Highlights

- Environmental air quality implies evaluating particulate matter from tobacco
- Ultrafine particles isolated both for cigarettes and HNBPs
- Around 50 mg of TPM /stick are collected in the mainstream
- Indoor PM, μg/m³: 100-500 cig, 1.4-15.5 HNBP, 1.3-14.7 background
- Cigarette smoking implies 3-6 times more particles than the use of HNBPs
- Higher volatility of the particulate matter in the aerosol from HNBPs
Review and comparative analysis of the particulate matter generated in conventional cigarettes and heated tobacco products - mainstream and environmental emissions

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Abstract

This study aims to revise and compare published data devoted to the identification, characterization, and quantification of suspended particulate matter (PM) in the smoke from combustible cigarettes or the aerosol from heat-not-burn products (HNBPs), analyzing mainstream and indoor scenarios. It has been motivated by the difficulty of a proper comparison from the published data, mostly due to the very different experimental conditions used in each published study, often not even clearly indicated.

Despite the difficulty in a straightforward comparison, important differences in the particulate matter present in the smoke from combustible cigarettes and the aerosols from HNBPs have been confirmed. In general, the concentration of particulate matter in the aerosol emitted by HNBPs is much lower than in cigarette smoke. However, in the mainstream, ultrafine particulate matter has been isolated both with combustible cigarettes and HNBPs, and the TPM collected is in the same range, around 50 mg/stick, slightly higher for HNBPs. The indoor concentration of PM usually ranges from 100-500 μg/m³ for combustible cigarettes, 1-2 orders of magnitude higher than the present in background air (1.3-14.7 μg/m³), whereas for HNBPs ranges from 1.4-15.5 μg/m³, which is similar to the background. Indoors, the number of particles generated from cigarette smoking is much larger than those from the use of HNBPs in a factor 3-6.
Nevertheless, the mean particle sizes and particulate composition are among the main differences between cigarette smoke and HNBP aerosols. The mean particle sizes are larger in the smoke from combustible cigarettes and contain black carbon particles (soot), whereas the particulate matter from HNPB presents a smaller size, is predominantly liquid-based, and is much more volatile.

**Keywords:** heat-not-burn products; combustible cigarettes; particulate matter size and concentration; indoor and outdoor air; environment.

### 1. Introduction

Cigarette consumption remains one of today’s major health hazards as it is associated with major burdens of mortality (Mallock et al., 2018; Peruzzi et al., 2020). Cigarette smoke has shown to be the cause of health problems, such as cardiovascular ones and, also, can increase the risk of lung infections such as pneumonia, and tuberculosis and, according to the American Cancer Society, it can worsen some existing lung diseases, such as asthma (Wyant et al., 2020). In fact, cigarette smoke approximately consists of more than 7000 compounds and, from them, 98 have been identified as carcinogens (Mallock et al., 2018; Rodgman and Perfetti, 2008). The different chemicals from smoke particles are associated with different diseases (U.S. Department of Health and Human Services, 2014) (Li et al., 2021).

Also, particulate matter pollution (especially solid particles) remains one of the most critical environmental risks to public health. Particles can be released from several heterogeneous sources, which are quite different for outdoor and indoor environments. While the main source of outdoor particulate matter in urban areas is vehicular traffic (Avino et al., 2016; Manigrasso & Avino, 2012), cooking activities and smoking are the most common sources of indoor particulate matter levels (Morawska & Salthammer, 2015). These pollution sources are typically related to combustion activities, which are
known to emit high amounts of toxicants, as well as black carbon (soot) particles. In particular, indoor particulate matter concentration dramatically increases during cigarette smoking (Protano et al., 2014).

Indeed, scientific evidence has shown that exposure to particulate matter containing toxicants is linked to a large number of adverse effects in humans, such as cardiovascular and pulmonary diseases, neurodegenerative diseases, and negative birth outcomes after intrauterine exposure (Protano et al., 2017).

In addition to the adverse effects linked to particulate matter toxicants, also the physical characteristics of the particulate matter can be linked to adverse health effects. For example, (You et al., 2015) highlighted that the black substance observed in the lung tissue of smokers are nano-sized black carbon particles, a universal constituent of smoke derived from the incomplete combustion of organic material, such as tobacco. The black lungs observed in long-term smokers resemble those in people suffering from long-term exposure to air pollution (Janssen; et al., 2017) and what is known as the black lung disease (or Coal Worker’s Pneumoconiosis) that is common in coal mine workers. Inhaled black carbon particles depositing in the lung cannot be easily cleared by the cilia and accumulate in the lung, which perpetuates chronic lung inflammation leading to scarring (fibrosis) and damage even long after the exposure stopped that can lead to complications like tuberculosis, COPD, coronary artery disease (CAD), heart failure, lung cancer as well as premature death and poor quality of life (Janssen; et al., 2017; You et al., 2015).

In general, cigarette smoke particles are typically sub-micrometric and easily deposited in the human respiratory tract during smoking (Li et al., 2021). Indeed, a strong association between exposure to particulate matter with an aerodynamic diameter smaller than 10 μm and respiratory, cardiovascular, neurodegenerative diseases or cancer has been established, with special attention to particulate matter emitted from combustion sources. For example, when cigarettes are smoked, not only water droplets are produced, but also liquid and solid particulate matter with a diameter of less than 10 μm are generated during combustion, which are being inhaled. Therefore, not only the particles sizes, but especially their composition and other physicochemical properties are responsible for their harmful profile (Protano et al., 2020).
Paying attention to the published data, 1.18 billion people regularly smoke tobacco (Dai et al., 2022), and the Institute for Health Metric and Evaluation (IHME) estimates that in 2017 about 13% of deaths worldwide were the result of direct smoking, and further 2% were estimated to be the result of second-hand smoke. This means that around 15% of deaths in the world – about 1-in-7 – are the result of cigarette smoking (Ritchie & Roser, 2013).

In recent years, new tobacco products have been developed as alternatives to combustible cigarettes, including the so-called electronic alternatives to tobacco cigarettes (EATC). Hence, many types of e-vapour products (EVP, as e-cigs or electronic vaping cigarettes) and heat-not burn products (referred to as HNBP, HNBT\(^1\), HNBC\(^2\) or HTP) are currently commercialized worldwide. HNBP are based on heating tobacco to much lower temperatures than in combustible cigarettes (typically in the range from 250-350ºC versus about 800ºC), avoiding combustion (Bechikhi et al., 2024; Cozzani et al., 2020; Eaton et al., 2018; Protano et al., 2020) leading to products that are claimed to be reduced-risk alternatives to cigarettes.

Several HNBP (tobacco sticks) and the corresponding devices to heat them, such as Heets used with IQOS and Terea used with IQOS ILUMA (produced by Philip Morris International), and Neo used with GLO (produced by British American Tobacco), are commercially available.

Some published studies have recently compared, from different perspectives, combustible cigarettes and heat-not-burn products (Sussman et al., 2023). As examples, recent research has proved that in the aerosols of tobacco products, the formation of carbon soot requires much higher temperatures than those involved in heat-not-burn devices (Torero Cullen et al., 2024), or that far lower levels of relevant harmful or potentially harmful constituents are emitted from these newly developed heat-not-burn products (Sussman et al., 2023). Despite this, in general, the indoor use of EATCs is not exempt from particulate matter emission (Protano et al., 2017).

Thus, for the assessment of risks related to tobacco products, it is necessary to take into account the health recommendation regarding the target maximum concentration of particles, both indoor and outdoor, and to have reliable data about the size,

\(^1\) heat-not-burn tobacco
\(^2\) heat-not-burn cigarette
concentration, and chemical composition of the particulate matter generated by the use of HNBPs. However, as the toxicological effect of inhaled particulate matter depends not only on the particle size, threshold values for tolerable exposure also need to consider the nature of such particulate matter, such as its physical and chemical composition.

Up to now, no “safe” specific values for particulate matter concentrations in private enclosed environments have been established. For the exposure of the general population to outdoor air, the World Health Organization (WHO) has indicated guideline maximum values, updated in 2021, for the allowed average daily of long-term exposure levels of PM$_{10}$ (15.0 μg/m$^3$) and PM$_{2.5}$ (5.0 μg/m$^3$), being PM$_{10}$ and PM$_{2.5}$ relative to particles with an aerodynamic diameter equal or lower than 10 μm and 2.5 μm (called fine), respectively. These values are usually based on particles that contribute to air pollution (i.e. black carbon) and, therefore, they do not take into account the physical and chemical characteristics of the particulate matter.

Focusing on the particulate matter released when using tobacco products, this study aims to review the published data on this topic (regarding concentration, size, and physico-chemical composition). Attention is paid to the brand of cigarettes and HNBP tobacco sticks, as well as the models of devices used with tobacco sticks, and also to experimental parameters like the “regime” and environment conditions of the puffing tests, the method of particulate matter collection, and the characterization techniques used to determine the physical and chemical characteristics of the collected particulate matter.

It should be highlighted that the most often used HNBP system involves the device commercially known as IQOS, which is part of the “Tobacco Heating System 2.2” (THS2.2), currently marketed in more than 73 countries (Fraser, 2023; Mallock et al., 2018) by Philip Morris International. A THS 2.2 is based on three components, the charger, the tobacco holder, and the tobacco sticks, named Heets. This THS 2.2 system is frequently reported in the studies on emissions and toxicity of HNBP systems, and the correspondent results are compared with those for combustible cigarettes, especially using the one identified as 3R4F (a standard reference cigarette developed by the Centre for Tobacco Reference Products from the University of Kentucky that is used throughout tobacco industry and academic laboratories as a constituent and uniform test item for inhalation toxicology research) (Shein and Jeschke, 2019, Xiangyu et al., 2019, Li et al., 2021), or with Marlboro Gold cigarettes (Mitova et al., 2016, Meišutovič-Akhtarieva et al., 2019, Peruzzi et al., 2020, Protano et al., 2020).
A straightforward comparison of the particulate matter concentration, absolute numbers, shapes, and physico-chemical nature, in smoke and aerosol emissions from different sources is challenging, on one side because of the limited number of studies devoted to HNBP s and, on the other side, because of the great variability of experimental conditions. In addition, information on the brand and model of the device and stick used is sometimes missing.

This review is organized as follows: a summary of the experimental conditions used in the reviewed studies is included in the supplementary material (including tobacco products, and the aerosol generation and sample collection procedures). Next, the results obtained in those studies are presented and commented on, attending to the concentration and size of the detected particles, the total amount of collected particulate matter, and the composition of such matter. Afterwards, all the results are discussed and, finally, the derived conclusions are outlined. The contents of each of these sections, excluding the conclusions, are organized in two parts: one devoted to the mainstream aerosol and another one devoted to environmental emissions, paying attention to particulate matter emitted into indoor air during the tobacco products use.

2. Results from the literature and discussion

The present section is devoted to the results obtained in the studies compiled in the Supplementary Materials Section, organized in three different sections; i) Particulate matter concentration and size, ii) Total collected particulate matter, and iii) Composition of the particulate matter. These sections are discussed in two blocks, a) the mainstream aerosol and b) the environmental emissions.

The obtained results are expressed in terms of total weight of particulate matter (mg/stick), number of particles, weight of particulate matter (mg), and dimensions of particles (µm). Data about the physico-chemical composition of the particulate matter is also presented.

It is important to highlight that, for size measurements, particle concentration, and total collected particulate matter analysis, most of the studies do not specify the physical and chemical composition of particulate matter (whether the particulate matter is solid, liquid, or both, and whether it contains many or only a few chemical constituents or high or low levels of these constituents).
2.1. Particles concentration and size

2.1.1. Mainstream aerosol

(Pratte et al., 2017) highlighted that the solid particle term refers to the possible combination of solid particulate matter and high boiling point droplets, and showed that no solid particles were formed and transferred in the mainstream aerosol of THS2.2 during use when compared to the blank, while a significant number of solid particles (approximately $10^{12}$ solid particles/stick, in an 11 puffs test) were collected from the mainstream smoke of 3R4F in comparison to the blank. The count median diameter of solid particles collected from 3R4F smoke was approximately 75 nm (this size corresponds to UFPs, typically found in combustion/pyrolysis processes). In this study it was noted that the presence of solid organic particles in the mainstream smoke of 3R4F is an indication that pyrolysis/combustion took place, while their absence in THS2.2 mainstream aerosol indicates that no combustion occurred and that the aerosol particulate matter is droplet (liquid) based.

(Pratte et al., 2018) used the thermo-denuder technology to demonstrate that for 3R4F mainstream smoke, solid particles or high boiling point droplets, approximately 100 times larger than the Lower Limit of Quantification (LLOQ is the minimum value that can be reported) were detected and quantified. In contrast, for THS2.2 mainstream aerosol, the obtained values were coincident with the LLOQ. These results proved that combustion-related particles were neither detected nor observed in the mainstream aerosol of THS2.2.

(Amorós-Pérez et al., 2021) performed tests bubbling cigarette smoke through water and found, in the water from these cigarette tests, particles or particle agglomerates of size ranging from 0.3 to 110 μm, with a main maximum at 15 μm. In the water samples collected in analogous Heets tests, no particles were detected. Laser diffraction was the technique used for this characterization. Moreover, using high-resolution transmission electron microscopy (HR-TEM) coupled with energy dispersive X-ray (EDX), these authors detected a noticeable amount of solid matter in the liquid samples from cigarettes experiments, while only very few in liquid samples from Heets experiments. In fact, for the latter, they had to be searched specifically in order to analyse them and were not statistically representative. Regarding the size and shape of the particulate matter, for cigarettes, well-defined homogeneous spherical structures, with a size distribution ranging between 30 and 180 nm and a maximum at about 110 nm were found. However, in the case of Heets, small areas that could be related to undissolved particulate matter
and/or soluble matter (“visible” after evaporation on the transmission electron microscope grid used for the characterization) were detected, generating an agglomerated structure with undefined shapes very different from the shapes of the solid particles found in the cigarette smoke samples.

(Kärkelä et al., 2021) proved that the combustible tobacco products (3R4F cigarettes) produce and release combustible-related solid particles, whereas tobacco in THS2.2 is heated and not combusted, forming a liquid-based aerosol which is free of combustible-related solid particles. Also, the authors related most of the 3R4F particulate matter collected on the impact plates after the thermo-denuder to submicron particles with a median diameter of 75 nm. Note that this is not the size of the particle in the smoke, but the size of the impacted particles after the thermo-denuder.

(Li et al., 2021) studied the distribution of aerosol particles deposited in the human respiratory tract in the range from 5 to 1000 nm. For 3R4F, the particle size of the smoke was mainly concentrated in the range of 50-600 nm, and it was close to 200 nm at the peak number concentration. The particulate matter size of the HNBP aerosol was mainly concentrated in the range of 10-200 nm, and it was close to 50 nm at the highest number concentration. Differences exist in the particulate matter size for the two product types, with mean size increasing in the following order: HNBP (50.6-55.3 nm) < combustible cigarettes (172-179 nm). Besides, these authors concluded that the deposition fraction (of aerosol particulate matter from the three tobacco products tested) in different regions of the human respiratory tract followed the trend: head airway < tracheobronchial region < pulmonary region.

(Amorós-Pérez et al., 2022) paid attention to the particulate matter deposited on different parts of their experimental simulation set-up. For the agglomerated matter deposited on the glass tube and collected with water, the mean particle sizes analysed by laser diffraction were 171 μm and 265 μm for Heets and cigarettes, respectively. On the flask walls, spherical particles embedded in a soluble shapeless structure were observed by TEM from liquid samples from cigarettes experiments, with sizes ranging from 5 to 100 nm (although most particle sizes are below 20 nm), whereas the shapes of deposited fragments in the samples recovered from Heets’ experiments present a very different aspect, with no clear particle limits, which suggest a liquid nature of the aerosol from Heets compared to the liquid and solid particles found in mainstream cigarette smoke.

(Kärkelä et al., 2022) showed that the deposition of 3R4F smoke was characterized by dark-yellow and brown colours, whereas the deposition from the IQOS
aerosol was a pale-yellow tone. The IQOS aerosol mass concentration ranged from 5 to 11 g/m$^3$, while for 3R4F cigarettes, the smoke mass concentration ranged from 49 to 56 g/m$^3$. Therefore, IQOS emissions resulted in approximately 5-10 times lower captured mass in comparison to 3R4F cigarette, likely due to evaporation of the high water content in the collected particulate matter on the filter during puffing. This indicates that the IQOS particulate matter is much more volatile than that of cigarette smoke, which was also confirmed by the SEM analysis which showed that the particulate matter from the IQOS aerosol is liquid-like.

2.1.2. Environmental emissions

(Mitova et al., 2016) studied indoor air mass concentration of breathable suspended particulate matter of size lower than 2.5 μm in diameter of Heets in THS2.2 and Marlboro Gold cigarette samples. Measured breathable suspended particulate matter in the simulated “Office” were <14.7 and 204 μg/m$^3$ for Heets in THS2.2 and Marlboro Gold, respectively (background: <14.7 μg/m$^3$); in “Residential” condition they were <14.7 and 268 μg/m$^3$ for Heets in THS2.2 and Marlboro Gold, respectively (background: <14.7 μg/m$^3$); and in “Hospitality” condition they were 15.5 and 147 μg/m$^3$ for Heets in THS2.2 and Marlboro Gold, respectively (background: <14.7 μg/m$^3$). The results, compiled in Figure 1, highlight the differences between cigarettes and Heets, from the point of view of suspended particulate matter and remark that the measured suspended particulate matter values from the use of Heets in THS2.2 were either equivalent to background levels for all the conditions tested.

![Figure 1](image.png)

**Figure 1.** Breathable suspended particulate matter of size < 2.5 μm in indoor air from Marlboro Gold cigarette and Heets in THS2.2, measured by (Mitova et al., 2016).

(Protano et al., 2017) analysed the emission of submicronic particles from combustible cigarettes (Pall Mall San Francisco) and Heat-not-burn electronic devices.
(IQOS, with a Marlboro Balanced Regular stick). They evaluated the number concentration of particulate matter with diameters ranging 5-560 nm. Their study showed peak concentrations ranging from $1.2 \cdot 10^5$ to $2.9 \cdot 10^5$ particles/cm$^3$ for combustible cigarettes, whereas peak concentrations for heat-not-burn devices were below $4.7 \cdot 10^4$ particles/cm$^3$. Besides, it is important to highlight that the authors report a big difference in volatility of HNBP aerosols compared to smoke from combustible cigarettes.

(Ruprecht et al., 2017) confirmed that combustible cigarettes are a significant source of PM emissions and measured particulate matter number concentration in indoor air for three micrometric size ranges, including PM$_{0.3 \mu m}$ (1.012 particles/cm$^3$), PM$_{1.0 \mu m}$ (1.1 particles/cm$^3$) and PM$_{nm}$ (122,672 particles/cm$^3$). For IQOS, PM$_{1.0}$ were non-detectable, whereas 24 particles/cm$^3$ for PM$_{0.3}$ and 27,745 particles/cm$^3$ for PM$_{nm}$ were detected. Focusing on PM mass, combustible cigarettes smoking released particulate matter mass concentration of 151, 500 and 529 µg/m$^3$ for PM$_1$, PM$_{2.5}$ and PM$_{10}$, whereas the release from IQOS was 1.4, 6.5 and 8.1 µg/m$^3$ for PM$_1$, PM$_{2.5}$ and PM$_{10}$, respectively. These data are compiled in Figure 2, highlighting the relevant differences between combustible cigarettes and Heets in IQOS, the latter in the range of background air.

![Figure 2. Particulate matter mass concentration in indoor air for three micrometric size ranges for combustible cigarette and Heets in THS2.2 samples, measured by (Ruprecht et al., 2017).](image)

The comparison between combustible cigarettes and IQOS was also performed measuring carbon content in the emissions measured at two wavelengths, 370 and 880 nm, reminding that 370 nm wavelength allows the quantification of organic compounds and 880 nm allows the quantification of black carbon (soot). Combustible cigarettes showed a high level of carbon mass concentrations, 78.0 and 2.3 µg/m$^3$ for 370 and 880 nm wavelengths, respectively. For IQOS, an organic carbon content level of 0.57 µg/m$^3$ was determined using 370 nm wavelength, while no detectable level of black carbon
(soot) was found using 880 nm wavelength. It is important to highlight that the carbon content in IQOS emissions detected at 370 nm wavelength represents organic compounds present in the aerosol (such as glycerol), whereas black carbon was not detected.

(Meišutovič-Akhtarieva et al., 2019) focused their analysis on a limited particle size ranging from 0.006 μm to 10.0 μm and concluded that, in each range size analysed, combustible cigarettes produced higher amount of particulate matter than THS (see Figure 3). Specifically, for PM$_{2.5}$ μm, 5.7 ± 7.6 μg/m$^3$ and 159.4 ± 57.1 μg/m$^3$ were found for THS and combustible cigarettes, respectively (the background levels were 3.3 ± 4.1 μg/m$^3$ for THS and 1.3 ± 8.4 μg/m$^3$ for combustible cigarettes). Focusing on PM$_{10}$ μm, values of 8.3 ± 54.9 μg/m$^3$ and 179.8 ± 191.2 μg/m$^3$ were found for THS and combustible cigarettes, respectively, (the background levels were 7.5 ± 6.0 μg/m$^3$ for THS and 5.8 ± 21.1 μg/m$^3$ for combustible cigarettes).

**Figure 3.** Particulate matter mass concentration in indoor air for two micrometric size ranges for combustible cigarette and THS, measured by (Meišutovič-Akhtarieva et al., 2019).

The authors also highlighted that the intensive use of THS in a confined space with limited ventilation might cause substantially elevated aerosol concentrations, although the particulate matter appeared as highly volatile, and evaporated within seconds.

(Peruzzi et al., 2020) measured the particulate matter from environmental emissions in a limited particle size range of 0.1-10 μm in three different real-life conditions: 5 min before use, during use, and 5 min after using, for one type of combustible cigarette and several different IQOS Heets variants (see Figure 4).

Before each experiment, in blank measurements to quantify the particulate matter present before the use of cigarettes or sticks, median background PM mass concentrations were 10 μg/m$^3$ for combustible cigarettes, and comprised between 12 and 21 μg/m$^3$ for the different IQOS Heets (Amber, Blue, Bronze, Sienna, Turquoise and Yellow), with an average background value before IQOS use of 16 μg/m$^3$. 
During the experiment, for combustible cigarettes, median PM levels rose to 1250 μg/m³, while for IQOS an average mass concentration of 31 μg/m³ was determined. Focusing on different IQOS Heets, Sienna led to the highest particulate matter mass concentration (90 μg/m³), followed by Turquoise (43 μg/m³), Amber (42 μg/m³), Yellow (26 μg/m³), Blue (22 μg/m³) and Bronze (20 μg/m³). The different IQOS Heets yielded significantly lower levels of emitted particulate matter in the indoor air than cigarettes.

After the experiments, for combustible cigarettes median PM levels rose to 1400 μg/m³, while for IQOS an average mass concentration of 28 μg/m³ was determined. Focusing on different IQOS Heets, Turquoise led to the highest particulate matter mass concentration (47 μg/m³), followed by Yellow (32 μg/m³), Sienna and Amber (both 25 μg/m³), Bronze (23 μg/m³) and Blue (16 μg/m³). It is important to highlight that, in the data shown, background values have not been removed from the values obtained during cigarettes smoking or Heets use.

Figure 4a evidences that there is particulate matter present in all the tests, before (in the background experiments), during, and after use, both for Heets and for cigarettes. Nevertheless, the particulate matter mass concentration for cigarettes during and after use is over three orders of magnitude larger than for any of the Heets. In the case of cigarettes, the particulate matter mass concentration after use is even a bit larger than during use.

Regarding Heets, Figure 4b shows that the particulate matter mass concentration in general increases slightly during the use of sticks (using Sienna sticks the mass concentration of particulate matter in air increases significantly, followed by Turquoise and Amber sticks). After the use of IQOS with Heets, two different behaviours are observed: (1) the mass concentration of particles is lower than during sticks use, but higher than for the background (Amber, Blue, and Sienna) and (2) after use, the mass concentration of particles is slightly higher than during use (Bronze, Turquoise and
In any case, it should be highlighted that, in general, the particulate matter during IQOS use is between 1-6 times higher than in background experiments (average 2.6 times larger), whereas the particulate matter during combustible cigarettes use is 125 times higher than in background experiments.

(Protano et al., 2020) evaluated the levels of particulate matter of different size fractions, ranging from 0.1 to 10 μm. The authors considered particulate matter with a diameter smaller than 1 μm (PM$_1$) as the most representative size fraction (>95% of the total PM emitted in all monitored combinations) emitted into indoor air before (background values) and during the use of combustible cigarettes (Marlboro Gold) and IQOS Heets (Amber, Blue, Bronze, Sienna, Turquoise, Yellow) in a test room with voluntary smokers.

Before each experiment (Background), the level of PM$_1$ measured in the combustible cigarettes was 4.0 μg/m$^3$. During the use of Heets with IQOS, median values were 13.0, 13.0, 9.0, 7.0, 22.0 and 10.0 μg/m$^3$ for Amber, Blue, Bronze, Sienna, Turquoise and Yellow, respectively. However, during each experiment, the level of PM$_1$ measured for the combustible cigarettes was 3430 μg/m$^3$. Using Amber, Blue, Bronze, Sienna, Turquoise and Yellow, median values were 70.0, 21.0, 11.0, 337.5, 32.0 and 21.0 μg/m$^3$, respectively. These results prove that the combustible cigarettes smoking involves much higher particulate matter emission (Figure 5a) than when using Heets with IQOS, although low levels of particulate matter could be detected after IQOS use as well (Figure 5b).

(Savdie et al., 2020) evaluated the mass concentration of particulate matter in the 0.1 to 15 μm range, concluding that in home simulation, combustible cigarettes led to the highest increase in PM$_1$ (3470 ± 1570 μg/m$^3$), PM$_{2.5}$ (3480 ± 1570 μg/m$^3$) and PM$_{10}$ (3480 ± 1570 μg/m$^3$), whereas for HNBP the values were (PM$_1$: 80.6 ± 51.3 μg/m$^3$; PM$_{2.5}$: 81.6
± 51.3 μg/m³; PM_{10}: 87.8 ± 51.7 μg/m³). PM_{1} was the dominant fraction for TCs (98.6%) and HNBP (92.1%), followed by PM_{2.5-10} (TCs: 1.2% and HNBP: 6.8%). Focused on ultrafine particles (0.001-1.0 μm), HNBP showed lower UFP number concentration (35700 particles/cm³) than TCs (110000 particles/cm³).

These results, compiled in Figure 6, highlight that the use of cigarettes resulted in much higher PM mass concentrations and higher ultrafine particle number concentrations than when IQOS were used. Analysing all the aerosol samples, UFP represent both liquid droplets and solid particles.

Figure 6. Concentration in indoor air of: a) PM mass concentration, expressed as µg/m³, and b) UFP number concentration, expressed as particles/cm³, comparing TC and HNBP. Measured by (Savdie et al., 2020).

These authors also performed a simulation of the average particulate matter mass concentration inside cars due to cigarettes smoking or HNBP use (not compensated for the background levels), evidencing that TC1 and TC2 led to the highest increase in PM_{1} (963 μg/m³ for TC1 and 905 μg/m³ for TC2), PM_{2.5} (967 μg/m³ for TC1 and 905 μg/m³ for TC2) and PM_{10} (973 μg/m³ for TC1 and 912 μg/m³ for TC2) in comparison to HNBP (PM_{1}: 23.3 μg/m³; PM_{2.5}: 24.7 μg/m³; PM_{10}: 26.7 μg/m³) and to the background values (PM_{1}: 46.2 μg/m³; PM_{2.5}: 49.5 μg/m³; PM_{10}: 57.2 μg/m³ for TC1 background; PM_{1}: 43.4 μg/m³; PM_{2.5}: 45.3 μg/m³; PM_{10}: 49.7 μg/m³ for TC2 background and PM_{1}: 14.5 μg/m³; PM_{2.5}: 15.9 μg/m³; PM_{10}: 18.3 μg/m³ for HNBP background). HNBP showed lower UFP number concentration than TC1 and TC2 (22100 versus 141000-142000 particles/cm³).

Note that the control UFP number concentrations for TC1, TC2 and HNBP experiments were 31733, 42700 and 7940 particles/cm³, respectively.

Peak mass concentrations of black carbon (not compensated for the background levels) were measured during home simulation, being 13.2 ± 5.2 μg/m³ for TCs and 1.2
± 0.7 μg/m³ for HNBP. Only the TC values were found to be clearly distinguishable from the background values. During car simulation, the peak black carbon mass concentrations were 6.1 ± 4.0 μg/m³, 2.1 ± 0.9 μg/m³ and 0.5 ± 0.3 μg/m³ for TC2, TC1 and HNBP, respectively. However, the authors stated that black carbon mass concentrations measured in vehicles are much more related to the outdoor environment rather than to indoor pollution sources.

### 2.2. Total collected particulate matter

#### 2.2.1. Mainstream aerosol

(Schaller et al., 2016a) evaluated the TPM in mainstream smoke from cigarettes and aerosol from IQOS, showing similar values for both, 49.0 mg/cigarette and 43.5-48.2 mg/stick (depending on the sticks version: Regular or Menthol). No evidence of tobacco combustion was found for the THS2.2 system with the used puffing regime.

(Schaller, Pijnenburg, et al., 2016) compared the TPM in mainstream smoke from cigarettes and aerosol from IQOS, showing values of 44.7 mg/cigarette and 46.8-57.8 mg/stick in the 43 different blend sticks. In the reference stick, the TPM value was 54.7 ± 3.2 mg/stick. The analysis of CO and nitrogen oxides as chemical markers of tobacco combustion confirmed that no combustion occurred in any of the THS2.2 systems.

(Mallock et al., 2018) detected 52.6 mg TPM/stick in the aerosol from THS2.2 and made a comparison with the lowest and highest levels found in combustible cigarettes by (Counts et al., 2005), which ranged 27.5-60.9 mg/cig., depending on the different combustible cigarette brand.

(Xiangyu et al., 2019) concluded that under ISO regime, TPM in 3R4F cigarettes and in Heets with THS2.2 system was 9.77 and 25.70 mg/stick, respectively, while under HCI regime, TPM collected for cigarettes and for Heets in THS2.2 was 37.70 mg/cigarette and 55.82 mg/stick, respectively. NFDPM from Heets in THS2.2 system was almost the same as for 3R4F (under ISO regime, NFDPM in cigarettes and THS2.2 system was 7.98 and 7.47 mg/stick, respectively, while under HCI regime 25.50 and 16.60 mg/stick of NFDPM were collected for 3R4F and THS2.2 device, respectively).

These authors concluded that puffing regime has shown to affect the comparison results between HNBP and combustible cigarettes.

(Cozzani et al., 2020) determined that under HCI regime, TPM values were 55.2 ± 1.6 and 45.8 ± 1.38 mg/unit for THS2.2 and 3R4F, respectively, and 16.5 ± 3.4 and 27.6 mg/unit of NFDPM for THS2.2 and 3R4F, respectively, were determined.
The average mass of collected insoluble particulate matter per experiment with combustible cigarettes by (Amorós-Pérez et al., 2022) was 13.3 mg (of viscous material) per cigarette in continuous smoking experiments (continuous air flow). This data was obtained from five repeated tests. For Heets, it was no possible to experiment with continuous air flow due to the device firmware relying on distinct puffs being taken to operate, but no viscous material was observed during Heets puffing experiments.

(Kärkelä et al., 2022) estimated the number of submicron particles to $6 \times 10^7$ (in six impaction spots) for 3R4F combustible cigarettes, while THS2.2 aerosol was free of combustible-related solid particles.

Figure 7 collects the values of the total particulate matter collected from experiments with cigarettes and sticks under the HCI regime. These data highlight that the values are slightly superior for the HTPs, in comparison with combustible cigarettes.

![Figure 7. TPM collected from mainstream experiments with cigarettes and with sticks under the HCI regime by the authors indicated.](image)

2.2.2. Environmental emissions

(Mitova et al., 2016) indicated that the volume of studied spaces was 72.3 m$^3$, being able to quantify the total particle matter in indoor air. Hence, the authors found that, for particles with size lower than 2.5 μm in diameter, measured breathable suspended particulate matter in the simulated “Office” were <1.06·10$^3$ μg and 1.47·10$^4$ μg for Heets in THS2.2 and Marlboro Gold, respectively (background: <1.06·10$^3$ μg); in “Residential” condition they were <1.06·10$^3$ μg and 1.94·10$^4$ μg for Heets in THS2.2 and Marlboro Gold, respectively (background: <1.06·10$^3$ μg); and in “Hospitality” condition they were 1.12·10$^3$ μg and 1.06·10$^4$ μg for Heets in THS2.2 and Marlboro Gold, respectively (background: <1.06·10$^3$ μg).

(Protano et al., 2017) used a 52.7 m$^3$ test room and evaluated the emitted particulate matter number concentrations. These values corresponded to peak emitted particulate matter values ranging from $6.32 \times 10^{12}$ to $1.53 \times 10^{13}$ particles for combustible...
cigarettes (Pall Mall San Francisco), whereas the peak of emitted particulate matter values for heat-not-burn devices (IQOS, with a Marlboro Balanced Regular stick) were below $2.48 \times 10^{12}$ particles.

(Ruprecht et al., 2017) discussed the environmental emission-related particles number in a 48 m$^3$ volume of studied space. The numbers for combustible cigarettes (where background is included) are: PM$_{0.3}$ ($4.86 \times 10^{10}$ particles), PM$_{1.0}$ ($5.28 \times 10^7$ particles) and PM$_{nm}$ ($5.89 \times 10^{12}$ particles). For IQOS, PM$_{1.0}$ were non-detectable, whereas $1.15 \times 10^9$ particles for PM$_{0.3}$ and $1.33 \times 10^{12}$ particles for PM$_{nm}$ were detected. Focusing on PM mass, combustible cigarettes smoking released $7.25 \times 10^3$, $2.40 \times 10^4$ and $2.54 \times 10^4$ μg for PM$_1$, PM$_{2.5}$ and PM$_{10}$, respectively. PM mass emissions from IQOS use were $6.72 \times 10^1$, $3.12 \times 10^2$ and $3.89 \times 10^2$ μg for PM$_1$, PM$_{2.5}$ and PM$_{10}$, respectively. These results highlight that the total particulate matter in the aerosol from IQOS systems is close to two orders of magnitude lower than the mass of particulate matter in smoke from combustible cigarettes. No indication of the physical state of the particulate matter was provided in this study.

(Shein & Jeschke, 2019) detected quantities of TPM similar to those previously reported by (Mallock et al., 2018) in 3R4F and THS2.2 with tobacco sticks: 32.6 mg/cigarette and 26.1 mg/stick, respectively.

(Peruzzi et al., 2020) measured the particulate matter from environmental emissions in a 53 m$^3$ room for particle size range of 0.1-10 μm in three different real-use conditions: 5 min before use, during use, and 5 min after using, for one type of combustible cigarette and several different IQOS Heets variants (Amber, Blue, Bronze, Sienna, Turquoise and Yellow). From the particulate matter concentration values and the room value, the TPM can be determined.

The background TPM values were $5.30 \times 10^2$ μg for combustible cigarettes and on average $8.48 \times 10^2$ μg before IQOS use. Focusing on the different IQOS Heets variants, the background values comprised between $6.36 \times 10^2$ and $1.11 \times 10^3$ μg.

During the experiment, for combustible cigarettes, median PM levels rose to $6.63 \times 10^4$ μg, while for IQOS an average load of $1.64 \times 10^3$ μg was determined. Focusing on different IQOS Heets variants, Sienna led to the highest particulate matter mass ($4.77 \times 10^3$ μg), followed by Turquoise ($2.28 \times 10^3$ μg), Amber ($2.23 \times 10^3$ μg), Yellow ($1.38 \times 10^3$ μg), Blue ($1.17 \times 10^3$ μg) and Bronze ($1.06 \times 10^3$ μg). The different Heets variants used with IQOS yielded significantly lower levels of indoor particulate matter than cigarettes.
After the experiments, for combustible cigarettes median PM levels rose to $7.42 \times 10^4 \, \mu g$, while for IQOS an average TPM value of $1.48 \times 10^3 \, \mu g$ was determined. Focusing on different IQOS Heets variants, Turquoise led to the highest particulate matter mass ($2.49 \times 10^3 \, \mu g$), followed by Yellow ($1.70 \times 10^3 \, \mu g$), Sienna and Amber (both $1.33 \times 10^3 \, \mu g$), Bronze ($1.22 \times 10^3 \, \mu g$) and Blue ($8.48 \times 10^2 \, \mu g$). It is important to highlight that, in the data shown, background values have not been removed from the values obtained during cigarettes smoking or Heets use.

Protano et al., 2020 indicated that the experiments were performed in a dedicated test room of 52.7 m$^3$ using voluntary smokers and evaluated the levels of particulate matter of different size fractions, ranging from 0.1-10 μm. Hence, the total particulate matter emitted in indoor air can be quantified from their data.

Before each experiment, the background level of PM$_1$ measured in air before smoking combustible cigarettes was $2.11 \times 10^2 \, \mu g$. Before using Heets with IQOS, median background values were $6.85 \times 10^2$, $6.85 \times 10^2$, $4.74 \times 10^2$, $3.69 \times 10^2$, $1.16 \times 10^3$ and $5.27 \times 10^2 \, \mu g$ for Amber, Blue, Bronze, Sienna, Turquoise and Yellow variants, respectively. However, during each experiment, the level of PM$_1$ measured for the combustible cigarettes was $1.81 \times 10^5 \, \mu g$. During the use of Heets with IQOS, the median values for each Heets stick variants were $3.69 \times 10^3$, $1.11 \times 10^3$, $5.80 \times 10^2$, $1.78 \times 10^4$, $1.69 \times 10^3$ and $1.11 \times 10^3 \, \mu g$ for Amber, Blue, Bronze, Sienna, Turquoise, and Yellow, respectively.

In the study by Savdie et al., 2020, not only the concentrations but also the volume of the spaces were indicated. So that the total particulate matter in the environmental air, in a 73 m$^3$ volume of studied space, can be quantified from their data. In the home simulation of the use of combustible cigarettes and HNBT, these authors evaluated the particulate matter in the 0.1 to 15 μm range, concluding that in home simulation, TC led to a higher content in PM$_1$ ($2.53 \times 10^5 \, \mu g$), PM$_{2.5}$ ($2.54 \times 10^5 \, \mu g$) and PM$_{10}$ ($2.54 \times 10^5 \, \mu g$) than in HNBT (PM$_1$: $5.88 \times 10^3$; PM$_{2.5}$: $5.96 \times 10^3$; PM$_{10}$: $6.41 \times 10^3 \, \mu g$). Focused on the number of ultrafine particulate matter, HNBT ($2.61 \times 10^9$ particles) showed lower UFP value than TCs ($8.03 \times 10^9$ particles).

The corresponding quantification values in cars as a result of cigarettes smoking or HNBP use were, for TC1: PM$_1$ ($7.03 \times 10^4 \, \mu g$), PM$_{2.5}$ ($7.06 \times 10^4 \, \mu g$) and PM$_{10}$ ($7.10 \times 10^4 \, \mu g$) mass, followed by TC2 (PM$_1$: $6.61 \times 10^4$; PM$_{2.5}$: $6.62 \times 10^4$; PM$_{10}$: $6.66 \times 10^4 \, \mu g$) and HNBP (PM$_1$: $1.70 \times 10^3$; PM$_{2.5}$: $1.80 \times 10^3$; PM$_{10}$: $1.95 \times 10^3 \, \mu g$). The number of UFP were $1.04 \times 10^{10}$ for TC1 and TC2 and $1.61 \times 10^9$ particles for HNBP.
Total particulate matter was calculated from the peak mass concentrations measured in this study and the indicated volume of the spaces, leading to values of 0.9636 μg for TCs and 0.0876 μg for HNBP during home simulation. During car simulation, the total particulate matter was 0.061, 0.021 and 0.005 μg for TC2, TC1 and HNBP, respectively.

Paying attention to those studies that provide information on the number of particles generated in indoor environments as a result of the use of cigarettes or Heets, Figure 8 compiles the ratio of the number of particles measured indoors as a result of smoking cigarettes and using Heets. This figure highlights that, in all those papers, the number of particles generated as a result of cigarette smoking is much higher than those from the use of Heets. The factor ranges from 3 to 6, depending on the study and the indoor scenario size and conditions.

![Figure 8. Ratio between the number of particles measured indoors as a result of smoking cigarettes and using Heets.](image.png)

2.3. Composition of the particulate matter

2.3.1. Mainstream aerosol

(Pratte et al., 2017) determined that the solid particles found in 3R4F mainstream smoke are mainly carbon-based material with oxygen. In addition, potassium and chlorine were found. Also, to a lesser extent, traces of aluminium, sulphur, and silicon were detected. For THS2.2 mainstream aerosol, no solid particles were found compared to the blank.

(Kärkelä et al., 2021) analysed by STEM/EDX that particles in the smoke from 3R4F were mainly composed of carbon, oxygen, potassium, and calcium. Other minor components were also detected, such as silicon, chlorine, sulphur, nitrogen, and aluminium. In the case of IQOS aerosol, the deposited particulate matter had the
appearance of droplet-like agglomerates, without any clear indication of primary particles. Also, the authors reported that the particulate matter was somewhat beam sensitive and easily evaporated during the imaging due to electron beam interaction. The authors could not obtain a clear view of the elemental composition of the particulate matter, but they stated that the particulate matter emitted from IQOS is most likely liquid agglomerates of the aerosol former glycerol, together with condensates of other emitted compounds.

(Amorós-Pérez et al., 2021) analysis by EDX concluded that both combustible cigarettes and Amber IQOS-derived particulate matter collected in water mainly contained carbon (60 wt.% for combustible cigarettes and 90 wt.% for Heets) and oxygen (30 wt.% for combustible cigarettes and 10 wt.% for Heets). For combustible cigarettes, the authors also detected other elements, such as Si, K and S, present in appreciable amounts, being all of them homogeneously distributed in the particulate matter. For Heets, very low amounts of Si, S and Ca homogeneously distributed were detected. It is important to highlight that there was almost no water insoluble particulate matter detected in collected aerosol from IQOS (implying that the particulate matter emitted by IQOS is liquid-based and soluble), while abundant solid particles were detected in cigarette smoke.

The solid matter collected for cigarettes tests by (Amorós-Pérez et al., 2022) was mostly composed of organic non water-soluble compounds (essentially formed by C and O). In addition, traces of other elements were detected by XRF, TEM-EDX, and ICP-MS. S, K, and Ca were identified by the three mentioned techniques and, besides, some elements were only detected in some of the used techniques (for example, Fe and As were detected by XRF and ICP-MS, and Na, Al, Si, and Ba by ICP-MS and TEM-EDX).

EDX analysis for particulate matter deposited on the rubber piece of the experimental setup and dissolved/dispersed in water from combustible cigarettes analysed by (Amorós-Pérez et al., 2022) revealed the presence of Ti, C, O, Si, and S. S, C, and O were detected in all the analysed particles, while Ti or Si was only present in some particles. The TEM-EDX elemental mapping images obtained for the samples collected on the glass tube after 15 Amber Heets tests show that they were mainly composed of C and O, and both elements were homogeneously distributed.

2.3.2. Environmental emissions

(Ruprecht et al., 2017) studied the indoor emission factors of metals and trace elements for IQOS (with tobacco sticks with and without menthol) and for combustible
cigarettes. Sn was the only metal detected in the emission from Heets with and without menthol, at considerable amounts for both, 18832 and 5668 ng/h, respectively, while it was non-detectable for combustible cigarettes. Significant emissions of S, K and Al were also exhibited from IQOS with menthol (3729, 2382 and 1505 ng/hr), while being non-detectable for IQOS without menthol. Both S and K were detected for combustible cigarettes in very high rates, 34540 and 297500 ng/hr, respectively. Other elements in lower mass concentrations were detected for IQOS with menthol (Ti, Sr, Mo Ag, Cd, Sb, La and Pb), for IQOS without menthol (Rb) and for combustible cigarettes (Ni, Cu, Zn, Rb, Ag, Cd, La and Pb).

It is important to indicate that this study took place in an apartment without controlling the air coming from the outside and, also, blanks were not done before each measurement, so the origin of the detected particulate matter was not clear. This suggests that analysis of mainstream emissions is more controlled and reliable when it comes to emission characterization, especially in absence of blank tests in analyses of environmental emissions.

3. Discussion and comparison of published results

The discussion of the results presented is organized in two parts as in the previous sections.

3.1. Mainstream aerosol

No evidence of tobacco combustion was found by (Schaller et al., 2016a), (Schaller, Pijnenburg, et al., 2016), (Cozzani et al., 2020), (Sussman et al., 2023), (Torero Cullen et al., 2024) and (Bechikhi et al., 2024) and when using tobacco sticks in THS2.2 system with HCI puffing regime. (Schaller et al., 2016a) found that TPM values were similar for THS2.2 and 3R4F, 48.2 ± 2.4 and 43.4 ± 1.5 mg/stick for both studied THS2.2 sticks, and 49.0 ± 4.8 mg/cigarette for 3R4F. (Schaller et al., 2016b) found TPM values for the 43 different THS2.2 tobacco sticks in the range of 46.8-57.8 mg/stick and 44.7 mg/cigarette for 3R4F. In the THS2.2 reference stick, the TPM value was 54.7 ± 3.2 mg/stick.

The obtained TPM values for THS2.2 by (Mallock et al., 2018) are comparable to those obtained by (Schaller, Keller, et al., 2016; Schaller, Pijnenburg, et al., 2016) using the THS2.2 system. Levels of 52.6 ± 3.2 and 51.2 ± 3.2 mg/stick were found for both variants of the studied sticks under an HCI regime. (Xiangyu et al., 2019) proved that higher values of TPM are obtained, in both regimes, ISO (25.70 mg/stick) and HCI (55.82 mg/stick), for TH2.2 device, while lower values were obtained for combustible cigarettes.
cigarettes under both regimes (9.77 mg/cigarette under ISO regime and 37.70 mg/stick under HCI regime). NFDPM (nicotine-free dry particulate matter) from THS2.2 is almost the same as for 3R4F under both regimes. The TPM values obtained under HCI regime by (Cozzani et al., 2020) are also comparable with the studies mentioned before, obtaining 55.2 ± 1.6 mg/unit for THS2.2 and 45.8 ± 1.38 mg/unit for 3R4F. The NFDPM levels are lower for THS2.2 (16.5 ± 3.4 mg/unit) in comparison with 3R4F (27.6 mg/unit).

(Amorós-Pérez et al., 2021) confirmed, by laser diffraction, the presence of solid particles/agglomerates ranging 0.3-110 μm in cigarettes samples, while no solid particles were detected in Heets samples. TEM analysis shown a high population of spherical particles with a size range between 0.03-0.18 μm in cigarettes samples, while very few water-insoluble particles were detected in Heets samples. The authors proved that the detected particulate matter is mainly composed of carbon and oxygen, but other elements like Si, K and S are also present in appreciable amounts in combustible cigarettes, while traces of Si, S, and Ca were found in the water-insoluble particulate matter of IQOS. In agreement, (Kärkelä et al., 2021) demonstrated that 3R4F mainstream smoke is mostly composed of C, O, K, and Ca, while IQOS’ aerosol is most likely formed by agglomerates of the aerosol former glycerol, together with condensates of other emitted compounds, and the deposited particulate matter had the appearance of droplet-like agglomerates, without any clear indication of primary particles.

(Li et al., 2021) obtained differences in the mean particle size among the studied products, 172-179 nm for 3R4F and 50.6-55.3 nm for HNBPs. The results obtained by (Pratte et al., 2017) and (Kärkelä et al., 2021) showed that 3R4F solid particles collected from mainstream smoke are submicron particles with a diameter of 75 nm.

(Amorós-Pérez et al., 2022) obtained a significantly lower amount of particulate matter for Heets than for cigarettes. Also, for cigarettes, 13.3 mg of particulate matter was collected per cigarette under continuous smoking regime and no particulate matter was collected from IQOS’ mainstream aerosol. In agreement with these results, (Kärkelä et al., 2022) obtained a higher mass concentration from 3R4F mainstream smoke (ranging 5-11 g/m³ for IQOS’ aerosol and 49-56 g/m³ for 3R4F’s smoke).

Focusing on smoke/aerosol physical composition the results obtained by (Kärkelä et al., 2021, 2022) and (Pratte et al., 2017, 2018) demonstrated that combustible tobacco products (3R4F combustible cigarettes) produce and release combustion-related solid particles, whereas the tobacco in THS2.2 is heated and not
combusted, forming a liquid-based aerosol free of heating and combustion-related solid particles, such as black carbon (soot).

3.2. Environmental emissions

(Mitova et al., 2016) concluded that the mass concentration of particulate matter emitted from HNBPs into the indoor air under three environmental conditions were equivalent to the concentrations found in background indoor air with the particle concentration being considerably lower than that found with Marlboro Gold combustible cigarettes. For Marlboro Gold, the mass concentration of breathable suspended particles ranged 181-278, 240-299 and 135-156 μg/m³ for “Office”, “Residential” and “Hospitality” simulation, respectively, under HCI regime.

(Protano et al., 2017) concluded that the IQOS device led to the emission of submicron particulate matter (<1 μm) during its use, but in a lower number concentration than combustible cigarettes. It is important to highlight that no information on the physical characteristics of the particulate matter was provided, but the authors recognized that IQOS aerosol was more volatile than cigarette smoke. Peak concentrations ranging 1.2·10⁵-2.9·10⁵ particles/cm³ (with an average of 2.05·10⁵ particles/cm³) were reached for combustible cigarettes, whereas peak number concentrations for sticks in IQOS were below 4.7·10⁴ particles/cm³.

(Ruprecht et al., 2017) highlighted that IQOS emissions were fairly clean in terms of metal emissions compared to combustible cigarettes. Metals like Al, S, K, and Sn were detected in considerable quantities for IQOS with menthol; Sn was the only metal detected in significant quantities for IQOS without menthol whereas for combustible cigarettes elements like S, K, Ni, Cu, Zn, Rb, Ag, Cd, La and Pb were all detected.

The IQOS aerosol seems to be mostly composed of nano-size particulate matter ranging from 10 to 1000 nm, while combustible cigarettes are a significant source of particulate matter, both including sub-micron particles (10-1000 nm) and particles with a diameter higher than 1000 nm. Besides, black carbon soot was not detected in IQOS aerosol and only organic matter was detected (which can be related to the glycerol used in the Heets preparation). The authors conclude that despite that the aerosol from HNBPs and electronic cigarettes are fundamentally different in physical and chemical characteristics, as shown in many of the related studies, they still contain some toxic compounds at low levels.
(Meišutovič-Akhtarieva et al., 2019) proved that combustible cigarettes produced a high amount of particulate matter in the range 0.38-0.60 μm, whilst in case of tobacco sticks used with a THS device, no particulate matter in this size range were registered both during the period of active usage, and post-usage period. Particulate matter with a lower size, 0.01-0.38 μm, were also detected in the aerosol from a THS device.

(Shein & Jeschke, 2019) found 32.6 mg of TPM in the smoke from 3R4F, and 26.1 ± 1.3 mg in the aerosol from IQOS under HCI regime.

(Peruzzi et al., 2020) concluded that IQOS seems to be associated with significantly lower emissions for all types of particulate matter compared to cigarettes. Paying attention to the different analysed sticks, Heets Bronze variant was associated with the lowest particulate matter emissions, in contrast with Sienna, which yielded the highest mass concentrations of particulate matter of the Heets variants tested. For all the studied sticks, much lower levels of particulate matter are obtained in comparison with combustible cigarettes. Particulate matter with diameters ranging 0.1-10 μm were found for all the studied samples, which were generated by volunteer smokers. No information of the physical state of the detected particulate matter was given.

(Protano et al., 2020) confirmed that, although particulate matter ranging 0.1-10 μm were found for all studied samples, both cigarettes and Heets, the highest levels of particulate matter with aerodynamic diameter smaller than 1 μm appeared during smoking of combustible cigarettes. Comparing the different Heets, the authors concluded that the lower mass particulate matter emission was for the Bronze variant, whereas Sienna yielded the highest mass concentrations of particulate matter. These results agree with those obtained by (Peruzzi et al., 2020).

(Savdie et al., 2020) showed that the particulate matter dominant size fraction for combustible cigarettes and HNBT was 1 μm, followed by 2.5-10 μm, and that the amount of particulate matter was significantly lower for HNBT in comparison with combustible cigarettes. The ultrafine particles (0.01-1.0 μm) mass concentrations were higher during combustible cigarettes use in both home and car studied scenarios compared to HNBT use. The levels of black carbon measured during HNBT use were substantially lower than those from combustible cigarettes in both studied scenarios (home and car), and the authors considered that the levels of black carbon detected for HNBT were not resulting from Heets use, but were likely from outdoor black carbon concentrations.
4. Summary and conclusions

The comparison of the published data would be easier and more reliable if in each study it is clearly defined if the emissions being measured and characterized are the mainstream emissions or the environmental ones.

From the analysis of mainstream aerosol particulate matter the different authors (Cozzani et al., 2020; Mallock et al., 2018; Schaller et al., 2016b; Xiangyu et al., 2019) have obtained, in general, the mass of particulate matter in mainstream emissions were 37.7 – 40.0 mg/cigarette for 3R4F combustible cigarette, and 43.5 – 55.8 mg/stick from THS2.2.

(Amorós-Pérez et al., 2021, 2022; Bentley et al., 2020; Kärkelä et al., 2022; Pratte et al., 2017, 2018; Schaller, Keller, et al., 2016; Sussman et al., 2023; Torero Cullen et al., 2024) studies have proved the different nature of the particulate matter found in mainstream smoke/aerosol from cigarettes and Heets used in IQOS, respectively. The particulate matter from HNBPs is volatile and liquid-like. Carbonaceous solid particles (soot) are not present in THS2.2 aerosol, while such solid particles are present in large quantities in the particulate matter of smoke from combustible cigarettes, in line with the absence of tobacco combustion in HNBPs. This literature has shown that the particulate matter in HNBP aerosols is formed when glycerol (added to the tobacco substrate as an aerosol former) nucleates, forming liquid nuclei onto which evaporated volatiles can condense. Not only the glycerol content but also the water content of the HNBP aerosols is much higher than in cigarette smoke. This explains the different nature and volatility of the particulate matter from HNBPs and cigarettes.

(Amorós-Pérez et al., 2021) and (Li et al., 2021) agree that the solid particle sizes range from 0.01 to 0.60 µm for combustible cigarettes, while the particulate matter sizes range from 0.01 to 0.38 µm for HNBPs.

In the nanometric scale, (Pratte et al., 2017) and (Kärkelä et al., 2022) agree that the solid particles in smoke have a mean particle size of 75 nm and the different comparative studies also show smaller mean particulate matter sizes for HNBP in
comparison with combustible cigarettes, such as (Li et al., 2021), showing mean particulate matter sizes around 55 and 180 nm for HNBP and cigarettes, respectively.

Focusing on particulate matter composition, the authors (Pratte et al., 2017), (Amorós-Pérez et al., 2021) and (Kärkelä et al., 2021) indicate that the particulate matter both for cigarettes and Heets are mainly based on carbon and oxygen. Particles from cigarette smoke originated during the combustion process, while the particulate matter from Heets is based on liquid-based agglomerates, which would include glycerol, water and other compounds.

Regarding the particulate matter characterization of environmental emissions, different size ranges, either micro or nanometric have been analyzed. Particulate matter mass concentration for combustible cigarettes varies from 151 to 3480 µg/m³, values obtained by (Ruprecht et al., 2017) and (Savdie et al., 2020), respectively. For HNBP, a lower particulate matter mass concentration of 1.4 µg/m³ was obtained by (Ruprecht et al., 2017), whereas a higher value, 337.5 µg/m³, was obtained by (Protano et al., 2020). No appreciable difference between THS2.2 particulate matter mass concentration in indoor air and background measurements was detected by (Mitova et al., 2016), while a higher number of particles (147 – 268 µg/m³) with a size below 2.5 µm were detected from combustible cigarettes. (Peruzzi et al., 2020) also show higher particulate matter mass concentration for combustible cigarettes (1250 µg/m³) than for HNBP (31 µg/m³).

Focusing on particles number concentration, the lower values for combustible cigarettes and HNBP were 1.1 and 24 particles/cm³, respectively, obtained by (Ruprecht et al., 2017), while the higher values were obtained by (Protano et al., 2017), being 2.05·10⁵ (average between concentrations ranging 1.23·10⁵-2.9·10⁵ particles/cm³) and <4.7·10⁴ particles/cm³ for combustible cigarettes and HNBP, respectively.

(Ruprecht et al., 2017) and (Meišutovič-Akhtarieva et al., 2019) also referred to the different volatility of the particulate matter that come from Heets and combustible cigarettes, which suggests a difference in the nature of the particulate matter. (Ruprecht et al., 2017) also focused their study on the mineral composition of the particulate matter, showing a significant concentration of Sn in Heets-particulate matter and K in combustible cigarettes-particulate matter.

Thus, the studies analysed have obtained much lower concentration and particulate matter concentrations for the HNBP in comparison with combustible cigarettes. Different HNBPs lead to some slight particulate matter concentration differences as well, while not being remarkable.
The TPM values obtained by (Shein & Jeschke, 2019) for HNBP and combustible cigarettes in an indoor environment were 26.1 mg/stick and 32.6 mg/cigarette.

Considering the guidelines values recommended by the WHO for the exposure to particulate matter of general population in outdoor air, HNBP generate particulate matter in higher mass concentration than those values considered as maximum allowed average daily levels for PM_{10} (15.0 µg/m³) and PM_{2.5} (5.5 µg/m³), but it is important to notice that these WHO guidelines refer to particulate matter from combustion sources and not especially for liquid-based aerosols containing significantly fewer and lower levels of harmful or potentially harmful constituents. However, it should be highlighted that the concentration of particulate matter generated when smoking combustible cigarettes is significantly higher, with different physicochemical composition, including both liquid and black carbon (soot) particles. Thus, although these new HNBP are still a source of detectable indoor air particulate matter and may worsen indoor air quality during and after their use depending on their composition, the results suggest that they are likely of lower risk compared with combustible cigarettes, due to the significantly different physical and chemical composition of the HNBP aerosol compared to cigarette smoke.

In fact, and most importantly, besides the number and/or concentration of dispersed particulate matter, it is important to consider its physical and chemical composition. For combustible cigarettes, a large amount of non-soluble solid particles was observed and analysed, while soluble liquid-based particulate matter was detected for HNBP. In addition to the difference in the physical state of the particulate matter, HNPB aerosols contain significantly fewer and lower levels of harmful or potentially harmful constituents than cigarette smoke (Sussman et al., 2023). Moreover, the finding in environmental emissions suggested by (Protano et al., 2017) demonstrated that the aerosol from HNBP is liquid-based, which agrees with mainstream aerosol analysis done by (Amorós-Pérez et al., 2021, 2022), (Pratte et al., 2017, 2018) and (Kärkelä et al., 2021, 2022).

Usage data, clinical exposure data and long-term epidemiological evidence would ultimately be required to fully quantify the risk reduction of HNBPs compared to cigarettes. However, the fundamental difference in physical and chemical characteristics of the particulate matter in the aerosol from HNBPs, compared to the smoke from cigarettes, including the liquid-based nature of the particulate matter from HNBPs aerosol in contrast to the presence of black-carbon particles in combustible cigarettes smoke, and
the different HNBP aerosol composition with significantly fewer and lower levels of harmful or potentially harmful constituents compare to cigarette smoke, already implies a potential reduction in risk of HNBPs compared to cigarettes. However, these aerosols still contain some toxic compounds at low levels and are, therefore, not without risk.

5. References


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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Maria Angeles Lillo-Rodenas reports a relationship with Philip Morris Products SA that included two funding grants to evaluate the presence of particulate matter in aerosols from tobacco products. Those grants have allowed to publish two papers cited as references in this review MS.

This review MS is an independent study, it has not been funded by any company and, based on our experience on aerosol characterization and on the lack of a review compiling info on this topic, it has been written with the aim of comparing the data for many authors to get conclusions of great relevance when evaluating the air quality in indoor and outdoor environments.