016). Fig. 4 compares the concentrations of PAHs and NPAHs in PM emitted by diesel vehicles (DEP), coal burning (CEP) and wood burning (WEP). WEP showed the highest concentration of PAHs, followed by CEP. DEP showed the lowest concentration. On the other hand, DEP showed the highest concentration of NPAHs, followed by CEP. WEP showed the lowest concentration.

The above result is explained as follows: The formation of NOx depends on combustion temperature and the formation of NPAHs from corresponding PAHs in the presence of NOx also depends on combustion temperature. Increased combustion temperature results in increased yield of NPAHs. The concentration ratio of NPAHs to their parent PAHs (= [NPAH]/[PAH]) increases depending on elevation of combustion temperature, suggesting an effective index for identifying the combustion source. Based on this principle, a new method using 1-NP and Pyr as monitoring markers has been developed for analyzing source contributions (Hayakawa *et al*., 2020 and 2021). The [1-NP]/[Pyr] ratio of PM from vegetation fires is more than two orders of magnitude smaller than that of PM from vehicles.

4.3 Vegetation Fires Globally

PAHs and their derivatives attract great attention because of their adverse health effects—not only carcinogenicity but also mutagenicity, endocrine disruption activity and reactive oxygen production activity. There have been many reports on the effects of combustion sources on organic and inorganic pollutants formed through biomass combustion. Among them, this report focuses on the combustion of biomass. Globally, the post-harvest burning of crops and forest fires results in widespread air pollution (Chuesaard *et al*., 2014; Pham *et al*., 2019; Tomaz *et al*., 2017; de Oliveira Galvao *et al*., 2018), and domestic heating and cooking using biomass

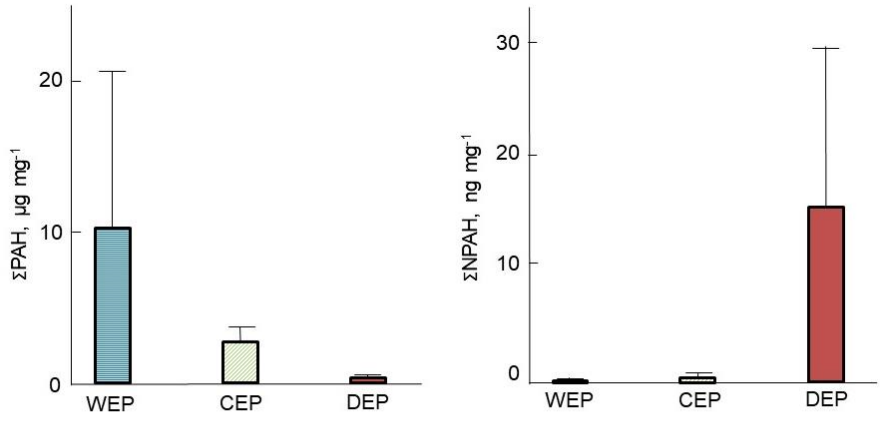


Fig. 4 Concentrations of ΣPAH and ΣNPAH in PMs from different sources.

PM sources: WEP=wood burning; CEP=coal burning; DEP=diesel-engine vehicles.
ΣPAH = FR + Pyr + BaA + Chr + BbF + BkF + BaP + BgPe + IDP. ΣNPAH = 1,3-DNP + 1,6-DNP + 1,8-DNP + 1-NP.

fuels causes indoor air pollution (Kitanovski *et al*., 2020; Chen *et al*., 2017; Orakij, 2017). These are summarized in Table 2. PAHs, OHPAHs and QPAHs and NPAHs were found characteristic. As a marker of vegetation fires, levoglucosan was determined. The decreasing concentration order of [PAHs] > [QPAHs] > [OPAHs] > [NPAHs] and the smaller [1-NP]/[[Pyr] concentration ratio were often observed in air carrying emissions from vegetation fires.

Table 2 Environmental Studies on PAHs and OPAHs from vegetation fires.

Sample	Source	Analyzed Compound	Characteristics	Ref.
Outdoor				
SPM in Chiang Mai, Thailand, in dry and wet seasons	Forest fire and agricultural burning	10PAHs, 19NPAHs	1. ΣPAH (4.1 ng m^{-3}) and ΣNPAH (523 pg m^{-3}) in dry season > ΣPAH (0.70 ng m^{-3}) and ΣNPAH (40.6 pg m^{-3}) in wet season 2. The larger [BaP]/[BgPe] in dry season suggested vegetation fire and the larger [1-NP]/[Pyr] in wet season suggested vehicles.	Chuesaard *et al*., 2014
PM in suburban area of Hanoi, Vietnam	Rice straw open burning	9PAHs, 4NPAHs	1. ΣPAH (4488 ng m^{-3}) and ΣNPAH (288 μg m^{-3}) in burning period > ΣPAH (14 ng m^{-3}) and ΣNPAH(25 μg m^{-3}) in background period 2. ΣPAH > ΣNPAH 3. Secondary formation of 2-NF and 2-NP	Pham *et al*., 2019
PM_{10} in Grenoble, France in winter	Residential heating	21PAHs, 32NPAHs, 27OPAHs, levoglucosan	1. ΣPAH > ΣOPAH > ΣNPAH 2. 2-Methylnaphthalene (48.6 ng m^{-3}), 2-methylfluoranthene (0.4 ng m^{-3}), 1-NP (46 pg m^{-3}) and levoglucosan (2963 ng m^{-3}) in winter were higher than those in summer. 3. Secondary formation of 2-NF and 2-NP	Tomaz *et al*., 2017
PM_{10} in Amazon, Brazil, in dry and wet seasons	Forest fire	11NPAHs, 4OPAHs	1. ΣPAH > ΣNPAH 2. 2-Methylanthraquinon (260 pg m^{-3}) and 1-NP (0.125 ng m^{-3}) in intense vegetation fire period were higher than 2-methylanthraquinon (70 ng m^{-3}) and 1-NP(70 pg m^{-3}) in moderate vegetation fire period.	de Oliveira Galvao *et al*., 2018
SPM (6 fractions less than 10 μm) in Thessaloniki, Greece, in winter	Residential heating	11NPAHs, 7OPAHs	1. ΣQPAH (47–1636 and 858–4306 pg m^{-3}) > ΣNPAH (≤ 90 and 76–578 pg m^{-3}) 2. Distribution dependent on PM size.	Kitanovski *et al*., 2020
Indoor				
PM (5 fractions) in rural areas, China	Cooking	10PAHs, 4OPAHs	1. ΣPAH > ΣNPAH 2. 1-Nitronaphthale: Kitchen (0.80 ng m^{-3}) and living room (0.26 ng m^{-3}) > outdoor (0.13 ng m^{-3}) 3. Benzanthrone: Kitchen (106 ng m^{-3}) > living room (21 ng m^{-3}) 4. Biomass > LPG	Chen *et al*., 2017
$PM_{2.5}$, in Thailand	Cooking	10PAHs, 11OPAHs, levoglucosan	1. ΣPAH (9980 ng m^{-3}) > ΣNPAH (18700 pg m^{-3}) 2. Cooking period > noncooking period 3. The carcinogenic risks exceeded the WHO guideline values.	Orakij *et al*., 2017
$PM_{2.5}$ from kangs and stoves under heating scenarios	Biomass (6 types) and coal (4 types) burning	22PAHs, 7alkyl PAHs, 12NPAHs 10OPAHs	1. ΣPAH (32.3–279 mg kg^{-1}) > ΣOPAH (5.18–42.5 mg kg^{-1}) > ΣNPAH (37.4–343 μg kg^{-1}). 2. Compositions of PAHs and derivatives were not affected by fuel type.	Zhang *et al*., 2021

Abbreviations of PAHs and Their Derivatives

PAHs	polycyclic aromatic hydrocarbons (PAHs), naphthalene (Nap), acenaphthene (Ace), fluorene (Fle), phenanthrene (Phe), anthracene (Ant), Fluoranthene (Flu), pyrene (Pyr), benz[*a*]anthracene (BaA), chrysene (Chr), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo[*a*]pyrene (BaP), dibenz[*a,h*]anthracene (DBA), benzo[*ghi*]perylene (BgPe), indeno[1,2,3-*cd*]pyrene (IDP)
NPAHs	nitrated PAHs (NPAHs), 1-, 2-, 4-nitropyrene (1-, 2-, 4-NP), 1,3-, 1,6-, 1,8-dinitropyrene (1,3-, 1,6-, 1,8-DNP), 1-, 10-nitrobenzanthrone (1-, 10-NBA), 2-nitrofluorene (2-NF), 2-, 9-nitroanthracene (2-, 9-NA), 5-nitroacenaphthene (5-NAc), 4-, 9-nitrophenanthrene (2-, 9-NPh), 3-nitrofluoranthene (3-NFL), 7-nitrobenz[*a*]anthracene (7-NBaA), 2-nitrotriphenylene (2-NTP), 6-nitrochrysene (6-NC), 6-nitrobenzo[*a*]pyrene (6-NBaP), 1-, 3-nitroperylene (1-, 3-NPer)
OHPAHs	halogenated PAHs (XPAHs), hydroxylated PAHs (OHPAHs), 1-, 2-hydroxynaphthalene (1-, 2-OHNap), 1-, 2-, 3-hydroxyfluoranthene (1-, 2-, 3-OHFlu), 1-, 2-, 3-, 9-hydroxyphenanthrene (1-, 2-, 3-, 9-OHPhe), 1-, 2-, 3-hydroxypyrene (1-, 2-, 3-OHPyr), 3-hydroxybenzo[*a*]pyrene (3-OHBaP), 6-hydroxychrysene (6-OHChr), 3-hydroxybenzo[*a*]pyrene (3-OHBaP)
PAHQs	1,4-benzoquinone (BQ), 2-methyl-1,4-benzoquinone (2-MBQ), 2,5- and 2,6-dimethylbenzoquinones (2,5- and 2,6-DMBQ), tetramethylbenzoquinone (TMBQ), 1,2- and 1,4-naphtoquinones (1,2- and 1,4-NQ), 2-methyl-1,4-naphthoquinone (2-MNQ), acenaphthoquinone (AceNQ), 1,4- and 9,10-phenanthrenequinones (1,4- and 9,10-PQ), 1,4- and 9,10-anthraquinones (1,4- and 9,10-AQ), 1,6-, 1,8- and 4,5-pyrenequinones (1,6-,1,8- and 4,5-PyrQ), fluoranthene-2,3-quinone (2,3- FluQ), aceanthraquinone (AceAQ), 1,4- and 5,6-chrysenequinones (1,4- and 5,6-CQ), 5,12-naphthacenequinone (5,12-NapQ), benzo[*c*]phenanthrene-5,6-quinone (5,6-BcPQ), 7,12-benzanthraquinone (7,12-BAQ), benzo[*e*]pyrene-4,5-quinone (4,5- BePQ), benzo[*a*]pyrene-1,6-, -3,6-, -4,5-, -6,12- and -11,12-quinones (1,6-, -3,6-, -4,5-, -6,12- and -11,12- BaPQ), dibenzo[*a,j*]anthracene-7,14-quinone (7,14-DBajAQ) and dibenzo[*a,h*]anthracene-5,6-quinone (5,6-DBahAQ)

5. Conclusion

5.1 Organic material that comes from plants and animals is converted not only to solid fuels but also to gas and liquid fuels. Biomass is attracting attention as a renewable energy source, because organic materials in biomass can be regenerated in a short time period from carbon dioxide, a global warming gas, in the atmosphere.

5.2 As mentioned in this report, combustion of this biomass produces various hazardous chemicals, including PAHs and their derivatives. It will be essential to develop technology to prevent these harmful substances from being released into the air, both outdoors and indoors.

5.3 On the other hand, although restrictions on incineration of post-harvest crop residues have been implemented in developed countries, it is still practiced in developing countries. In addition, forest fires occur frequently around the world, and the number of such fires has been increasing due to global warming. These also raise the atmospheric concentration of PAHs and their derivatives over wide areas—a big problem.

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Kazuichi HAYAKAWA

Kazuichi Hayakawa graduated from the Graduate School of Pharmaceutical Sciences of the University of Tokyo. He became a research assistant at Kanazawa University (1977), was promoted to professor (1996) and then dean of faculty of Pharmaceutical Sciences and director of the Institute of Nature and Environmental Technology (2012–2015). He is now a professor emeritus at Kanazawa University. He led the 21st Century Center of Excellence Program, organized by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) from 2002 to 2008. He has been awarded by the Japan Society of Atmospheric Environment and others, including receiving the Commendation for Science and Technology from MEXT. His research interests are environmental pollution and the health effects of PAHs. He has published more than 400 original papers.

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