Review

A review of the impacts of tobacco heating system on indoor air quality versus conventional pollution sources

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HIGHLIGHTS

- THS generated pollution was compared against general indoor air quality.
- The usage of THS indicated as a low emitting indoor air pollution source.
- Exposure to significantly higher pollution levels occurs in public environments.
- Conventionally measured pollutants are not able to represent IAQ due to THS use.

ARTICLE INFO

ABSTRACT

With the introduction of novel and potentially less polluting nicotine containing products to the market, the impacts of their usage to indoor air quality as opposed to conventional pollution sources must be reviewed and considered. This review study aimed to comparatively analyse changes in indoor air quality as the consequence of tobacco heating system (THS) generated pollution against general indoor air quality in various micro-environments, especially with combustion-based pollution sources present. Indoor concentrations of formaldehyde, acetaldehyde, benzene, toluene, nicotine and $PM_{2.5}$ were reviewed and compared; concentrations of other harmful and potentially harmful substances (HPHCs) were discussed. Generally, the usage of THS has been associated with lower or comparable indoor air pollutant concentrations compared against other conventional indoor sources or environments, in most cases distinguishable above background, thus potentially being associated with health effects at pro-longed exposures as any other artificial air pollution source. In the controlled environment the use of THS (as well as an electronic cigarette) resulted in the lowest concentrations of formaldehyde, benzene, toluene, $PM_{2.5}$ among majority researched pollution sources (conventional cigarettes, waterpipe, in-cense, mosquito coils). The exposure to significantly higher pollution levels of benzene, toluene, and formaldehyde occurred in public environments, especially transport micro-environments. Such low levels of conventionally-assessed indoor pollutants resulting from the use of new nicotine containing products raise challenges for epidemiological studies of second-hand exposure to THS aerosol in real-life environments.

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1. Introduction

In recent years, much attention has been focused on alternative nicotine-containing products to traditional tobacco-based cigarettes for reducing the risk of smoking, known to adversely affect nearly every organ of a human body, to result in diseases, and to reduce health status in general (U S Department of Health and Human Services, 2014). A comparative risk assessment of the burden of disease and injury attributable to 67 risk factors in 21 worldwide regions concluded that tobacco smoking (including second-hand) and household air pollution were among the leading risk factors for global disease burden (Lim et al., 2012). It is evident that the traditional smoking must be ceased or at least modified to reduce the risk to both the smokers and the bystanders.

The first widespread alternative products on the market were electronic cigarettes (ECs) — devices electrically heating and vaporizing a liquid solution to produce an inhalable aerosol typically containing nicotine, flavourings, and other compounds (Nayir et al., 2016). Another viable approach to reduce the levels of hazardous substances associated with cigarette burning smoke is the generation nicotine-containing aerosol by heating tobacco in reduced temperatures as opposed to burning, thus entitling the process as "heat-not-burn". Initially such devices were referred to as Electrically Heated Cigarette Smoking System (EHCSS) (Pineda et al., 2008). In later developments, the term Tobacco Heating System (THS) has been established. The mainstream aerosol here is produced by "distilling" nicotine and flavours at temperatures up to 350 °C via a heating blade inserted into a uniquely processed tobacco plug. Such electronically controlled heating prevents high temperature pyrolysis/combustion from occurring (Smith et al., 2016). There is a big selection of THS or other heat-not-burn products on the market already, though slightly differing in their working principle: IQOS from Philip Morris International, 3T from Vapour Tobacco Manufacturing, Glo from Britsh American Tobacco, Ploom Tech from Japan Tabacco, and others. Both the e-cigarettes and THSSs are gaining increasing popularity among users (Caputi et al., 2017).

The data on the mainstream and exhaled aerosol produced by the THS is yet sparse. The aerosol produced by experimental tobacco plug blends in the THS was shown to contain significantly lower concentrations of harmful and potentially harmful constituents (HPHCs) than found in the mainstream smoke of reference cigarette 3R4F (Schaller et al., 2016; Jaccard et al., 2017). Importantly, the reduced formation of HPHCs also was indicated to lead to the reduced exposure when used ad libitum in a short-term clinical study conducted in adult smokers in a controlled environment (Smith et al., 2016).

The THS does not produce any side-stream smoke emissions, thus the potential impacts to indoor air quality from the usage of THS may come from only exhaled aerosol. In case of an electronic cigarette, several studies have demonstrated that the exhaled aerosol is very volatile due to being composed of fast-evaporating liquid particles (Bertholon et al., 2013; Zhao et al., 2017). The comparison between the background and THS environmental aerosol samples generated by smoking machines in an environmentally controlled room showed a statistically significant increase in concentration of only five compounds (nicotine, acetahaldehyde, toluene, benzene, and solanesol) (Mottier et al., 2016). Such testing, however, did not take into account the transformation of mainstream aerosol in human body. The comparisons were later extended with smokers in an environmentally controlled room simulating "Office", "Residential", and "Hospitality" environments and was compared with smoking a lit-end conventional cigarette (CC) (Mitova et al., 2016). The concentrations of most measured indoor air constituents during the use of THS were similar to background levels (with the exception of acetaldehyde and nicotine) and for most analytes were an order of magnitude lower than found in assessments with the traditional cigarette.

Malysheva et al. (2017) reported 10% increase in carbon monoxide and formaldehyde air concentration above the background during the usage of THS. Ruprecht et al., 2017 investigated the second-hand exposure to particulate metals and organic compounds, gas-phase aldehydes from THS, e-cigarettes, and traditional cigarettes. Polycyclic aromatic hydrocarbons (PAHs) were mostly non-detectable in the particulate emission of organic matter from these devices. Metal concentrations were similar to the background levels and lower during THS usage compared to both ECs and CCs. Concentrations of aldehydes in the environmental tobacco aerosol of THS were higher in comparison with the EC aerosol, however the levels were substantially lower compared to CCs.

The above presented data indicates that the usage of new nicotine containing products result in significantly lower levels of ambient air pollutants in indoor environments as compared to a conventional cigarette. This raises a question on the distinguishability of such air pollution from not only a process of smoking, but from environments containing other pollution sources that are common in households or other micro-environments around the globe. Thus the aim of this study was to review available data on the indoor air quality and compare the levels of pollutants in

environments where THS is used against general indoor micro-environments. A specific attention was paid to environments having combustion based pollution sources present, such as candles, incense, or mosquito coils.

2. Methods

2.1. Sources of information

Scientific articles served as a primary source of references reporting indoor air quality in settings described below. Web of Science search engine (Clarivate Analytics, Philadelphia, USA) was employed for searching specific keywords. Afterwards, a cross-reference check was performed to search for additional studies.

2.2. Indoor environments

Two types of environments were compared against those used with THS: "controlled" and "real-life". The "controlled" included studies performed in environmentally controlled chambers as well as chamber-type environments, conducted not exactly in a completely controlled manner, but having the aim of investigating environmental pollution generated by a particular source, also studies representing pollution levels in various non-smoking indoor environments. The "real life" included studies reporting indoor concentration of pollutants in two major categories: residential and public. The latter one comprised of a wide span of environments including schools, kinder-gardens, offices, coffee shops, libraries, copy centres, pharmacies, newspaper stands, gymnasiums, hairdressers, restaurants, supermarkets, as well as various modes of motorized transport. 12 references on chamber studies and 25 on indoor environment were researched. Detailed information on sampling conditions and analytical methods employed in researched studies is summarized in Tables 1 and 2.

2.3. THS

The effects of THS on indoor air quality has so far been reported in the references of Mitova et al. (2016) and Ruprecht et al. (2017). Both of these references report data obtained in chamber or chamber type environments, where the effects of the usage of THS are clearly distinguished in a controlled manner. The chamber studies in Mitova et al. (2016) represented "residential", "office", and "hospitality" scenarios based on the air exchange rate. The data resulting from "residential" setting was compared against the other chamber-based studies since the conditions were the most comparable to the reported elsewhere. Ruprecht et al. (2017) investigated environmental pollution from THS, e-cigarettes, and conventional cigarettes at a sitting room of a flat owned by habitual smokers, furnished with typical home appliances, where the use of nicotine containing products was performed in a controlled manner. Only background subtracted data was reported thus allowing the data to be only used in the comparative analysis of controlled environments.

2.4. Analytes

The selection of analytes included the most commonly investigated indoor air pollutants having sufficient number of references reporting their levels. Concentrations of aldehydes (formaldehyde, acetaldehyde), monoaromatic hydrocarbons (benzene, toluene), nicotine, and particulate matter ($PM_{2.5}$ or respirable fraction) were compared in case of chamber studies while in the real-life studies only concentrations of formaldehyde, acetaldehyde, benzene, and toluene were considered. Formaldehyde and benzene are among the most researched pollutants known for their hazardousness to health and often found indoors in concentrations of health concern (WHO, 2010). Formaldehyde, acetaldehyde, and nicotine are common indicators of nicotine containing product aerosol, as is toluene (U.S. Department of Health and Human Services, 2010). The critical appraisal of the setting and implementation of indoor exposure limits in the EU has identified formaldehyde and benzene as high priority chemicals, while acetaldehyde and toluene were identified as the chemicals of second priority based on the risk assessment (Koistinen et al., 2004). The inhalable PM is also a well-documented pollutant associated with smoking and having health effects including respiratory and cardiovascular morbidity, such as aggravation of asthma, respiratory symptoms and an increase in hospital admissions; mortality from cardiovascular and respiratory diseases, and from lung cancer (WHO, 2013).

Indoor concentrations of other pollutants such as carbon monoxide, nitrogen oxides, PAHs, heavy metals, other harmful and potentially harmful constituents (HPHC) were reported in too few chamber studies and were not sufficient for quantitative comparison, however are also briefly discussed.

2.5. Data processing

The data was collected as reported by the researchers in each paper prior to recalculations or adjustments for background. Such adjustment was later carried out for the cases reporting background. A variety of descriptive statistics estimates have been reported, including parametric ones (mean, standard deviation) and non-parametric ones (median, interquartile range), as well as min-max range. Such various estimates pose a challenge of inter-comparing of them due to a different nature of the statistical estimate. All these estimates were plotted on the same graph but visually denoting the statistics used (Figs. 1 and 2). A logarithmic concentration scale was applied as the data spans over several orders of magnitude.

The concentration data from chamber studies has been obtained in the variety of chambers having various volume and air change rate values. Such data was normalised for the chamber volume and air change rate in order to match conditions suggested by the CEN/TS 16516 standard (CEN standards), i.e. chamber volume of 30 m³ and air change rate of 0.5 ach. At the same time the data has not been normalised for the number of test products used assuming that the realistic use scenarios were chosen by the investigators.

The statistical significance of differences in THS vs other groups of pollution sources was tested by the independent-samples *t*-test, setting confidence interval percentage to 95%. Such test was conducted only for cases where 3 and more data points were available, and indicated by the reported p-value.

3. Discussion

3.1. Chamber studies

3.1.1. Formaldehyde and acetaldehyde

Generally, the so far reported levels of carbonyls for THS were lower than most of other sources, except of several cases of EC. The usage of THS in chambers resulted in average levels of formaldehyde at 15.3 µg/m³ (Mitova et al., 2016) and 13.3 µg/m³ (Ruprecht et al., 2017), as well as 29.3 µg/m³ and 17.2 µg/m³ for acetaldehyde, respectively (Fig. 1). Such levels are an order of magnitude lower (p < 0.05) compared to the smoking of CC in chambers, e.g. 205.9 µg/m³ and 197.1 µg/m³ for formaldehyde as well as 528.1 µg/m³ and 349.9 µg/m³ for acetaldehyde. Interestingly, Schripp et al. (2013) reported CC generated concentrations of aldehydes by an order of magnitude lower than Mitova et al. (2016) and Ruprecht

Table 1
List of references and summarized parameters on simulated indoor environments (chambers).

Test product	Pollutants taken for comparison	Analytical methods	Chamber type	Chamber volume, m³	Air exchange, h⁻¹	Background/Air Purification	Number of test products	Delay of sampling from the start of product use, h	Sampling duration, h	Reference
THS Conventional cigarette	benzene toluened formaldehyde acetaldehyde nicotine	active sampling on Anasorb sorbent tubes, GC MS active sampling on DNPH cartridges, GC MS active sampling Tenax TA sorbent tubes, GC MS	walk-in room imitating residential conditions	72.3	1.2	Background reported.	3/h 2 smokers	1	4	(Mitova et al., 2016)
Incense with spice fragrances	benzene toluene formaldehyde acetaldehyde	HS-PTR-MS; active sampling Tenax TA sorbent tubes, thermal desorption, GC MS active sampling on DNPH cartridges, HPLC-UV		32.3	0.8	The room was flushed during 12 h with outdoor air in order to reach the atmospheric background level for VOCs and particles	1	0.5	1	(Manoukian et al., 2013)
Incense: traditional, aromatic, church incense	benzene toluene formaldehyde acetaldehyde PM$_{2.5}$	grab samples, GC MSD active sampling on DNPH cartridges, HPLC-UV dust-track air monitors	environmental test chamber	18.26 stainless steel	0.5	The chamber was purged by blower air, which was passed through a clean air system with activated charcoal particle filters and High-Efficiency Particulate Air (HEPA) filters.	3 at a time; 10 different tested	0 when burning 0.5 after the incense has extinguished	~0.5—1 depending on an incense type	(Lee and Wang, 2004)
Scented and unscented candles	benzene toluene formaldehyde acetaldehyde PM$_{2.5}$	active sampling Tenax TA sorbent tubes, thermal desorption, GC MS active sampling on DNPH cartridges, HPLC-UV Continuous particle concentration monitor; gravimetric method	ISO 9001:2000 registered Indoor Air Quality Laboratory, stainless steel and aluminum surfaces	26	0.5 1	After each experiment, the testing chambers were cleaned by flushing with HEPA filtered ambient air for at least 6 h.	1 3	2 6	0.5	(Petry et al., 2014)
Mosquito coils Scented candles	benzene toluene formaldehyde acetaldehyde PM$_{2.5}$	grab samples, GC MSD active sampling on DNPH cartridges, HPLC-UV dust-track air monitors	environmental test chamber	18.26 stainless steel	0.5	The chamber was purged by blower air, which was passed through a clean air system with activated charcoal particle filters and high-efficiency particulate air (HEPA) filters.	1 at a time; 5 different mosquito coils and 5 different candles tested	0 when burning 0.5 after the tested specimens have extinguished	1 for mosquito coils ~1.5—2 depending on a candle type	(Lee and Wang, 2006)
THS, e-cigarette, conventional cigarette	formaldehyde acetaldehyde PM$_{2.5}$	active sampling on DNPH cartridges, HPLC PM mass monitor particle counter	sitting room of a flat owned by habitual smokers	48	1.54		10 iQOS with menthol and 14 without menthol in sequence 13 EC in sequence 9 CC in sequence smokers	0	3 iQOS ~2—3 EC 1.5	(Ruprecht et al., 2017)
E-cigarette, conventional cigarette	benzene formaldehyde acetaldehyde PM$_{2.5}$	active sampling on Tenax GR, thermal desorption, GC MS active sampling on DNPH cartridges, HPLC LAS	stainless- steel emission test chamber	8	0.3		3 at a time; 3 smokers; 3 e-cigarette liquids tested	at puff 4	2	(Schripp et al., 2013)

Table 1 (*continued*)

Test product	Pollutants taken for comparison	Analytical methods	Chamber type	Chamber volume, m³	Air exchange, h⁻¹	Background/Air Purification	Number of test products	Delay of sampling from the start of product use, h	Sampling duration, h	Reference
E-cigarette	formaldehyde acetaldehyde benzene nicotine	active sampling on DNPH cartridges, HPLC; active sampling on Tenax GR, thermal desorption, GC MS	office room	45	0.56	Background reported.	3 at a time; 3 nicotine free and 3 nicotine containing liquids tested	0	2	(Schober et al., 2014)
E-cigarette	nicotine	active sampling on Tenax TA tubes, GC–MS	walk-in environmental chamber	30	0.5	The chamber was filled with ultra-clean pre-dried and filtered air.	1 at a time; 6 replicates for each of 7 liquids; smoking machine.	0		(Geiss et al., 2011)
E-cigarette	nicotine PM₂.₅	active sampling on XAD-7 tubes, GC light-scattering integrating nephelometer		0.4425	1.53	To improve reliability of the experimental results, the system was purged with pure air.	2 at a time; 2 puffing intensities and 2 liquids tested			(Lee et al., 2017)
Waterpipe	benzene nicotine PM₂.₅	active sampling on Tenax GR, thermal desorption, GC MS LAS WRAS	office room	57	not indicated	Background reported.	4 tablets in sequence; 4 smokers	0	4	(Fromme et al., 2009)

et al. (2017), but the amount of CC smoked is not clearly presented.

The reported data for EC varies broadly, and was found to be not statistically different from the THS ($p > 0.05$). Schober et al. (2014) determined similar levels of formaldehyde to THS ($16.0 \, \mu g/m^3$) while acetaldehyde levels were 2–3 times higher. Schripp et al. (2013) and Ruprecht et al. (2017) reported substantially lower EC generated concentrations of aldehydes. Such variation of the airborne levels of carbonyls is predetermined by the large variation in carbonyl concentrations generated by ECs, as determined by multiple studies. The emission of formaldehyde ($\mu g/10$ puffs) from 13 brands of Japanese e-cigarettes varied from 0.7 ± 0.8 to 34 ± 35 and from 0.2 ± 0.1 to 26 ± 28 for acetaldehyde (Bekki et al., 2014). The content of formaldehyde ranged from 2.0 to $56.1 \, \mu g$, and acetaldehyde from 1.1 to $13.6 \, \mu g$ per one EC (150 puffs) as determined in 12 brands of ECs distributed within Poland (Goniewicz et al., 2014). Similarly high variation of aldehyde emission from 10 various ECs of the same brand was reported by Uchiyama et al. (2013). Formaldehyde, acetaldehyde, acrolein, and other aldehydes are known to form during heating of mixtures of glycerol and propylene glycol, the most common solvent formulation for EC liquids (Hess et al., 2016). Emission of aldehydes from ECs are very much dependant on the temperature of a heating coil (Gillman et al., 2016, Geiss et al., 2016, Flora et al., 2017, Farsalinos et al., 2017) as well as composition of EC liquids (Flora et al., 2016). EC solutions may contain numerous compounds in addition to the vendor listed propylene glycol, glycerin, and nicotine (Herrington and Myers, 2015) resulting in a very different aerosol composition.

Burning of incense resulted in a high mean concentration of formaldehyde ($158 \, \mu g/m^3$) and acetaldehyde ($94.8 \, \mu g/m^3$) (Manoukian et al., 2013), almost reaching the CC generated levels $205.9 \, \mu g/m^3$ (Mitova et al., 2016) and $197.1 \, \mu g/m^3$ (Ruprecht et al., 2017). Candle burning produced formaldehyde at the same level ($p > 0.05$), while concentration of acetaldehyde was lower than in case of THS.

3.1.2. Benzene and toluene

While mono-aromatic hydrocarbons are some of the most researched indoor pollutants related to combustion processes, very few studies on nicotine containing products reported benzene concentrations. The usage of THS has resulted in $0.93 \, \mu g/m^3$ (Mitova et al., 2016), while the use of EC resulted in lower levels of benzene ($0.17 \, \mu g/m^3$, Schober et al., 2014). Water pipe smoking appeared to be a strong emitter of benzene producing levels at $17.0 \, \mu g/m^3$ (Fromme et al., 2009). As a non-nicotine containing product, candle burning also resulted in higher concentrations of benzene and toluene ($2.7 \, \mu g/m^3$ and $3.1 \, \mu g/m^3$, respectively (Petry et al., 2014). Toluene levels were below the background for THS, while CC smoking has resulted in $151.1 \, \mu g/m^3$ (Mitova et al., 2016). In case of incense and mosquito coil burning toluene concentrations were at the similar level ranging from 4.6 to $53.6 \, \mu g/m^3$ (Lee and Wang, 2004) and from $2.9 \, \mu g/m^3$ to $60.0 \, \mu g/m^3$ (Lee and Wang, 2006), respectively.

3.1.3. Nicotine

THS generated a concentration of $10.4 \, \mu g/m^3$, which is again an order of magnitude lower compared to CC ($168.0 \, \mu g/m^3$, Mitova et al., 2016). EC generated lower nicotine levels, although similarly to aldehydes, demonstrated a high variation from $0.08 \, \mu g/m^3$ (Lee et al., 2017), 0.2–$0.6 \, \mu g/m^3$ (Geiss et al., 2015) to $3.1 \, \mu g/m^3$ (Schober et al., 2014). Smoking of water pipe resulted in a twice higher concentration of nicotine ($20.5 \, \mu g/m^3$, Fromme et al., 2009).

3.1.4. Particulate matter

The use of THS resulted in the lowest levels of fine particulate matter among the sources investigated, with the reported

Table 2
List of references and summarized parameters on "real-life" indoor environments.

Environment type, location	Number of environments investigated	Pollutants taken for comparison	Analytical methods	Air exchange, h^{-1}	Reference
suburban houses, mostly detached Perth, Australia	study 1—68 houses study 2—250 houses study 3—69 houses	formaldehyde benzene toluene	DNPH treated glass filters exposed for 24 h, HPLC passive diffusion over 7 days (study 1,2) active sampling on Radiello and Custom (study 3) samplers (study 3), GCMS	not specified	(Maisey et al., 2013)
urban houses, mostly detached Edmonton, Canada	26 houses in summer and winter	formaldehyde acetaldehyde benzene toluene	7 consecutive 24-h periods passive collection into Summa canisters, GCMS HPLC for carbonyls	not specified	(Bari et al., 2015)
low VOC emitting and conventional new houses, detached California, USA	9 houses with controlled ventilation 13 houses with low VOC emitting materials	formaldehyde acetaldehyde	active sampling on DNPH cartridges, HPLC	0.2; 0.4; 0.8 0.08—0.48	(Hult et al., 2015)
suburban houses Melbourne, Australia	31 detached 9 semi-detached, or flat	formaldehyde acetaldehyde benzene toluene	active sampling on DNPH cartridges, HPLC active sampling on multi-sorbent tubes, GC MS 7 day sampling	closed-up state 0.5 typical open state 5.7	(Cheng et al., 2016)
high-performance houses California, USA	24 new or deeply retrofitted houses	formaldehyde acetaldehyde	active sampling on DNPH Sep-Pak cartridges, HPLC 6 day sampling	~0.3	(Less et al., 2015)
residential houses nationwide, Japan	602 in winter and summer	formaldehyde acetaldehyde benzene toluene	passive sampling on DSD-BPE/DNPH cartridges, HPLC passive sampling on VOC-SD, GC MS 24 h sampling	not specified	(Uchiyama et al., 2015)
new energy-efficient houses, detached Centre, Pays-de-la-Loire, Ile-de-France and Rhône-Alpes, France	7 in winter and summer	formaldehyde acetaldehyde benzene toluene	passive sampling by DNPH coated Florisil cartridges, HPLC passive sampling by Carbograph 4 adsorbents, GC MS, FID 7 day sampling	0.02—1	(Derbez et al., 2014)
new apartment houses with low emitting materials Helsinki, Turku, Finland	14 apartments in 8 houses	formaldehyde benzene toluene	active sampling into a sulphuric acid-solution, spectrometric acetyl-acetone method active sampling on Tenax TA tubes, GC MS, FID	0.79—1.61	(Järnström et al., 2006)
residential houses nationwide, France	567	formaldehyde acetaldehyde benzene	passive sampling by DNPH coated Florisil cartridges, HPLC passive sampling by Carbograph 4 adsorbents, GC MS, FID 7 day sampling	0.65 night time	(Langer et al., 2016)
new low energy houses, detached Lithuania	11	formaldehyde benzene toluene	passive sampling by DNPH coated Florisil cartridges, HPLC passive sampling by charcoal adsorbents, GC MS 7 day sampling	0.08—0.69	(Kaunelienė et al., 2016)
residential apartment houses Dalian, China	53 in summer 100 in winter	formaldehyde benzene toluene	passive sampling on Sep-Pak DNPH-Silica cartridge, HPLC passive sampling on activated charcoal cartridges, GC MS 24 h sampling	not specified	(Song et al., 2017)
residential houses, public buildings and schools/kindergartens in eleven European cities	103 private homeplaces, 182 different working environments (offices, classrooms, waiting halls)	formaldehyde acetaldehyde benzene toluene	passive sampling by DNPH coated cartridges, HPLC passive sampling on activated charcoal cartridges, GC FID 7 day sampling	not specified	(Geiss et al., 2011)
low-energy school buildings northern and eastern France	10	benzene toluene formaldehyde acetaldehyde	passive sampling on activated charcoal cartridges, GC FID passive sampling by DNPH coated cartridges, HPLC 7 day sampling	2.05—3.33	(Verriele et al., 2016)
early childhood education facilities California, USA	40	formaldehyde acetaldehyde	passive sampling on Sep-Pak DNPH-Silica cartridge, HPLC	0.28—5.63	(Bradman et al., 2017)
schools Porto, Portugal	73 classrooms	formaldehyde acetaldehyde benzene toluene	passive sampling by DNPH coated cartridges, HPLC passive sampling on Tenax TA tubes, GC MS, FID 5 day sampling	not specified	(Madureira et al., 2016)

Table 2 (continued)

Environment type, location	Number of environments investigated	Pollutants taken for comparison	Analytical methods	Air exchange, h^{-1}	Reference
office suburb of Athens, Greece	1	formaldehyde benzene toluene	active sampling on DNPH cartridges, HPLC active sampling on Tenax TA tubes, GC FID	not specified	(Saraga et al., 2011)
shopping mall four cities, Western China	4 malls, 67 sampling sites	formaldehyde	Analyzer Formaldehyde 400	not specified	(Shang et al., 2016)
shopping mall suburbs of Bari, Italy	96 samples − 1st campaign 146 samples − 2nd campaign	benzene toluene	passive sampling on Carbograph 4 cartridges, GC FID 3 × 48 h sampling	not specified	(Amodio et al., 2014)
coffee shops, libraries, copy centres, pharmacies, newspaper stands, offices, gymnasiums, hairdressers, restaurants, and supermarkets Bari, Italy	24 different environments	benzene toluene	passive sampling on Carbograph 4 cartridges, GC MS 7 × 24 h sampling	not specified	(Bruno et al., 2008)
used cars, driven Varese, Northern Italy	23 car cabins	formaldehyde acetaldehyde benzene toluene	passive sampling by DNPH coated cartridges, HPLC passive sampling on activated charcoal cartridges, GC FID 7 day sampling	not specified some of cars driven windows opened, some with air conditioning	(Geiss et al., 2009)
new cars, unoccupied Beijing, China	monitoring was conducted in 802 car cabins in an underground ventilated parking garage	formaldehyde benzene toluene	active sampling by hydroxybenzene solution, spectrophotometry active sampling on activated charcoal cartridges, GC FID	<0.01−0.63	(Zhang et al., 2008)
new and used cars Poland	10 new cars, unoccupied 2 cars, driven at mileage of 2100 to 20,200 km	benzene toluene	active sampling on Carbograph 1TD cartridges, GC FID, MS	not specified	(Faber et al., 2013)
trams, cars Ghent, Belgium	144 samples (3 days × 4 times/day × 6 sections × 2 modes of transport)	benzene toluene	active sampling on Tenax TA tubes, GC MS	not specified	(Do et al., 2014)
buses highways, Taiwan	16 one-way journeys	formaldehyde benzene toluene	formaldemeter active sampling on Tenax TA tubes, GC FID 2 h sampling	not specified	(Hsu and Huang, 2009)

concentration of PM$_{2.5}$ of 32.0 μg/m³ (Ruprecht et al., 2017). Mitova et al. (2016) found even lower levels of fine PM as represented by the respirable suspended particle concentration, which fell below the limit of quantification (<14.7 μg/m³). At the same time, the smoking of CC resulted in 268 μg/m³ RSP median concentration, thus again exceeding that of THS by an order of magnitude. Burning of mosquito coil (Lee and Wang, 2006) resulted in PM$_{2.5}$ mean concentration of 4324 μg/m³, what is almost twice higher than in case of CC smoking (2464 μg/m³) (Ruprecht et al., 2017). Concentration of PM$_{2.5}$ from candle burning varied from actually the same level (31.6 μg/m³) (Lee and Wang, 2006) as THS generated to more than five times higher mean concentration (168.0 μg/m³) (Petry et al., 2014). It must be considered that the reported level of fine particulate matter may be affected by the measurement method. Environmental aerosol formed from the exhaled vapours of new nicotine products is composed primarily of volatile liquid particles (water vapour, propylene glycol). Thus standard gravimetric methods may report lower concentration that those measuring real time aerosol particles. At the same time, evaporation also occurs in environment, thus potentially minimizing the health risk associated with liquid particles.

The above presented review of the effects of various sources on chamber air quality suggests that the usage of THS is a relatively weak source of pollution based on carbonyl, mono-aromatic hydrocarbon, nicotine, and fine particulate data, compared to traditional cigarettes (p < 0.05) and water pipes, although statistically insignificantly higher emitter than electronic cigarettes (p > 0.05). Among the non-nicotine sources higher levels of aldehydes, VOCs, and PM$_{2.5}$ were generated by incense and mosquito coil, although

at the same levels for candle in case of formaldehyde (p > 0.05). This implies that indoor combustion of incense and especially of mosquito coils if used in a similar temporal pattern may provide a higher exposure to pollutants than the by standing near a user of novel nicotine containing products, including THS.

The potential health effects of the above reported concentration levels may be discussed through the proximity of the values to the guideline threshold values.

Interestingly, the guideline values vary broadly among different regions and organisations as presented in Table 3, making such comparison rather complicated. Guideline values for some pollutants (acetaldehyde, toluene) differ by an order of magnitude. Only occupational exposure limit values for nicotine are defined in Europe (EU, 2006) and the USA (OSHA, 1978). No guidelines for indoor particulate matter are available thus ambient air annual limit values are presented instead.

The median concentration of formaldehyde in chambers exceeded WHO guideline (100 μg/m³) value in case CC smoking (Mitova et al., 2016; Ruprecht et al., 2017) as well as burning incense (Manoukian et al., 2013). Smoking of CC also resulted in exceedance of the EU exposure limit for acetaldehyde (200 μg/m³) (Mitova et al., 2016; Ruprecht et al., 2017) as well as US inhalation RfC for benzene (30 μg/m³) (Mitova et al., 2016). Concentrations of toluene did not exceed any guideline value.

3.1.5. Other combustion-related pollutants

A group of 93 pollutants has been established by the US FDA in tobacco products and tobacco smoke entitled harmful and potentially harmful constituents (HPHCs), including carcinogens,
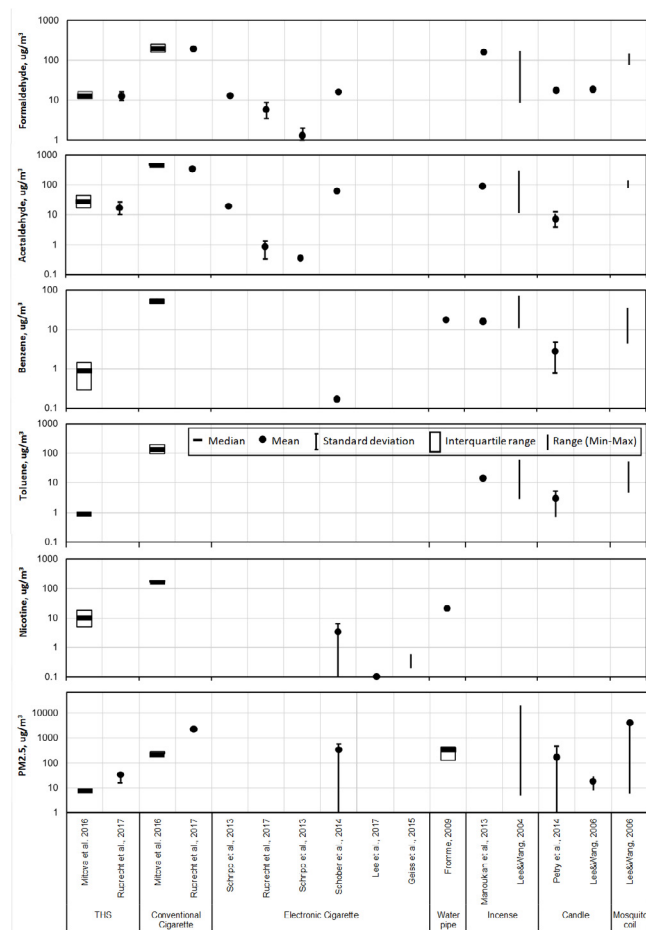
Fig. 1. Concentrations of airborne formaldehyde, acetaldehyde, benzene, toluene, nicotine, and PM$_{2.5}$ as reported in chambers with active pollution sources.

Fig. 2. Concentrations of airborne formaldehyde, acetaldehyde, benzene, and toluene as reported various indoor environments.

respiratory, cardiovascular, reproductive or developmental toxicants, and additives (HPHC and Tobacco Smoke:Established List. (n.d.)). Jaccard et al. (2017) reported a mean reduction of about 90% observed on average across a broad range of HPHCs measured in the THS mainstream aerosol, compared against the levels of HPHCs of CC.

Use of THS was reported not to increase indoor concentrations of carbon monoxide and nitrogen oxides (Mitova et al., 2016), which are listed as WHO priority pollutants. This is expected since no high temperature combustion/pyrolysis takes place in THS. The combustion-related sources, on the other hand, have been indicated to result in significant increases of the combustion oxides. Lee and Wang (2004) concluded that incense burning is an important indoor air pollution source for CO. It was the major gas pollutant resulting from the smoldering effect of mosquito coils (Lee and Wang, 2006).

Polycyclic aromatic hydrocarbons (PAHs) is another indicator of incomplete combustion, reported as mostly non-detectable in the THS smoke (Ruprecht et al., 2017). At the same time, concentration of putative carcinogenic PAHs in indoor air increased by 20% during the vaping of EC (Schober et al., 2014). The pyrolysis-related smoking is undoubtedly a strong source, e.g., seven carcinogenic PAHs were found to be a factor 2.6 higher during the smoking session of water pipe compared to the control day (Fromme et al., 2009).

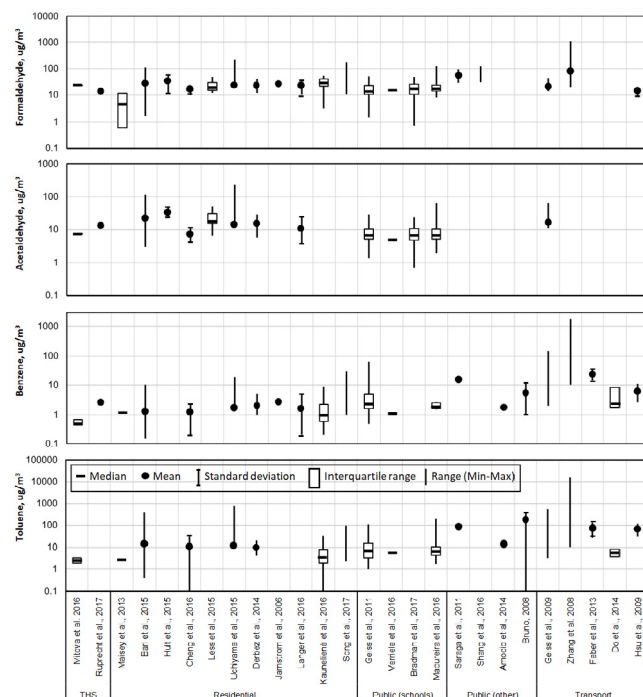Metal concentrations were not significantly higher compared to background levels during the use of THS. At the same time, ECs were reported to emit higher amounts of trace metals (Ruprecht et al., 2017) Moreover, emission factors of Cr, Ni, Ag from ECs and La were even higher than from CCs.

Ruprecht et al. (2017) investigated the concentrations of particle-phase alkanes, organic acids, and levoglucosan from the use of THS and provided comparison with previously reported values from the use of EC and CC (Saffari et al., 2014). Several n-alkanes and organic acids after THS use were found at elevated concentrations (two fold) indoors compared to outdoors. Concentrations of heptacosane, nonacosane, hentriacontane, titriacontane, linoleic and eicosanoic acids, and levoclucosan were significantly higher in THS generated aerosol, while hexatriacontane, octatriacontane, dodecanoic and tetradecaoic acid concentrations were significantly higher in EC, although they were well below the levels associated with the CC environmental smoke. The information on the health risks associated with the above mentioned organic compounds is very limited and none of them are included in the US FDA list of tobacco aerosol HPHCs (HPHC and Tobacco Smoke: Established List). Moreover, the comparison of the HPHC levels resulting from the conventional household non-nicotine combustion sources is not possible, since the list of compounds reported from these studies is much shorter.

3.2. Real-life indoor non-smoking environments

3.2.1. Formaldehyde

Formaldehyde is among the most abundant pollutants having reported occurrences in a broad range of indoor environments. Besides smoking, there are numerous other sources that can result in an increased human exposure to formaldehyde, including insulating materials, particle board or plywood furniture, water based paints, fabrics, household cleaning agents, disinfectants, pesticide formulations, paper products and adhesives containing formaldehyde used for plastic surfaces, parquet, carpets, and other building materials containing urea-formaldehyde resins (Koistinen et al.,

Table 3
Indoor air quality guideline values.

Pollutant	WHO guideline value, µg/m³ (WHO, 2005)	Proposed EU exposure limits, µg/m³ (Koistinen et al., 2004)	US EPA Inhalation RfC[a], µg/m³
Acetaldehyde	NA	200	9 (US EPA IRIS. Acetaldehyde, 1991)
Formaldehyde	100 short-term (30-min) guideline value	30 (NOAEL)[b]	NA
Benzene	NA[c]	NA[c]	30 (US EPA.IRIS. Benzene, 1991)
Toluene	NA	300	5000 (US EPA. IRIS. Toluene, 2005)
Nicotine	NA	500[d] (EU, 2006)	500[d] (OSHA, 1978)
No guidelines for indoor particulate matter are available. Ambient air annual limit values are presented.			
PM$_{2.5}$	10 (WHO, 2005)	25 (EU, 2008)	15 (US EPA, 2013)

[a] **Reference Concentration (RfC):** An estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime (US EPA, IRIS).
[b] NOAEL — no observed adverse effect level is not equivalent to exposure limit, but used in deriving it.
[c] Benzene is a genotoxic carcinogen in humans and no safe level of exposure can be recommended.
[d] Occupational exposure limit value, 8 h average.

2004).

In residential settings, a broad range of concentrations were reported, ranging from 5.3 µg/m³ (Maisey et al., 2013) to 33 µg/m³ (Hult et al., 2015). In the majority of residential environments concentration of formaldehyde was higher compared to the levels of formaldehyde in simulated indoor environments where THS was used (22.4 µg/m³, Mitova et al. (2016), and 13.3 µg/m³, Ruprecht et al. (2017) however the overall difference among mean of reviewed concentration did not appear to be statistically significant ($p > 0.05$).

In schools, concentrations of formaldehyde varied from 14.1 µg/m³ (Geiss et al., 2011) to 17.8 µg/m³ (Bradman et al., 2017) and were at the same level as the THS generated in the "office" conditions (14.0 µg/m³, Mitova et al., 2016). Office environments have been reported to contain a relatively high concentration of formaldehyde (52.3 µg/m³, Saraga et al., 2011), same noticed in shopping malls 30—120 µg/m³ (Shang et al., 2016), or in transportation microenvironments, such as new cars 80.0 µg/m³ (Zhang et al., 2008). This may be attributed to the release of formaldehyde from plastic materials abundant in these environments. Generally, the levels of formaldehyde in public environments were statistically significantly ($p < 0.05$) higher than THS generated in the "office" conditions (14.0 µg/m³, Mitova et al., 2016).

3.2.2. Acetaldehyde

Acetaldehyde is used in the production of perfumes, polyester resins, and basic dyes, also as a fruit and fish preservative, as a flavoring agent, and as a denaturant for alcohol, in fuel compositions, for hardening of gelatin, and as a solvent in the rubber, tanning, and paper industries. It is an intermediate product of higher plant respiration and formed as a product of incomplete wood combustion in fireplaces and woodstoves, coffee roasting, burning of tobacco, and vehicle exhaust fumes. Residential fireplaces and woodstoves are the two most releasing sources indoors (US EPA. Acetaldehyde). The presence of humans and their habits might appear as another important factor influencing acetaldehyde levels as it is an abundant component of human exhaled breath being a metabolic product of sugars and ethanol (De Lacy Costello et al., 2014).

The highest median concentration of 23.5 µg/m³ among all environments was reported by Bari et al. (2015) measured in winter and summer time in residencies in Canada. Hult et al. (2015) found the mean concentration of 18.6 µg/m³ at the air exchange rate of 0.5 h⁻¹ at US residences, Derbez et al. (2014) reported the concentration of 16.5 µg/m³ in 6 newly build energy efficient homes in France. Such concentrations were statistically significantly higher ($p < 0.05$) compared to those obtained during the use of THS in simulated residential setting (7.4 µg/m³, Mitova et al., 2016).

In schools concentrations of acetaldehyde were at the same

order of magnitude (5.2 µg/m³, (Verriele et al., 2016), 7.7 µg/m³ (Madureira et al., 2016)) as THS generated in simulated public environment (9.4 µg/m³, Mitova et al., 2016). Transportation microenvironments (cabin air of used private cars) were found to contain 15.6 µg/m³ of acetaldehyde (Geiss et al., 2009).

3.2.3. Benzene

Benzene is found in the air from coal and oil burning, gasoline service stations, and motor vehicle exhaust. Benzene is also used in the manufacture of detergents, explosives, pharmaceuticals, and dyestuffs. Tobacco smoke contains benzene and accounts for nearly half the national exposure (US EPA. Benzene).

Concentrations of benzene in the residential environment ranged from 0.8 µg/m³ (Kaunelienė et al., 2016) to 3 µg/m³ (Järnström et al., 2006), in schools from 1.1 µg/m³ (Verriele et al., 2016) to 2.6 µg/m³ (Geiss et al., 2011) and were statistically insignificantly ($p > 0.05$) higher than THS generated (0.57 µg/m³ (Mitova et al., 2016), 2.7 µg/m³ (Ruprecht et al., 2017)). In other public environments the concentrations were higher than THS generated by an order of magnitude (15.3 µg/m³, Saraga et al., 2011) in the office, 14.8 µg/m³ in a drugstore (Bruno et al., 2008)). In new cars average benzene concentration was 11.8 µg/m³ but increased after 20k km to 38.5 µg/m³, as attributed to the fuel leakage (Faber et al., 2013). The highest benzene levels were observed in parked new cars (Zhang et al., 2008), reaching a concentration level of 270.0 µg/m³.

3.2.4. Toluene

The major use of toluene is as an additive to gasoline to improve octane ratings. Toluene is used to produce benzene and as a solvent in paints, coatings, synthetic fragrances, adhesives, inks, cleaning agents, in the production of polymers used to make polyamide, plastic bottles, polyurethanes, for pharmaceuticals, dyes, cosmetic nail products, and the synthesis of organic chemicals. The highest concentrations of toluene usually occur in indoor air from the use of common household products (paints, paint thinners, adhesives, synthetic fragrances, and nail polish) and a cigarette smoke (US EPA. Toluene).

THS generated median toluene concentration in simulated "residential" conditions was 0.57 µg/m³ in the "office" and "hospitality" conditions — 0.25 µg/m³ (Mitova et al., 2016) while in residences concentrations varied in the range from 2.62 µg/m³ (Maisey et al., 2013) to 14.1 µg/m³ (Bari et al., 2015) and was statistically significantly higher ($p < 0.05$). In schools it varied from 5.5 µg/m³ (Verriele et al., 2016) to 7.1 µg/m³ (Geiss et al., 2011). Bruno et al. (2008) reported toluene concentration as high as 589.0 µg/m³ in a newspaper kiosk, 303.4 µg/m³ in a drugstore, 243.0 µg/m³ in a photocopy shop. High mean toluene concentration (90.2 µg/m³) was also measured in an office (Saraga et al., 2011). Transportation micro-environments also stand out as a site for high exposure of

toluene. In used cars a mean concentration of 98.8 μg/m^3 was reported (Geiss et al., 2009), while in new vehicles it was as high as 1220.0 μg/m^3 (Zhang et al., 2008).

4. Conclusions

Generally, the usage of THS has been associated with lower or comparable indoor air pollutant concentrations compared against other conventional indoor sources or environments, in most cases distinguishable above background, thus potentially being associated with health effects at prolonged exposures as any other artificial air pollution source.

In the controlled environment the use of THS (as well as an electronic cigarette) resulted in the lowest concentrations of formaldehyde, benzene, toluene, PM$_{2.5}$ among majority researched pollution sources (conventional cigarettes, waterpipe, incense, mosquito coils). The exposure to significantly higher pollution levels of benzene, toluene and formaldehyde may occur in public environments, especially transport micro-environments.

Such data indicates that the levels of the main indoor air pollution markers in case of THS environmental aerosol may be too low to distinguish from the background, thus raising additional challenges for epidemiological studies aiming at the assessments of second-hand exposure in real-life environments. Possibly, a set of specific HPHCs needs to be developed to represent THS environmental aerosol from the matrix of indoor pollutants.

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References

Amodio, M., Dambruoso, P.R., de Gennaro, G., de Gennaro, L., Loiotile, A.D., Marzocca, A., Tutino, M., 2014. Indoor air quality (IAQ) assessment in a multi-storey shopping mall by high-spatial-resolution monitoring of volatile organic compounds (VOC). Environ. Sci. Pollut. Control Ser. 21 (23), 13186–13195. https://doi.org/10.1007/s11356-014-2544-1.

Bari, M.A., Kindzierski, W.B., Wheeler, A.J., Héroux, M.È., Wallace, L.A., 2015. Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Build. Environ. 90, 114–124. https://doi.org/10.1016/j.buildenv.2015.03.023.

Bekki, K., Uchiyama, S., Ohta, K., Inaba, Y., Nakagome, H., Kunugita, N., 2014. Carbonyl compounds generated from electronic cigarettes. Int. J. Environ. Res. Publ. Health 11 (11), 11192–11200. https://doi.org/10.3390/ijerph111111192.

Bertholon, J.-F., Becquemin, M.H., Roy, M., Roy, F., Ledur, D., Annesi Maesano, I., Dautzenberg, B., 2013. [Comparison of the aerosol produced by electronic cigarettes with conventional cigarettes and the shisha]. Rev. Mal. Respir. 30 (9), 752–757. https://doi.org/10.1016/j.rmr.2013.03.003.

Bradman, A., Gaspar, F., Castorina, R., Williams, J., Hoang, T., Jenkins, P.L., Maddalena, R., 2017. Formaldehyde and acetaldehyde exposure and risk characterization in California early childhood education environments. Indoor Air 27 (1), 104–113. https://doi.org/10.1111/ina.12283.

Bruno, P., Caselli, M., De Gennaro, G., Iacobellis, S., Tutino, M., 2008. Monitoring of volatile organic compounds in non-residential indoor environments. Indoor Air 18 (3), 250–256. https://doi.org/10.1111/j.1600-0668.2008.00528.x.

Caputi, T.L., Leas, E., Dredze, M., Cohen, J.E., Ayers, J.W., 2017. They're heating up: internet search query trends reveal significant public interest in heat-not-burn tobacco products. PLoS One 12 (10) e0185735. https://doi.org/10.1371/journal.pone.0185735.

CEN standards. (2010). Retrieved March 7, 2018, from https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:41188,510793&cs=1216364B7D630CA10EDC767A41CE75645.

Cheng, M., Galbally, I.E., Molloy, S.B., Selleck, P.W., Keywood, M.D., Lawson, S.J., Dunne, E., 2016. Factors controlling volatile organic compounds in dwellings in Melbourne, Australia. Indoor Air 26 (2), 219–230. https://doi.org/10.1111/ina.12201.

COMMISSION DIRECTIVE 2006/142/EC (2008). Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0015&from=EN.

De Lacy Costello, B., Amann, A., Al-Kateb, H., Flynn, C., Filipiak, W., Khalid, T., Ratcliffe, N.M., 2014. A review of the volatiles from the healthy human body. J. Breath Res. 8 (1). https://doi.org/10.1088/1752-7155/8/1/014001.

Derbez, M., Berthineau, B., Cochet, V., Pignon, C., Ribéron, J., Wyart, G., …, Kirchner, S., 2014. A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses. Build. Environ. 82, 288–299. https://doi.org/10.1016/j.buildenv.2014.08.028.

Do, D.H., Van Langenhove, H., Chigbo, S.I., Amare, A.N., Demeestere, K., Walgraeve, C., 2014. Exposure to volatile organic compounds: comparison among different transportation modes. Atmos. Environ. 94, 53–62. https://doi.org/10.1016/j.atmosenv.2014.05.019.

EU, 2008. Commission directive 2008/50/EC of the European parliament and of the council of 21 May 2008 on ambient air quality and cleaner air for Europe. Off. J. Eur. Commun. 152, 1–43. https://doi.org/http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ: L:2008:152:0001:0044:EN: PDF.

Faber, J., Brodzik, K., Gołda-Kopek, A., Łomankiewicz, D., 2013. Benzene, toluene and xylenes levels in new and used vehicles of the same model. J. Environ. Sci. 25 (11), 2324–2330. https://doi.org/10.1016/S1001-0742(12)60333-7.

Farsalinos, K.E., Voudris, V., Spyrou, A., Poulas, K., 2017. E-cigarettes emit very high formaldehyde levels only in conditions that are aversive to users: A replication study under verified realistic use conditions. Food Chem. Toxicol. 109, 90–94. https://doi.org/10.1016/j.fct.2017.08.044.

Flora, J.W., Meruva, N., Huang, C.B., Wilkinson, C.T., Ballentine, R., Smith, D.C., McKinney, W.J., 2016. Characterization of potential impurities and degradation products in electronic cigarette formulations and aerosols. Regul. Toxicol. Pharmacol. 74, 1–11. https://doi.org/10.1016/j.yrtph.2015.11.009.

Flora, J.W., Wilkinson, C.T., Wilkinson, J.W., Lipowicz, P.J., Skapars, J.A., Anderson, A., Miller, J.H., 2017. Method for the determination of carbonyl compounds in E-cigarette aerosols. J. Chromatogr. Sci. 55 (2), 142–148. https://doi.org/10.1093/chromsci/bmw157.

Fromme, H., Dietrich, S., Heitmann, D., Dressel, H., Diemer, J., Schulz, T., Völkel, W., 2009. Indoor air contamination during a waterpipe (narghile) smoking session. Food Chem. Toxicol. 47 (7), 1636–1641. https://doi.org/10.1016/j.fct.2009.04.017.

Frost-Pineda, K., Zedler, B.K., Liang, Q., Roethig, H.J., 2008. Environmental tobacco smoke (ETS) evaluation of a third-generation electrically heated cigarette smoking system (EHCSS). Regul. Toxicol. Pharmacol. 52 (2), 118–121. https://doi.org/10.1016/j.yrtph.2008.06.007.

Geiss, O., Bianchi, I., Barahona, F., Barrero-Moreno, J., 2015. Characterisation of mainstream and passive vapours emitted by selected electronic cigarettes. Int. J. Hyg Environ. Health 218 (1), 169–180. https://doi.org/10.1016/j.ijheh.2014.10.001.

Geiss, O., Bianchi, I., Barrero-Moreno, J., 2016. Correlation of volatile carbonyl yields emitted by e-cigarettes with the temperature of the heating coil and the perceived sensorial quality of the generated vapours. Int. J. Hyg Environ. Health 219 (3), 268–277. https://doi.org/10.1016/j.ijheh.2016.01.004.

Geiss, O., Giannopoulos, G., Tirendi, S., Barrero-Moreno, J., Larsen, B.R., Kotzias, D., 2011. The AIRMEX study -VOC measurements in public buildings and schools/kindergartens in eleven European cities: statistical analysis of the data. Atmos. Environ. 45, 3676–3684. https://doi.org/10.1016/j.atmosenv.2011.04.037.

Geiss, O., Tirendi, S., Barrero-Moreno, J., Kotzias, D., 2009. Investigation of volatile organic compounds and phthalates present in the cabin air of used private cars. Environ. Int. 35 (8), 1188–1195. https://doi.org/10.1016/j.envint.2009.07.016.

Gillman, I.G., Kistler, K.A., Stewart, E.W., Paolantonio, A.R., 2016. Effect of variable power levels on the yield of total aerosol mass and formation of aldehydes in e-cigarette aerosols. Regul. Toxicol. Pharmacol. 75, 58–65. https://doi.org/10.1016/j.yrtph.2015.12.019.

Goniewicz, M.L., Knysak, J., Gawron, M., Kosmider, L., Sobczak, A., Kurek, J., Benowitz, N., 2014. Levels of selected carcinogens and toxicants in vapour from electronic cigarettes. Tobac. Contr. 23 (2), 133–139. https://doi.org/10.1136/tobaccocontrol-2012-050859.

Herrington, J.S., Myers, C., 2015. Electronic cigarette solutions and resultant aerosol profiles. J. Chromatogr. A 1418, 192–199. https://doi.org/10.1016/j.chroma.2015.09.034.

Hess, I., Lachireddy, K., Capon, A., 2016. A systematic review of the health risks from passive exposure to electronic cigarette vapour. Publ. Health Res. Pract. 26 (2). https://doi.org/10.17061/phrp2621617.

HPHC and Tobacco Smoke:Established List. (n.d.). Retrieved March 15, 2018, from https://www.fda.gov/TobaccoProducts/Labeling/RulesRegulationsGuidance/ucm297786.htm.

Hsu, D.J., Huang, H.L., 2009. Concentrations of volatile organic compounds, carbon monoxide, carbon dioxide and particulate matter in buses on highways in Taiwan. Atmos. Environ. 43 (36), 5723–5730. https://doi.org/10.1016/j.atmosenv.2009.08.039.

Hult, E.L., Willem, H., Price, P.N., Hotchi, T., Russell, M.L., Singer, B.C., 2015. Formaldehyde and acetaldehyde exposure mitigation in US residences: in-home measurements of ventilation control and source control. Indoor Air 25 (5), 523–535. https://doi.org/10.1111/ina.12160.

Jaccard, G., Djoko, D.T., Moennikes, O., Jeannet, C., Kondylis, A., Belushkin, M., 2017. Comparative Assessment of HPHC Yields in the Tobacco Heating System THS2.2 and Commercial Cigarettes. https://doi.org/10.1016/j.yrtph.2017.08.006.

Järnström, H., Saarela, K., Kalliokoski, P., Pasanen, A.L., 2006. Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. Atmos. Environ. 40 (37), 7178–7191. https://doi.org/10.1016/j.atmosenv.2006.06.021.

Kaunelienė, V., Prasauskas, T., Krugly, E., Stasiulaitienė, I., Čiužas, D., Šeduikytė, L.,

Martuzevičius, D., 2016. Indoor air quality in low energy residential buildings in Lithuania. Build. Environ. 108, 63—72. https://doi.org/10.1016/j.buildenv.2016.08.018.

Koistinen, K., Kotzias, D., Schlitt, C., Carrer, P., Maroni, M., Management, R., Seifert, B., 2004. Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU. The INDEX project. Retrieved from. http://ec.europa.eu/health/ph_projects/2002/pollution/fp_pollution_2002_frep_02.pdf.

Langer, S., Ramalho, O., Derbez, M., Ribéron, J., Kirchner, S., Mandin, C., 2016. Indoor environmental quality in French dwellings and building characteristics. Atmos. Environ. 128, 82—91. https://doi.org/10.1016/j.atmosenv.2015.12.060.

Lee, M.S., LeBouf, R.F., Son, Y.S., Koutrakis, P., Christiani, D.C., 2017. Nicotine, aerosol particles, carbonyls and volatile organic compounds in tobacco- and menthol-flavored e-cigarettes. Environ. Health Glob. Access Sci. Source 16 (1). https://doi.org/10.1186/s12940-017-0249-x.

Lee, S.C., Wang, B., 2004. Characteristics of emissions of air pollutants from burning of incense in a large environmental chamber. Atmos. Environ. 38 (7), 941—951. https://doi.org/10.1016/j.atmosenv.2003.11.002.

Lee, S.C., Wang, B., 2006. Characteristics of emissions of air pollutants from mosquito coils and candles burning in a large environmental chamber. Atmos. Environ. 40 (12), 2128—2138. https://doi.org/10.1016/j.atmosenv.2005.11.047.

Less, B., Mullen, N., Singer, B., Walker, I., 2015. Indoor air quality in 24 California residences designed as high-performance homes. Sci. Technol. Built. Environ. 21 (1), 14—24. https://doi.org/10.1080/10789669.2014.961850.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Ezzati, M., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380 (9859), 2224—2260. https://doi.org/10.1016/S0140-6736(12)61766-8.

Madureira, J., Paciência, I., Pereira, C., Teixeira, J.P., Fernandes, E.de O., 2016. Indoor air quality in Portuguese schools: levels and sources of pollutants. Indoor Air 26 (4), 526—537. https://doi.org/10.1111/ina.12237.

Maisey, S.J., Saunders, S.M., West, N., Franklin, P.J., 2013. An extended baseline examination of indoor VOCs in a city of low ambient pollution: Perth, Western Australia. Atmos. Environ. 81, 546—553. https://doi.org/10.1016/j.atmosenv.2013.09.008.

Malysheva, O., Podrushniak, A., Prodanchuk, M.G., 2017. Risk assessment of electrically heated tobacco product (EHTP) and combustible cigarettes: comparatory human exposure study. Toxicol. Lett. 280, S246—S247. https://doi.org/10.1016/J.TOXLET.2017.07.683.

Manoukian, A., Quivet, E., Temime-Roussel, B., Nicolas, M., Maupetit, F., Wortham, H., 2013. Emission characteristics of air pollutants from incense and candle burning in indoor atmospheres. Environ. Sci. Pollut. Control Ser. 20 (7), 4659—4670. https://doi.org/10.1007/s11356-012-1394-y.

Mitova, M.I., Campelos, P.B., Goujon-Ginglinger, C.G., Maeder, S., Mottier, N., Rouget, E.G.R., Tricker, A.R., 2016. Comparison of the impact of the Tobacco Heating System 2.2 and a cigarette on indoor air quality. Regul. Toxicol. Pharmacol. 80, 91—101. https://doi.org/10.1016/j.yrtph.2016.06.005.

Mottier, N., Tharin, M., Cluse, C., Crudo, J.R., Lueso, M.G., Goujon-Ginglinger, C.G., Solioz, J., 2016. Validation of selected analytical methods using accuracy profiles to assess the impact of a Tobacco Heating System on indoor air quality. Talanta 158, 165—178. https://doi.org/10.1016/j.talanta.2016.05.022.

Nayir, E., Karacabey, B., Kirca, O., Ozdogan, M., 2016. Electronic cigarette (e-cigarette). J. Oncol. Sci. 2 (1), 16—20. https://doi.org/10.1016/j.jons.2016.04.001.

Organization, W.H., 2013. Health Effects of Particulate Matter, p. 20. https://doi.org/10.5124/jkma.2007.50.2.175.

OSHA, 1978. Occupational Health Guideline for Nicotine. Retrieved from. https://www.cdc.gov/niosh/docs/81-123/pdfs/0446.pdf.

Petry, T., Vitale, D., Joachim, F.J., Smith, B., Cruse, L., Mascarenhas, R., Singal, M., 2014. Human health risk evaluation of selected VOC, SVOC and particulate emissions from scented candles. Regul. Toxicol. Pharmacol. 69 (1), 55—70. https://doi.org/10.1016/j.yrtph.2014.02.010.

Ruprecht, A.A., De Marco, C., Saffari, A., Pozzi, P., Mazza, R., Veronese, C., Boffi, R., 2017. Environmental pollution and emission factors of electronic cigarettes, heat-not-burn tobacco products, and conventional cigarettes. Aerosol. Sci. Technol. 51 (6), 674—684. https://doi.org/10.1080/02786826.2017.1300231.

Saffari, A., Daher, N., Ruprecht, A., De Marco, C., Pozzi, P., Boffi, R., Sioutas, C., 2014. Particulate metals and organic compounds from electronic and tobacco-containing cigarettes: comparison of emission rates and secondhand exposure. Environ. Sci. Process. Impacts 16 (10), 2259—2267. https://doi.org/10.1039/C4EM00415A.

Saraga, D., Pateraki, S., Papadopoulos, A., Vasilakos, C., Maggos, T., 2011. Studying the indoor air quality in three non-residential environments of different use: a museum, a printery industry and an office. Build. Environ. 46 (11), 2333—2341. https://doi.org/10.1016/j.buildenv.2011.05.013.

Schaller, J.P., Pijnenburg, J.P.M., Ajithkumar, A., Tricker, A.R., 2016. Evaluation of the Tobacco Heating System 2.2. Part 3: influence of the tobacco blend on the formation of harmful and potentially harmful constituents of the Tobacco Heating System 2.2 aerosol. Regul. Toxicol. Pharmacol. 81, S48—S58. https://doi.org/10.1016/j.yrtph.2016.10.016.

Schober, W., Szendrei, K., Matzen, W., Osiander-Fuchs, H., Heitmann, D., Schettgen, T., Fromme, H., 2014. Use of electronic cigarettes (e-cigarettes) impairs indoor air quality and increases FeNO levels of e-cigarette consumers. Int. J. Hyg Environ. Health 217 (6), 628—637. https://doi.org/10.1016/j.ijheh.2013.11.003.

Schripp, T., Markewitz, D., Uhde, E., Salthammer, T., 2013. Does e-cigarette consumption cause passive vaping? Indoor Air 23 (1), 25—31. https://doi.org/10.1111/j.1600-0668.2012.00792.x.

Shang, Y., Li, B., Baldwin, A.N., Ding, Y., Yu, W., Cheng, L., 2016. Investigation of indoor air quality in shopping malls during summer in Western China using subjective survey and field measurement. Build. Environ. 108, 1—11. https://doi.org/10.1016/j.buildenv.2016.08.012.

Smith, M.R., Clark, B., Lüdicke, F., Schaller, J.P., Vanscheeuwijck, P., Hoeng, J., Peitsch, M.C., 2016. Evaluation of the tobacco heating system 2.2. Part 1: description of the system and the scientific assessment program. Regul. Toxicol. Pharmacol. 81, S17—S26. https://doi.org/10.1016/j.yrtph.2016.07.006.

Song, G., Yu, A., Sakai, K., Khalequzzaman, M., Nakajima, T., Kitamura, F., Piao, F., 2017. Levels of volatile organic compounds in homes in Dalian, China. Air Qual. Atmos. Health 10 (2), 171—181. https://doi.org/10.1007/s11869-016-0422-3.

US Department of Health and Human Services, 2010. How Tobacco Smoke Causes Disease: The Biology and Behavioral Basis for Smoking-attributable Disease. How Tobacco Smoke Causes Disease: The Biology and Behavioral Basis for Smoking-Attributable Disease: A Report of the Surgeon General. https://doi.org/10.1037/e590462011-001.

US Department of Health and Human Services, 2014. The Health Consequences of Smoking—50 Years of Progress: a Report of the Surgeon General. U S Department of Health and Human Services,Centers for Disease Control and Prevention National Center for Chronic Disease Prevention and Health Promotion Health, Office on Smoking and Health, pp. 1—36. https://doi.org/NBK179276.

Uchiyama, S., Ohta, K., Inaba, Y., Kunugita, N., 2013. Determination of carbonyl compounds generated from the E-cigarette using coupled silica cartridges impregnated with hydroquinone and 2,4-dinitrophenylhydrazine, followed by high-performance liquid chromatography. Anal. Sci.: Int. J. Jpn. Soc. Anal. Chem. 29 (12), 1219—1222. https://doi.org/10.2116/bunsekikagaku.60.791.

Uchiyama, S., Tomizawa, T., Tokoro, A., Aoki, M., Hishiki, M., Yamada, T., Kunugita, N., 2015. Gaseous chemical compounds in indoor and outdoor air of 602 houses throughout Japan in winter and summer. Environ. Res. 137, 364—372. https://doi.org/10.1016/j.envres.2014.12.005.

US EPA. Acetaldehyde. Retrieved from https://www.epa.gov/sites/production/files/2016-09/documents/acetaldehyde.pdf.

US EPA. Benzene. Retrieved from https://www.epa.gov/sites/production/files/2016-09/documents/benzene.pdf.

US EPA. IRIS. Toluene. Integrated Risk Information System. Retrieved from https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0118_summary.pdf.

US EPA. National Ambient Air Quality Standards for Particulate Matter, 2013. Fed. Regist. 78 (10). Retrieved from. https://www.gpo.gov/fdsys/pkg/FR-2013-01-15/pdf/2012-30946.pdf.

US EPA. Toluene. Retrieved from https://www.epa.gov/sites/production/files/2016-09/documents/toluene.pdf.

US EPA IRIS. Acetaldehyde. Integrated Risk Information System. Retrieved from https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0290_summary.pdf.

Verriele, M., Schoemaecker, C., Hanoune, B., Leclerc, N., Germain, S., Gaudion, V., Locoge, N., 2016. The MERMAID study: indoor and outdoor average pollutant concentrations in 10 low-energy school buildings in France. Indoor Air 26 (5), 702—713. https://doi.org/10.1111/ina.12258.

WHO, 2005. Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update. https://doi.org/10.1016/0004-6981(88)90109—6. Retrieved from.

WHO, 2010. Selected Pollutants. Retrieved from. http://indoor-air-quality.jrc.ec.europa.eu/documents/e94535.pdf.

Zhang, G.S., Li, T.T., Luo, M., Liu, J.F., Liu, Z.R., Bai, Y.H., 2008. Air pollution in the microenvironment of parked new cars. Build. Environ. 43 (3), 315—319. https://doi.org/10.1016/j.buildenv.2006.03.019.

Zhao, T., Nguyen, C., Lin, C.-H., Sherry, Middlekauff, H.R., Peters, K., Moheimani, R., Zhu, Y., 2017. Characteristics of secondhand electronic cigarette aerosols from active human use. Aerosol. Sci. Technol. 0(0), 0—0 https://doi.org/10.1080/02786826.2017.1355548.