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Environmental Impact Statement

Since their commercialization, electronic cigarettes (e-cigarettes) have been marketed and used as "safer" surrogates of conventional tobacco-containing cigarettes. The increasing popularity of these devices during the past decade necessitates accurate identification of the environmental impacts of e-cigarette consumption and its potential health endpoints. While most of the few previous research efforts in this area have focused on characterization of gas-phase e-cigarette emissions, the much-needed data regarding e-cigarette's particulate emissions is scarce. This manuscript quantifies the level of exposure, as well as indoor emission rates of inorganic elements and organic compounds, providing insight regarding the toxico-chemical properties of e-cigarette's secondhand emissions and potential needs for regulatory supervision on the manufacturing of these devices.

Particulate Metals and Organic Compounds from Electronic and Tobacco-containing Cigarettes: Comparison of Emission Rates and Secondhand Exposure

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Abstract

In recent years, electronic cigarettes have gained increasing popularity as alternatives to normal (tobacco-containing) cigarettes. In the present study, particles generated by e-cigarettes and normal cigarettes have been analyzed and the degree of exposure to different chemical agents and their emission rates were quantified. Despite the 10-fold decrease in the total exposure to particulate elements in e-cigarettes compared to normal cigarettes, specific metals (e.g. Ni and Ag) still displayed a higher emission rate from e-cigarettes. Further analysis indicated that the contribution of e-liquid to the emission of these metals is rather minimal, implying that they likely originate from other components of the e-cigarette device or other indoor sources. Organic species had lower emission rates during e-cigarette consumption compared to normal cigarettes. Of particular note was the non-detectable emission of polycyclic aromatic hydrocarbons (PAHs) from e-cigarettes, while substantial emission of these species was observed from normal cigarettes. Overall, with the exception of Ni, Zn, and Ag, the consumption of e-cigarettes resulted in a remarkable decrease in secondhand exposure to all metals and organic compounds. Implementing quality control protocols on the manufacture of e-cigarettes would further minimize the emission of metals from these devices and improve their safety and associated health effects.

Keywords: Electronic cigarette, Particulate Matter, Metals, Organic compounds, Emission Rate

1. Introduction

Use of electronic cigarettes (e-cigarettes) has rapidly increased worldwide during the past decade.[1] E-cigarettes are battery-operated electronic nicotine delivery devices (ENDD) that provide an aerosol from a liquid mixture of nicotine, propylene glycol, glycerol and flavorings (known as "e-liquid").[2,3] Considering that nicotine delivery by e-cigarettes is achieved by aerosolizing the "e-liquid" as opposed to the combustion of tobacco, e-cigarette consumption is presumed to carry with it lower health risks compared to normal cigarettes.[1,4,5] E-cigarettes, however, pose a significant regulatory challenge for the medical community and public health authorities. Although e-cigarettes are promoted as aids to reduce the use of tobacco-containing cigarettes,[4] there are still uncertainties regarding the degree to which they promote a clinically relevant cessation rate in smokers.[6] Moreover, unregulated production of e-cigarettes and e-liquids, in addition to the very limited scientific evidence regarding the chemical composition of the vapors and aerosols generated by e-cigarettes, have raised concerns about the potential adverse health effects of e-cigarette consumption.[7–9]

Based on recent studies, there is considerable inconsistencies in the levels of nicotine as well as organic compounds (such as propylene glycol and glycerol) in the vapors generated by different brands of e-cigarettes.[10,11] Another recent study reported generally lower levels of organic species, including volatile organic compounds (VOCs), carbonyls, polycyclic aromatic hydrocarbons (PAHs) and glycols, in the vapors emitted from e-cigarettes compared to tobacco smoke.[12] Williams et al.[13] analyzed 11 particulate elements in the aerosol generated by e-cigarettes and reported the presence of tin, silver, iron, nickel and aluminum in super-micron particles, and tin, chromium and nickel in sub-micron particles. Further analyses indicated that

these potentially toxic elements originate from the e-cigarette's cartomizer, alerting us to the need for improved quality control in e-cigarette manufacture and further investigations on the potential adverse health impacts of e-cigarette consumption.[13]

The majority of the few previous studies on the chemical characterization of e-cigarette emissions focused on vapor-phase emissions, emphasizing the need for fundamental data pertaining to aerosols emissions from e-cigarettes. In this study, particles generated by the consumption of e-cigarettes as well as normal cigarettes were collected in a room under controlled conditions and comprehensive chemical analyses (including the quantification of 42 inorganic elements and various organic compounds) have been performed on the samples, in order to quantify the degree of secondhand exposure to particulate organic compounds and metals in a real-life setting. Moreover, emission rates of individual metals and organic compounds were determined using a single-compartment mass balance model and Monte-Carlo error estimation analysis.

2. Methodology

2.1. Sampling protocol

Samples of total suspended particles were collected indoors on quartz filters (Whatman International Ltd, Maidstone, England), using a high-volume PM sampler operating at a flow rate of 240 liters per minute (lpm), in a room having a volume of 48 m^3 on the fifth floor of the Fondazione IRCCS Istituto Nazionale dei Tumori, an Italian cancer research center in Milan. The room was furnished with typical office furniture. In order to ensure a homogenous distribution of the aerosol, the air inside the room was well-mixed by means of three fans

blowing into different directions during all experiments. The room's window faced a terrace, where outdoor particulate matter (PM) was simultaneously sampled and collected on similar quartz filters, using a similar high-volume PM sampler, operating at 240 lpm. The initial air exchange rate (AER) inside of the sampling room was estimated to range between 0.80 and 0.86 hr^{-1}, by measuring the decay rate of carbon monoxide (CO) generated by combustion of incense sticks, and further increased to about 1.1 hr^{-1} during the sampling periods due to the additional AER caused by the sampler pump (operating at 240 lpm in a room of 48 m^3).

One of the most popular European brands of e-cigarette (Elips Serie C, Tank System, Ovale Europe Srl) and a typical, widely used brand of normal (i.e. tobacco-containing) cigarette was used for all experiments. E-cigarettes and normal cigarettes were smoked by three volunteer smoker subjects, including two males (aged 55 and 64 years old) and one female (aged 32 years old). Both the smoking procedure and indoor environment were designed in a way to simulate real-life conditions. Normal cigarettes were smoked '*ad libitum*' by the subjects, with an average rate of one puff every minute, leading to an average total time of seven minutes for completion of one tobacco-containing cigarette. A 3 minute pause was applied between two subsequent cigarettes. To enable a robust comparison between normal cigarette and e-cigarette emissions, the e-cigarette smoking procedure was designed to be similar to the smokers' conventional cigarette smoking habit. E-cigarettes were therefore vaped at a rate of one puff per minute, lasting for seven minutes, followed by three minutes of pause and continuing again for another seven minutes. During the vaping/smoking, two people were present in the room, one smoker and one person for instrument operation. Smokers were positioned on one side of the room while all instruments and samplers were positioned on the other side in order to avoid direct blowing of vapors into the inlets of the instruments and to ensure the highest posible mixing in the room.

The cartridge of the e-cigarette had a volume of 1.5 ml and was filled with the commercial e-liquid (consisting of propylene glycol, glycerol, aroma and water, based on the manufacturer). In order to investigate nicotine emission rate, e-cigarette samples were collected both without and with adding nicotine to the e-liquid (a concentration of 16 mg/ml nicotine was used in the e-liquid for the latter). Using the above-mentioned smoking protocol, an approximate e-liquid volume of 1.3 ml was consumed per hour and the e-liquid cartridge was refilled frequently throughout the experiments. A total of 6 e-cigarette samples (3 with nicotine and 3 without nicotine) and 3 normal cigarette samples were collected, each with parallel outdoor samples. With the exception of the nicotine analysis, e-cigarette samples with and without nicotine were combined for all other analyses, in order to increase the statistical power of the results and comparisons.

2.2. Chemical analyses

The concentration of black carbon (BC) was measured inside the smoking room, using an aethalometer (7-wavelength AE 31, Magee Scientific). Concentration of carbon monoxide (CO) was quantified by an indoor air quality analyzer (Graywolf Sensing Solutions, Shelton, CT, USA). Inorganic elements as well as organic compounds were measured by time-integrated PM samples collected on quartz filters. To measure the total concentration of elements in the PM, portions of the quartz filters were digested in an acid mixture (comprised of nitric acid, hydrochloric acid and hydrogen peroxide), inside of a microwave-assisted Teflon digestion bomb (Milestone ETHOS+), followed by analysis using a high-resolution magnetic sector inductively coupled plasma mass spectrometry (ICP-MS) (Thermo-Finnigan Element 2). Further details regarding this method can be found in Herner et al.[14] Concentration of individual organic species

was measured by gas chromatography mass spectrometry (GC-MS) method (GC-6980, quadrupoleMS-5973, Agilent Technologies), as described in Stone et al.[15] In brief, portions of quartz filters were extracted in a 1:1 solution of dichloromethane and acetone, using Soxhlets, followed by volume reduction using rotary evaporation, under high purity nitrogen and derivitization of carboxylic acids with diazomethane, and then analyzed by GC-MS. Concentration of elements and metals, as well as speciated organic compounds was also quantified in the e-liquid, using the same ICP-MS and GC-MS methods, respectively. For all of the analyses, detection limits of the measurements were calculated as 2 times the total analytical uncertainties, in the limit as the concentrations of the species approach zero (presented in Table S1).

2.3. Determination of emission rates

In order to calculate the emission rate of particle-bound species, a single-compartment mass balance model was applied to the smoking room for each species. The overall mass balance equation in the room is given in Equation 1:

$$\mathbf{V}\frac{\mathbf{dC_{in}}}{\mathbf{dt}} = \mathbf{S_i} + \mathbf{C_{out}}\,\mathbf{P(AER)}\,\mathbf{V} - \mathbf{C_{in}(AER)V} - \mathbf{kC_{in}V} \qquad \textbf{(Eq. 1)}$$

where C_{out} and C_{in} represent outdoor (i.e. ambient) concentration and indoor (i.e. inside of the smoking room) concentration, respectively (expressed in ng/m^3). P represents the penetration efficiency of particles and is dimensionless.[16] AER and k are the air exchange rate and particle deposition loss, respectively, both measured in units of hr^{-1}. V represents the volume of the smoking room (48 m^3) and S_i is the indoor emission rate of the species (ng/hr). Assuming steady

state conditions (i.e. $dC_{in}/dt=0$, achieved by rather long sampling periods as well as relatively high air exchange rate) and homogeneous distribution of compounds in the room (achieved by continuously mixing the air using three fans during all experiments), the mass balance for each compound is simplified to Equation 2:

$$\mathbf{C_{in}} = \frac{\mathbf{P\ (AER) C_{out}}}{\mathbf{(AER+k)}} + \frac{\left(\mathbf{S_i}/\mathbf{V}\right)}{\mathbf{(AER+k)}} \qquad \textbf{(Eq. 2)}$$

Indoor and outdoor concentrations were determined following the chemical analyses on the filter samples and a total air exchange rate (AER) of 1.1 (±0.06) hr^{-1} was determined for the experimental conditions (including 0.8 hr^{-1} based on the decay rate of CO, in addition to 0.3 hr^{-1} to account for the AER caused by the pump, operating at 240 lpm in a 48 m^3 room). Rate of deposition loss (k) and penetration efficiency (P) were estimated to vary between 0.1-0.2 hr^{-1} and 0.7-0.85, respectively, based on the study by Long et al.[16] Based on the variables' uncertainties, the uncertainties of indoor emission rates (S_i) were propagated using a Monte Carlo error estimation analysis,[17] by calculating the standard deviation of the mean emission rate values after performing the Monte Carlo based on 1000 iterations using randomly selected variables.

3. Results and Discussion

3.1. Mass concentration overview

Figure 1 presents an overview of the total PM mass concentration indoors (i.e. inside of the smoking room) and outdoors, during e-cigarette and normal cigarette consumption. As seen in the figure, the overall increase in the indoor PM mass concentration level compared to the simultaneously-measured outdoor concentration is remarkable during normal cigarette smoking

(from about 55 μg/m^3 to more than 250 μg/m^3), while for e-cigarette vaping, similar levels are observed for indoor and outdoor PM concentrations. As will be shown later in the emission rate calculation section, despite similar levels of total PM concentrations indoor compared to outdoor during e-cigarette vaping, indoor emission rates of specific metals and organic compounds are significant. We should also note that presence of nicotine in the e-liquid had a very small effect (less than 0.1 %) on the e-cigarette's total PM emissions (as shown in Figure S1, supplementary information). Emission rate and indoor concentration of particle-phase nicotine during e-cigarette vaping are discussed separately, in section 3.4.

Figure 2 presents the mass fraction of aggregated elements, and groups of organic compounds (including PAHs, alkanes, organic acids, hopanes and levoglucosan). Concentration of these chemical groups in the air (i.e. normalized by the volume of air) is also presented in Figure S2 (supplementary information). Specific chemical species in each group and their corresponding concentrations are given in Table S1 (supplementary information) for reference. As seen in Figure 2, the mass fraction of alkanes and organic acids is 5-10-fold greater for normal cigarette samples compared to both e-cigarette and outdoor samples. Hopanes, tracers of gasoline and diesel engine combustion emissions,[18] were only detected outdoors. PAHs were found in larger proportions in normal cigarette samples compared to outdoor ambient air (about 10 times), while they were undetected for indoor samples collected during e-cigarette vaping. Considering the potential carcinogenic effects of PAHs,[19,20] reduced emission of PAHs is one of the most desirable outcomes of e-cigarette vaping compared to normal cigarette consumption. The mass fraction of inorganic elements was highest for outdoor samples, driven by the considerably higher (10-60-fold) concentration of dust/soil dominated elements (such as Mg and Ca) in the

ambient air (Table S1-a). In the following sections, exposure concentrations as well as emission rates of specific chemical components are discussed.

3.2. Level of exposure to chemical species

3.2.1. Black Carbon

Real-time aethalometer-based black carbon (BC) measurements at 7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nanometers) inside of the smoking room are presented in Figure 3. BC concentrations in the aerosol are estimated from the absorption at the 880 nm wavelength (i.e. infrared).[21] The light absorption associated with shorter wavelengths may provide insights on possible composition of the aerosol in terms of organic species. Typically, aerosols with a high content of light-absorbing organic compounds would exhibit higher light absorbance at shorter wavelengths.[21] Therefore, for an aerosol with low organic content, the reported BC concentration at 880 nm (i.e. actual or "standard" BC) would be close to that at shorter wavelengths, whereas for an aerosol with a high organic content (such as PAHs in tobacco smoke), the BC concentration reported for shorter wavelengths will be higher than that of standard BC concentration. As shown in Figure 3, BC concentration during e-cigarette vaping is consistently close to zero, while during the period of normal cigarette consumption, a spectrum of distinct BC concentrations at different wavelengths is observed. The standard (i.e. actual) BC concentration during normal cigarette smoking (corresponding to 880 nm) peaks at 4.1 $\mu g/m^3$, while the reported BC concentration at shorter wavelengths is much higher (e.g. 24.8 $\mu g/m^3$ at 470 nm ("blue" light) and 65.4 $\mu g/m^3$ at 370 nm ("ultraviolet" light)), likely due to the presence of

196 ultraviolet-absorbing organic compounds in the tobacco smoke.[21] As will be discussed in the
197 following sections, results of our GC-MS analysis confirm the abundance of organic species
198 (including, but not limited to, alkanes, organic acids and PAHs) in tobacco smoke.

199

200 **3.2.2. Inorganic Elements and Metals**

201 Indoor to outdoor concentration ratios (I/O) of the elements that were detected in e-cigarette
202 samples are presented in Table 1, along with Pearson correlation coefficient (R) between indoor
203 and outdoor concentrations. The actual air concentrations of 47 elements that were quantified by
204 the ICP-MS analysis are also included in Table S1-a (supplementary information). I/O ratio and
205 correlation coefficient (R) together provide insights on the origin of the indoor aerosol. An I/O
206 ratio greater than 1 and a low R indicate that indoor PM is originating predominantly from
207 indoor sources, whereas an I/O ratio smaller than 1 with moderate to high (i.e. greater than 0.7)
208 R is an indication of significant infiltration of outdoor PM. As shown in Table 1, the average I/O
209 ratio for 6 elements (including B, K, Ni, Zn, Ag and La) is greater than unity with a low
210 correlation coefficient ($-0.16<R<0.22$), indicating the presence of indoor emission source(s) for
211 these elements during e-cigarette vaping. In order to investigate the potential influence of the e-
212 liquid's elemental content on the observed indoor levels of the aforementioned 6 elements, ICP-
213 MS analysis was performed on the e-liquid samples and concentration of these elements in the e-
214 liquid was quantified (results of the e-liquid analysis are presented in Table S3, supplementary
215 information). To segregate the contribution of e-liquid and other e-cigarette components to the
216 emissions (which is of utmost importance from a regulatory standpoint), the single-compartment
217 mass balance model (discussed in the section 2.3.) was employed to determine the portion of the

indoor concentrations that originate from the e-liquid. The results are presented in Figure 4. As seen in Figure 4, for all of these elements (specifically Ni, Zn Ag and La), the estimated contribution of the e-liquid to the indoor concentration is lower than the actual indoor levels during e-cigarette vaping, suggesting that these elements originate from another indoor source. In a recent study by Williams et al.,[13] the cartomizer's elemental content was examined using electron microscopy and compared to the aerosol's elemental content. Their analysis confirmed the presence of metals such as Sn, Ag, Fe, Ni, Al and Cr in the cartomizer and their emission thereof in the aerosol generated by the e-cigarette, suggesting that the material used in the cartridge of the e-cigarette is a likely source contributing to the total emission of these metals in our study as well. Indoor concentration of B, K, Ni, Zn, Ag and La during e-cigarette vaping and normal cigarette smoking are compared in Figure 5. The concentrations of B, K and La were statistically significantly ($p<0.05$) higher in normal cigarettes. On the other hand, there was no statistically significant difference between e-cigarette and normal cigarette samples for Zn, Ni and Ag (potentially toxic and redox active species[22,23]). Considering the potential adverse health effects associated with the inhalation of these metals (particularly Ni and Zn, and the emission observed both in our analysis as well as the study by Williams et al.[13]), attention should be directed toward eliminating the use of these metals in the cartridges during the manufacturing process of e-cigarettes.

3.2.3. Organic Species

The concentration of individual organic species for both indoor and outdoor samples is shown in Table S1 (b-e). PAH concentrations, including benz(a)anthracene, chrysene, benzo(b)fluoranthen, benzo(k)fluoranthene, benzo(e)pyrene, benzo(a)pyrene, indeno(1,2,3-

cd)pyrene and benzo(g,h,i)perylene, were found to be substantially higher indoors than outdoors during normal cigarette smoking (ranging between 1.4 to 5.1 ng/m^3 for indoor and 0.19 ng/m^3 or less for outdoor), while they were not detected in the indoor samples that were collected during e-cigarette vaping. Hopanes and steranes, tracers of lubricating/engine oil in diesel and gasoline vehicles,[24] were non-detected for all indoor samples associated with e-cigarettes. Levoglucosan, a tracer of biomass combustion,[25] was detected in all indoor and outdoor samples, with indoor concentration during e-cigarette vaping about 80-fold lower than that during normal cigarette smoking (which was expected due to the presence of biomass in normal tobacco-containing cigarettes) and about 3-fold lower than ambient levels. N-alkanes and organic acids were the only groups of organic species that were found at higher concentrations indoor than outdoor during e-cigarette use.

For all of the organic species with detectable indoor concentrations during e-cigarette vaping, the I/O concentration ratios as well as Pearson correlation coefficients between indoor and outdoor concentrations were determined (presented in Table 2). As seen in the table, levoglucosan is the only organic compound with an I/O ratio smaller than unity. Considering the strong association between outdoor and indoor levoglucosan levels during e-cigarette vaping (R=0.99), the indoor levels of levoglucosan for e-cigarette samples are most likely associated with ambient levoglucosan that infiltrated indoors. Alkanes and organic acids presented in Table 2 had average I/O ratios greater than one, indicating the presence of an indoor source for these species during e-cigarette consumption. This observation was further investigated by an analysis of the organics content of the e-liquid (presented in Table S3). Excluding hexadecanoic acid and octadecanoic acid, which respectively displayed concentrations of 511 (±148) and 247 (±118) µg/ml in the e-

liquid, this analysis resulted in non-detectable levels for all measured compounds. Considering the non-detectable concentration of most n-alkanes and organic acids in the e-liquid, definitive conclusion regarding the sources of these organics in the indoor environment is not possible based on our data. The rather low concentration of these compounds during e-cigarette vaping (i.e. less than 100 ng/m^3 for most of the species, as shown in Tables S1-d and S1-e), is most likely indicative of a dominant background indoor level and is not representative of a specific source. It is important to note that additional quantification of the gas-phase organics in the indoor environment is needed to accurately determine the sources of indoor organic compounds, the emission of which may have disproportional partitioning in the gas-phase and particulate-phase. I/O ratio for alkanes and organic acids during normal cigarette smoking is also presented in Table S2 (supplementary information), with all of the compounds exhibiting I/O ratios greater than unity (ranging from a minimum of 4.3 for hexatriacontane, up to more than 300 for species such as tritriacontane), demonstrating the presence of strong indoor emission source(s) for these species during normal cigarette smoking. Indoor emission rate of these organic species are calculated and discussed in the next section.

3.3. Emission rates of chemical species

A single-compartment mass balance model was employed to determine and compare the indoor emission rates of chemical species during e-cigarette vaping and normal cigarette smoking. The results are presented in Tables 3 (inorganic elements) and 4 (organic species). A non-detectable (N.D.) emission rate indicates that there was no detectable indoor emission source for the species and the observed indoor concentrations were, therefore, mostly due to the penetration of outdoor aerosol to the indoor environment as a result of air exchange (AER=1.1 hr^{-1}) between the indoor

and outdoor environments. The indoor emission rates of several elements with adverse health effects upon inhalation are substantially decreased in e-cigarette's aerosol compared to that from normal cigarette. Cadmium and Lead, for instance, are particularly toxic metals that have been consistently found in tobacco smoke in previous studies (e.g.[26,27]). Indoor emission rates associated with these metals during smoking of normal cigarettes were as high as 1012 ng/hr and 657 ng/hr for Pb and Cd, respectively, while for e-cigarette vaping these rates are lower by 2-3 orders of magnitude. Similarly, sulfur (another element commonly present in high concentrations in tobacco smoke[28]) had an indoor emission rate of about 34 µg/hr during normal cigarette smoking, while it had no detectable indoor emission during e-cigarette consumption. With the exception of Ni, Ti, Cr and Ag (elements also found in the e-cigarette's aerosol in a previous study by Williams et al.[13]), the indoor emission rate of all elements was higher for normal cigarette smoking compared to e-cigarette vaping. This observation suggests that even though e-cigarette's aerosol contains fewer deleterious elements, and at lower concentrations, it does contain several metals such as Ag, Cr, and Ni (which are toxic metals[22,23]) that are being emitted in higher rates from e-cigarettes. This is most likely due to the low quality and lack of supervision and control on the manufacturing process of e-cigarette's cartridges, as explained in the article by Williams et al.[13] Moreover, although the emission of Pb was substantially decreased in e-cigarette compared to normal cigarette, its presence in e-cigarette's aerosol can still be further reduced or eliminated by implementing better quality control procedures in the manufacturing process of e-cigarettes.

Tables 4 and 5 highlight the emission rates associated with organic species (n-alkanes and alkanoic acids in Table 4 and PAHs in Table 5). As seen in Table 4, the emission rate of all particulate alkanes and organic acids decreased by 2-3 orders of magnitude for e-cigarette

compared to normal cigarette. Seven PAHs were detected in normal cigarette samples (including chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(e)pyrene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene and benzo(g,h,i)perylene) with indoor emission rates ranging from 105 ng/hr benzo(e)pyrene to 307 ng/hr benzo(b)fluoranthene, while none of these species were detected indoors during e-cigarette vaping. We note here that although our analysis indicates that the particle-phase organic content of e-cigarette's aerosol is considerably lower than that of normal cigarette smoke, another portion of e-cigarette's emissions are expected to be in the vapor phase, the evaluation of which was not part of our analysis. Further analysis of vapor-phase e-cigarette emissions might be useful to uncover the vapor-phase levels of organic emissions from e-cigarettes.

3.4. Indoor concentration and emission rate of nicotine

In order to examine particle-phase nicotine levels and emission rates, e-cigarette samples without the addition of nicotine (i.e. loaded with e-liquid only) and with a nicotine concentration of 16 mg/ml (a typical dose of nicotine in commercially available nicotine-containing e-liquid) were collected and examined by GC-MS. The nicotine content of the e-liquid was also verified using our GC-MS methodology, which resulted in a nicotine concentration of 17.2 (±0.5) mg/ml, indicating a very good agreement between the commercial nicotine label (i.e. 16 mg/ml) and the actual nicotine content of the e-liquid. Indoor concentrations and emission rates, as well as I/O ratio of nicotine for normal cigarette as well as e-cigarette samples with and without the addition of nicotine are presented in Table 6. The indoor concentration and emission rate of particle-phase nicotine were both about 13 times higher during smoking of normal cigarette compared to the consumption of e-cigarette containing 16 mg/ml of nicotine in the e-liquid (1524 ng/m^3 versus

123 ng/m^3 and 91161 ng/hr versus 7103 ng/hr, respectively). Detectable levels of nicotine were found in particles collected during the experimental trials of e-cigarette without nicotine in the e-liquid. Nicotine is a semi-volatile compound, with strong affinity and persistence on indoor surfaces.[29,30] The observed (small) nicotine levels in e-cigarette samples without nicotine could, therefore, be due to particle-bound nicotine re-suspension in the room during sampling and can be considered as a "background" or "blank" emission level. Re-suspension of residual nicotine in indoor environments has been previously considered as one of the pathways of passive exposure to nicotine in houses with active smoker residents.[30] It should be mentioned that the concentration of residual and side-stream nicotine in an indoor environment can be significantly affected by gas-to-particle partitioning of nicotine, which is strongly dependent on the environmental conditions such as temperature, pressure and acidity of the aerosol.[31,32] In our study, the average consumption rate of the e-liquid was about 1.3 ml/hr, which, considering a nicotine concentration of 17.2 mg/ml in the e-liquid (measured by the GC-MS method), would result in a total emission rate of about 22.36 mg/hr nicotine from e-cigarettes (including both gas-phase and particle-phase nicotine). Based on our data, the indoor emission rate of particle-phase nicotine (after subtraction of nicotine level from e-cigarette without nicotine; which was considered as a "background" level) was about 4344 ng/hr, accounting for about 0.02 % of the total nicotine emission, implying that a trivial fraction of the total nicotine emissions from e-cigarettes is found in secondhand particulate emissions. Further investigation is required for accurate determination of nicotine's gas-to-particle partitioning ratio in e-cigarette's aerosol, which can provide useful insight about secondhand exposure to nicotine during e-cigarette vaping under different conditions.

4. Summary and Conclusions

Analysis of secondhand emissions from a popular and widely-used e-cigarette brand indicated a very large reduction of particle-phase emissions compared to normal tobacco-containing cigarettes in a real-life setting. BC and particle-phase PAHs, deleterious chemical species present in high concentrations in tobacco smoke, were not detected in e-cigarette's aerosol. Emission rates of organic compounds (including alkanes and organic acids) as well as total emission of inorganic elements and metals were also significantly reduced (more than 100 times for organics and 10 times for elements) in e-cigarettes compared to normal cigarettes. Analysis of elemental emissions indicated the presence of toxic metals (such as Ni, Zn and Ag) in e-cigarette's aerosol, with Ni and Ag having higher indoor emission rates compared to normal cigarettes. Moreover, analysis of nicotine indicated that secondhand particle-phase nicotine accounted for about 21% of the total nicotine generation and emission during e-cigarette vaping. Based on our results, use of e-cigarettes from a public health perspective appears to be an improvement compared to normal tobacco-containing cigarettes, as exposure to most of the toxic and/or undesirable chemical species was found to be much lower than that for normal cigarettes. However, considering the lack of regulation on the manufacturing process of e-cigarettes, there appears to be a potential for utilization of toxic material (such as metals) in e-cigarettes, which could lead to their emission in e-cigarette's vapor and aerosol.[1,13] Implementing quality control regulations on the design and manufacturing process of e-cigarettes is therefore necessary to prevent potential utilization of non-desirable material in e-cigarettes and e-liquids.

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We wish to dedicate the work *in memoriam* of Giovanni Invernizzi.

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Figures and Tables

Figure 1. Average outdoor and indoor (i.e. inside of the smoking room) mass concentration (µg/m^3) during smoking and vaping of normal cigarettes and e-cigarettes. Error bars represent one standard error.

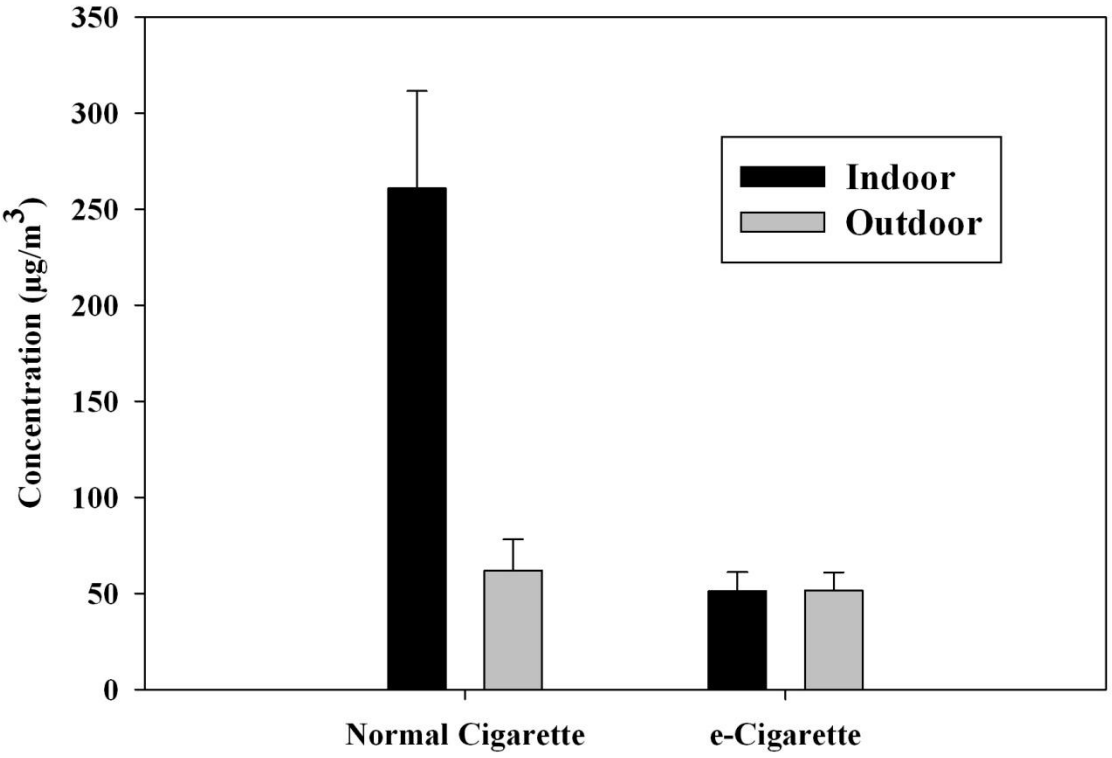


Figure 2. Average total concentration of elements as well as organic groups (polycyclic aromatic hydrocarbons (PAHs), hopanes, n-alkanes, organic acids and levoglucosan), normalized by PM mass concentration (ng/µg PM). Error bars represent analytical uncertainties.

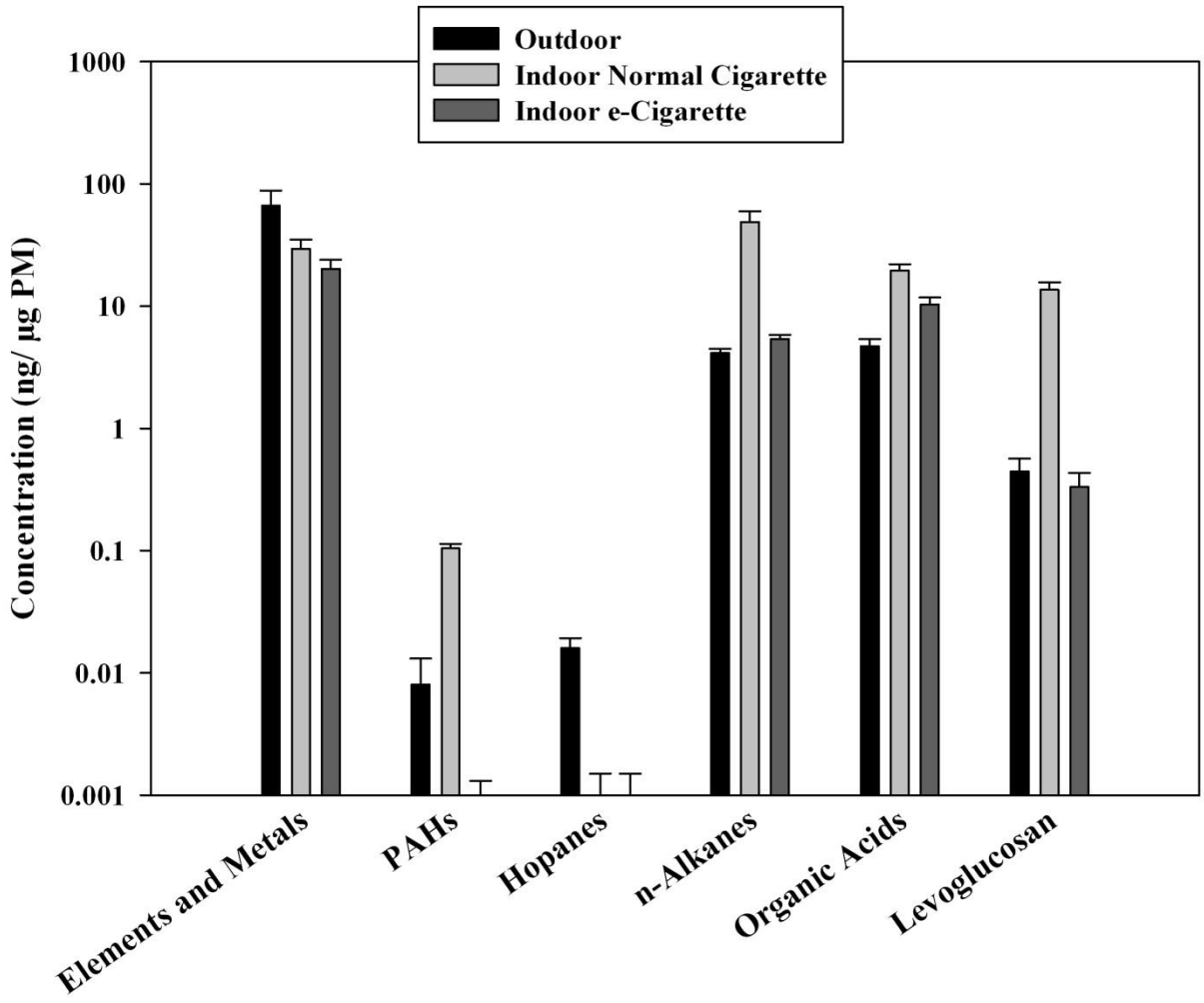


Figure 3. Comparison of indoor black carbon (BC) mass concentration (ng/m^3) inside of the smoking room, between periods of normal cigarette and e-cigarette consumption.

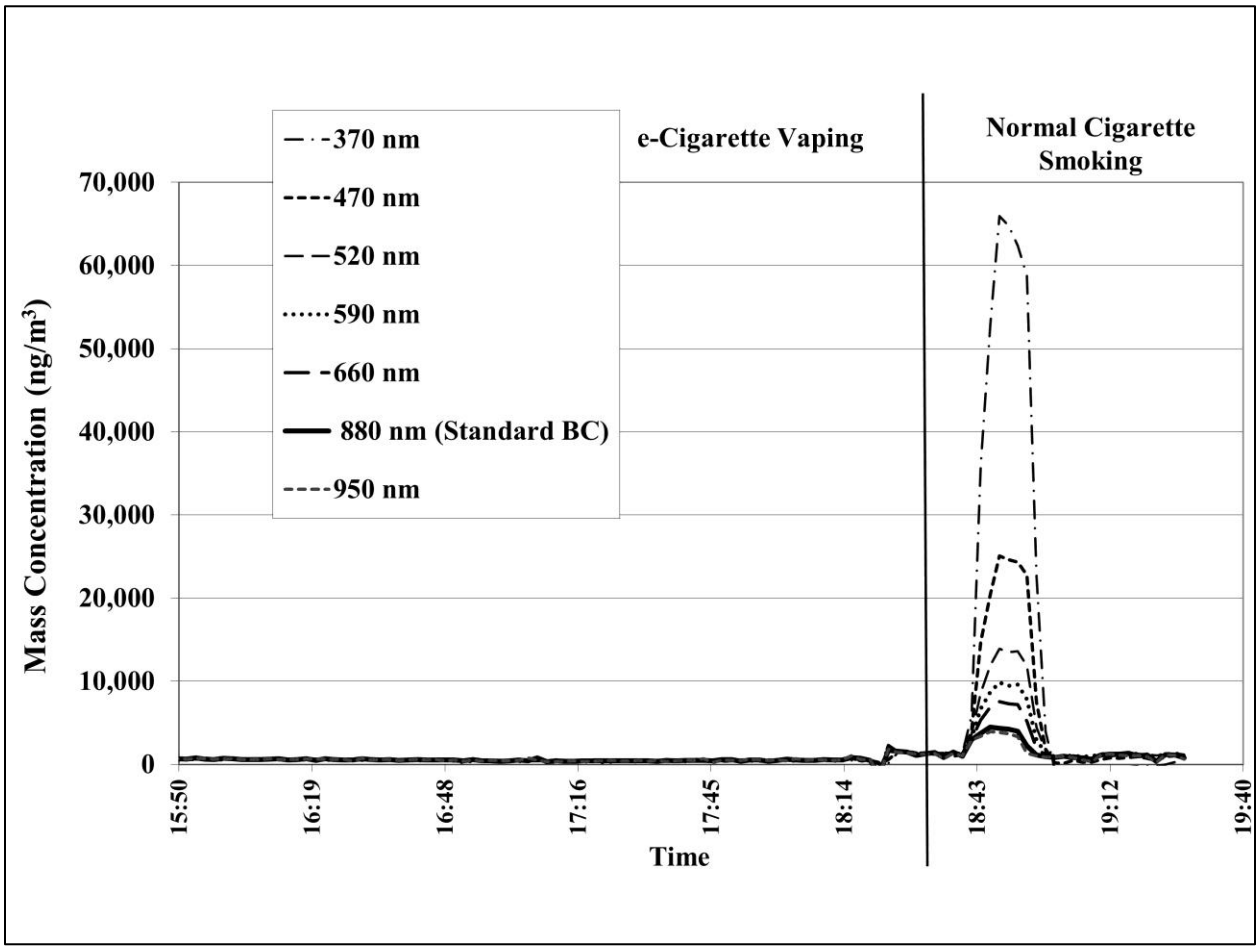


Table 1. Average indoor (i.e. inside of the smoking room) to outdoor mass concentration ratio and Pearson correlation coefficient (R) of elemental constituents of e-cigarette samples. Values correspond to average ±standard error.

Element	In/Out Ratio	R	Element	In/Out Ratio	R
B	13.13 (±7.47)	0.17	Cu	0.43 (±0.2)	-0.49
Mg	0.10 (±0.06)	-0.35	Zn	1.26 (±0.33)	0.13
Al	0.48 (±0.11)	0.89	Rb	0.56 (±0.07)	0.26
S	0.81 (±0.27)	0.77	Sr	0.30 (±0.09)	0.82
K	1.53 (±0.56)	0.22	Mo	0.52 (±0.17)	0.61
Ca	0.18 (±0.16)	0.54	Ag	3.39 (±1.15)	-0.10
Ti	0.80 (±0.18)	0.45	Cd	0.91 (±0.2)	0.66
V	0.48 (±0.18)	0.37	Sn	0.37 (±0.33)	-0.18
Cr	0.92 (±0.44)	-0.12	Sb	0.30 (±0.05)	0.95
Mn	0.33 (±0.1)	-0.09	La	1.47 (±0.68)	0.01
Fe	0.26 (±0.1)	-0.27	W	0.85 (±0.38)	0.08
Co	0.44 (±0.23)	-0.07	Pb	0.89 (±0.26)	0.00
Ni	1.75 (±0.72)	-0.16			

Figure 4. Average indoor (i.e. inside of the smoking room) concentration (ng/m^3) of elements with average indoor to outdoor mass ratio greater than unity, compared to their estimated concentration caused by the e-liquid's elemental content. Error bars represent one standard error for the former and analytical uncertainties for the latter.

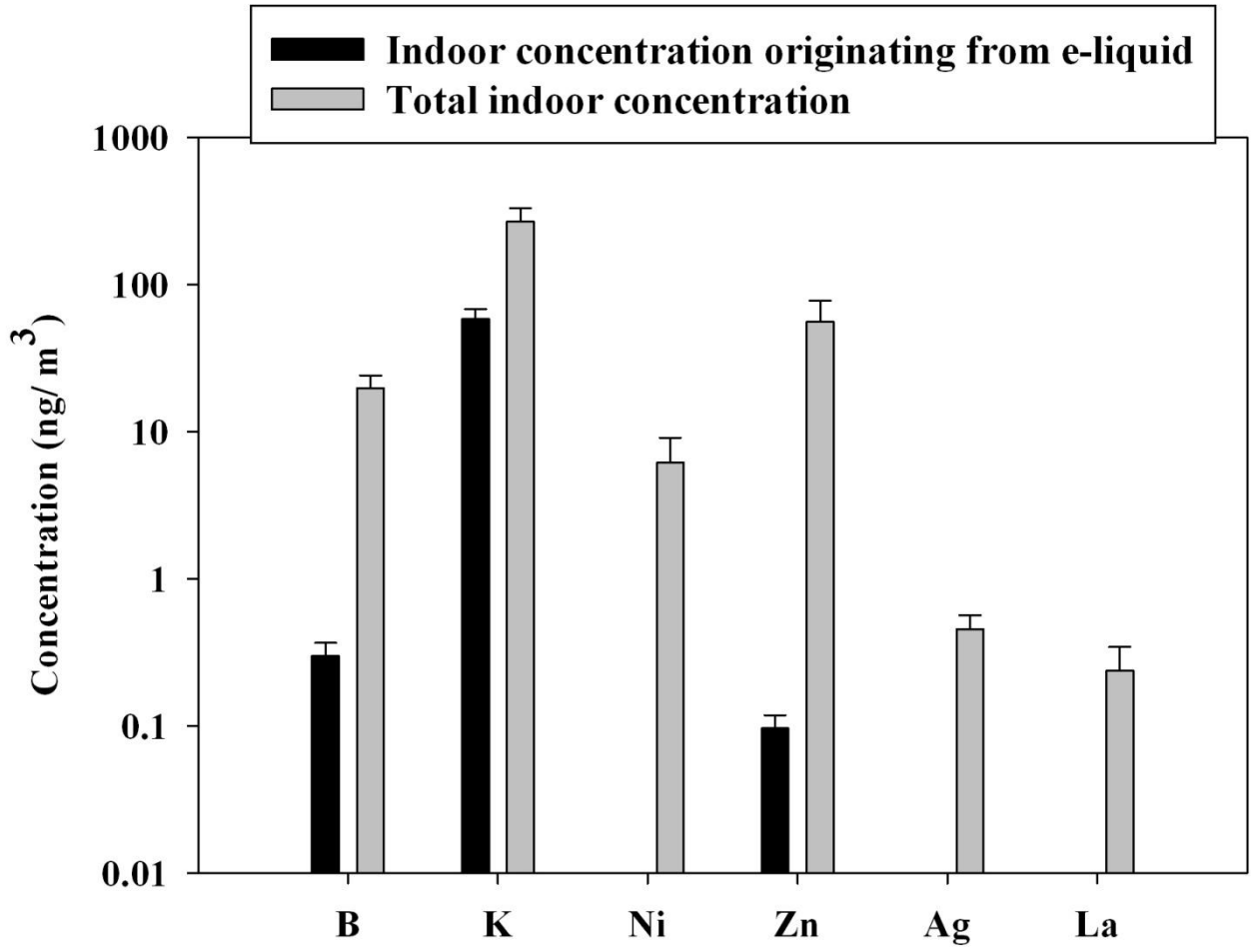
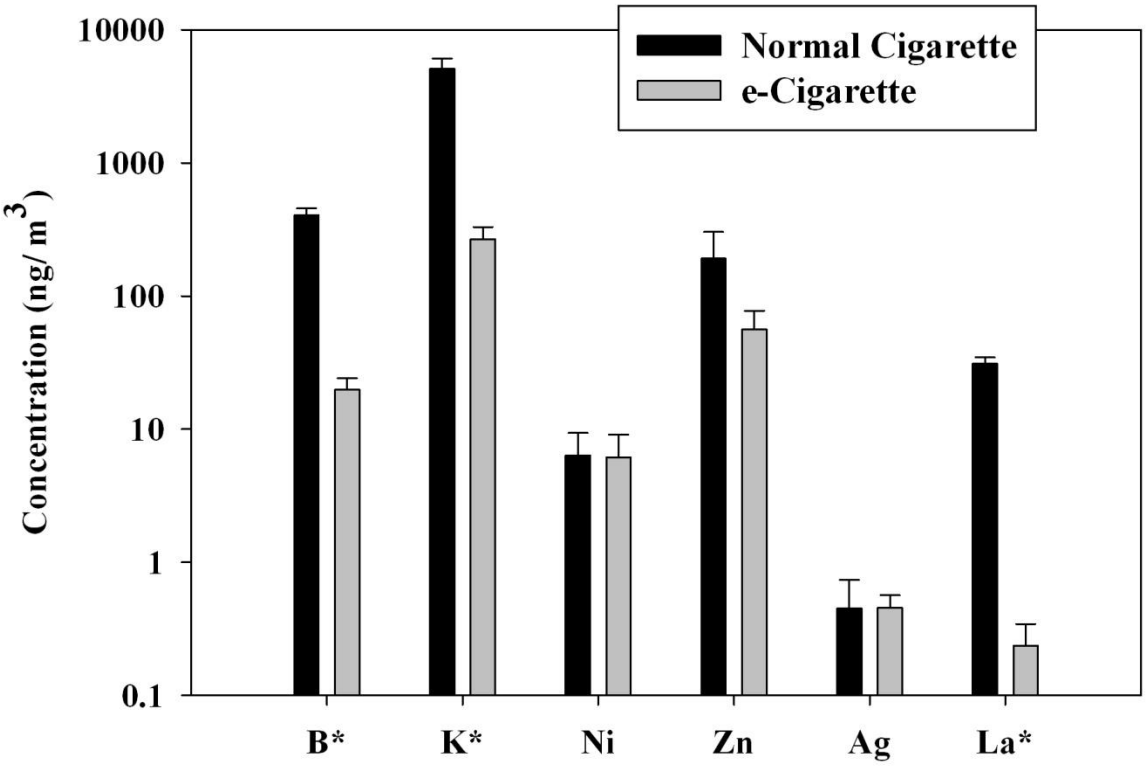


Figure 5. Average indoor (i.e. inside of the smoking room) levels (ng/m^3) of e-cigarette versus normal cigarette emissions pertaining to the elements with average indoor to outdoor mass ratio greater than unity. Error bars represent one standard error.



***Indicates elements with statistically significant difference ($p<0.05$) between regular cigarettes and e-cigarettes.**

Table 2. Average indoor (i.e. inside of the smoking room) to outdoor mass concentration ratio and Pearson correlation coefficient (R) of organic species for e-cigarette samples. Polycyclic aromatic hydrocarbons (PAHs) were undetected for indoor e-cigarette samples and therefore not included in this table. Values correspond to average ±standard error.

Species	I/O Ratio	R	Species	I/O Ratio	R
n-Eicosane	1.72 (±0.33)	0.97	Tetradecanoic Acid	8.25 (±1.46)	-0.41
n-Docosane	1.83 (±0.33)	0.93	Pentadecanoic Acid	8.3 (±1.34)	-0.4
n-Tetracosane	8.55 (±3.06)	0.63	Hexadecanoic Acid	13.57 (±5.5)	-0.3
n-Pentacosane	8.35 (±4.08)	0.55	Heptadecanoic Acid	23.12 (±5.55)	-0.62
n-Hexacosane	2.2 (±0.3)	0.72	Nonadecanoic Acid	3.91 (±2.26)	0.1
n-Heptacosane	3.15 (±2.08)	0.25	Palmitoleic Acid	37.98 (±8.05)	-0.86
Nonacosane	2.26 (±1.14)	-0.26	Linoleic Acid	4.53 (±1.35)	0.73
Triacontane	7.39 (±4.4)	-0.16	Eicosanoic Acid	3.46 (±2.26)	0.56
Hentriacontane	2.5 (±1.25)	-0.07	Docosanoic Acid	1.52 (±0.36)	0.9
Dotriacontane	2.55 (±1.18)	-0.2	Tricosanoic Acid	1.65 (±0.31)	0.16
Tritriacontane	1.52 (±0.43)	-0.25	Tetracosanoic Acid	2.72 (±0.56)	0.15
Tetratriacontane	1.49 (±0.43)	-0.29	Pentacosanoic Acid	8.06 (±2.64)	-0.65
Pentatriacontane	1.41 (±0.34)	-0.25	Hexacosanoic Acid	1.87 (±0.27)	-0.07
Hexatriacontane	1.45 (±0.34)	-0.34	Octacosanoic Acid	1.31 (±0.14)	-0.55
Heptatriacontane	1.3 (±0.26)	-0.31	Triacontanoic Acid	5.3 (±4.15)	-0.65
Octatriacontane	1.5 (±0.33)	-0.48	Suberic Acid	1.66 (±0.47)	-0.26
Decanoic Acid	5.91 (±1.81)	0.82	Azelaic Acid	1.79 (±0.47)	-0.07
Dodecanoic Acid	2.5 (±0.6)	0.68	Levoglucosan	0.77 (±0.31)	0.99

Table 3. Average emission rates (ng/hr) of selected metals and elements during e-cigarette and normal cigarette consumption. Values correspond to average ±propagated uncertainty. "N.D" represents the emission rates that were not detectable based on the mass balance model (i.e. indicating zero emission rate from indoor sources).

Species	e-Cigarette (ng/hr)	Normal-Cigarette (ng/hr)	Species	e-Cigarette (ng/hr)	Normal-Cigarette (ng/hr)
B	963.8 (±30.18)	23680 (±582.9)	Cu	N.D	1029 (±113.8)
Mg	N.D	N.D	Zn	1142 (±143.8)	8252 (±332.3)
Al	N.D	N.D	Rb	N.D	200.1 (±6.450)
S	N.D	34540 (±1580)	Sr	N.D	N.D
K	7765 (±560.3)	297500 (±7044)	Mo	N.D	N.D
Ca	N.D	N.D	Ag	20.91 (±0.730)	14.65 (±0.900)
Ti	50.16 (±26.29)	N.D	Cd	0.480 (±0.300)	657.3 (±15.10)
V	N.D	N.D	Sn	N.D	N.D
Cr	28.10 (±13.64)	N.D	Sb	N.D	N.D
Mn	N.D	N.D	La	3.210 (±0.690)	1846 (±45.36)
Fe	N.D	N.D	W	N.D	N.D
Co	N.D	N.D	Pb	96.16 (±29.93)	1012 (±248.7)
Ni	130.5 (±15.73)	36.39 (±10.42)			

Table 4. Average emission rates (ng/hr) of selected alkanes and organic acids during e-cigarette and normal cigarette consumption. Values correspond to average ±propagated uncertainty

Species	e-Cigarette (ng/hr)	Normal-Cigarette (ng/hr)	Species	e-Cigarette (ng/hr)	Normal-Cigarette (ng/hr)
n-Eicosane	529.3 (±40.54)	11240 (±287.3)	Tetradecanoic Acid	8308 (±240.3)	16100 (±397.6)
n-Docosane	477.3 (±31.67)	9407 (±240.1)	Pentadecanoic Acid	2289 (±65.12)	7685 (±183.2)
n-Tetracosane	604.9 (±20.12)	5131 (±127.1)	Hexadecanoic Acid	13960 (±395.4)	129300 (±3098)
n-Pentacosane	255 .5 (±9.143)	5765 (±138.6)	Heptadecanoic Acid	572.4 (±20.12)	8113 (±189.6)
n-Hexacosane	125.5 (±6.123)	3593 (±83.49)	Palmitoleic Acid	1813 (±46.77)	8308 (±190.2)
Triacontane	241.4 (±21.02)	23490 (±545.4)	Linoleic Acid	444.1 (±14.78)	65100 (±1477)
Hentriacontane	317.2 (±34.21)	165900 (±3934)	Eicosanoic Acid	136.4 (±6.983)	13900 (±318.2)
Dotriacontane	312.6 (±37.67)	35900 (±839.4)	Docosanoic Acid	160.4 (±10.36)	12570 (±287.4)
Tritriacontane	274.3 (±38.72)	94420 (±2115)	Tricosanoic Acid	112.6 (±7.978)	6479 (±157.2)
Tetratriacontane	284.1 (±39.78)	4706 (±114.3)	Tetracosanoic Acid	449.3 (±18.13)	10260 (±239.9)
Pentatriacontane	220.1 (±28.34)	3887 (±98.88)	Pentacosanoic Acid	208.2 (±8.873)	2842 (±65.67)
Hexatriacontane	228.5 (±26.35)	943.1 (±29.34)	Hexacosanoic Acid	218.6 (±12.84)	3505 (±84.23)
Heptatriacontane	153.7 (±19.55)	1110 (±30.33)	Octacosanoic Acid	222.2 (±18.93)	9880 (±226.2)
Octatriacontane	208.8 (±20.93)	776.6 (±24.46)	Triacontanoic Acid	228.6 (±18.95)	6720 (±163.8)
Decanoic Acid	229.2 (±8.981)	1368 (±32.82)	Suberic Acid	282.3 (±20.13)	2264 (±60.23)
Dodecanoic Acid	2421 (±102.2)	12270 (±278.8)	Azelaic Acid	743.5 (±48.80)	4979 (±134.8)

Table 5. Average emission rate (ng/hr) of polycyclic aromatic hydrocarbons (PAHs) during e-cigarette and normal cigarette consumption. Values correspond to average ±propagated uncertainty. "N.D" represents the emission rates that were not detectable based on the mass balance model (i.e. indicating zero emission rate from indoor sources)

Species	e-Cigarette (ng/hr)	Normal-Cigarette (ng/hr)
Chrysene	N.D	213.3 (±5.983)
Benzo(b)fluoranthene	N.D	307.2 (±7.237)
Benzo(k)fluoranthene	N.D	130.4 (±3.235)
Benzo (e) pyrene	N.D	105.6 (±3.982)
Benzo(a)pyrene	N.D	281.7 (±6.873)
Indeno(1,2,3-cd)pyrene	N.D	270.2 (±6.532)
Benzo(g,h,i)perylene	N.D	187.0 (±4.231)

Table 6. Indoor to outdoor mass concentration ratio and emission rates (ng/hr) of nicotine for e-cigarette samples with and without nicotine as well as normal cigarette. Values correspond to average ±standard error for indoor to outdoor ratios and mass concentrations, and average ±propagated uncertainty for emission rates.

Parameter	Sample	Nicotine
Concentration (ng/m^3)	Normal Cigarette	1524 (±80.4)
	e-Cigarette	60.68 (±20.91)
	e-Cigarette+Nicotine	123.0 (±34.5)
Indoor/outdoor mass ratio	Normal Cigarette	254.3 (±13.4)
	e-Cigarette	6.7 (±3.5)
	e-Cigarette+Nicotine	18.6 (±7)
Emission Strength (ng/hr)	Normal Cigarette	91161 (±2170)
	e-Cigarette	2759 (±93)
	e-Cigarette+Nicotine	7103 (±172)