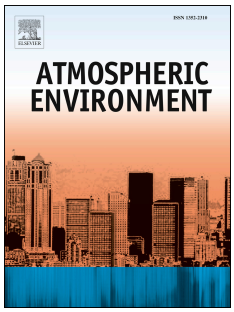

Characteristics of secondhand cannabis smoke from common smoking methods: Calibration factor, emission rate, and particle removal rate

Tongke Zhao, Kai-Chung Cheng, Wayne R. Ott, Lance Wallace, Lynn M. Hildemann

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Wayne R Ott: Methodology, Formal analysis, Investigation, Data Curation, Writing - Review & Editing

Lance Wallace: Methodology, Writing - Review & Editing

Lynn M Hildemann: Writing - Review & Editing, Supervision, Funding acquisition

Characteristics of Secondhand Cannabis Smoke from Common Smoking Methods: Calibration Factor, Emission Rate, and Particle Removal Rate

Tongke Zhao, Kai-Chung Cheng, Wayne R Ott, Lance Wallace, Lynn M Hildemann

Civil and Environmental Engineering, Stanford University,

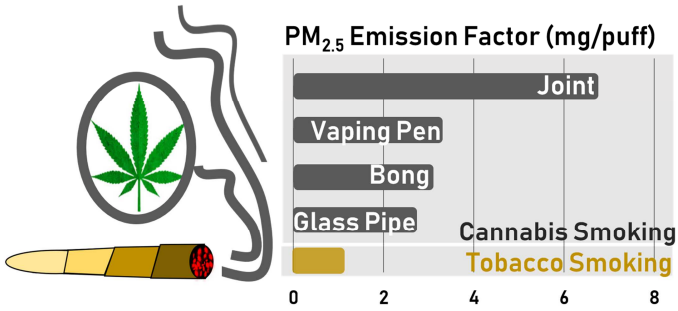
Stanford, California 94305, United States

Abstract

The widespread legalization of recreational cannabis use raises growing concerns about exposure to secondhand cannabis smoke (SCS). However, few studies are characterizing fine particulate matter ($PM_{2.5}$) exposure from SCS. Here, we determined $PM_{2.5}$ calibration factors (CFs) for SCS from four common cannabis consuming methods—glass pipe smoking, joint smoking, bong smoking, and cannabis pen vaping—for widely used optical monitors (SidePak™ AM510, TSI Inc., Shoreview, MN) by comparing the monitors with gravimetric mass measurements. We furthermore investigated the emission rate, particle size distribution, and particle removal rate of SCS. The CFs of SidePak $PM_{2.5}$ monitors measuring the four types of SCS were 0.31 (SE=0.02), 0.39 (SE=0.02), 0.40 (SE=0.01), and 0.44 (SE=0.03), respectively. The arithmetic mean emission rates of the four SCS sources were ~2-6 times that of secondhand tobacco smoke (STS) on a per-puff basis. The fresh SCS (1-min after smoking) showed a bimodal size distribution—one mode located at ~380-420 nm and another at ~800-840 nm. Under low-ventilation conditions, the indoor removal rates of SCS from cannabis vaping were slightly higher (i.e., 0.61-0.77/h) than those for the other three sources (i.e., 0.35-0.53/h).

Key Words: *cannabis; marijuana; particulate matter; calibration factor; size distribution; emission rate; removal rate; $PM_{2.5}$; aerosols;*

Graphical Abstract



1. Introduction

With the expanding worldwide legality of adult recreational cannabis use (Shi et al., 2019), the popularity of consuming cannabis continues to grow. As in June of 2019, eleven states in the United States had legalized recreational cannabis use, and Canada and Uruguay have legalized cannabis nationwide (Wikipedia, 2019). Studies showed that in legalized states, cannabis use increased in both over and under 21-year-old people (Kerr et al., 2017; Parnes et al., 2019; Parnes et al., 2018). Also, the legalization of cannabis use stimulates the growth of cannabis dispensaries, which tends to increase the consuming population (Dills et al., 2016).

When smoking or vaping cannabis, the high-temperature combustion or vaporization process produces high levels of fine particulate matter ($PM_{2.5}$) emissions, which is well-known to cause respiratory and cardiovascular diseases (Dominici et al., 2006). This makes secondhand cannabis smoke (SCS) an emerging air quality and health concern (Gates et al., 2014). The delta-9-tetrahydrocannabinol (THC) in cannabis, which may cause psychosis-like effects (D'Souza et al., 2004), is emitted into the air, leading to passive exposure (Balducci et al., 2009). It has been found that children living in homes with indoor cannabis smoking had 83% higher odds of adverse health

outcomes compared to children in homes with no indoor cannabis smoking (Posis et al., 2019).

Cannabis smoking methods are varied—including glass pipe, joint, and bong smoking, as well as vaping—making the characteristics and exposure assessment of SCS complex. Glass pipe smoking is a combustion particle source. The smoker lights up cannabis buds in the bowl of a glass pipe and gives a puff. The joint is a pre-rolled cigarette filled with loose cannabis leaves. Unlike regular commercial cigarettes, which are usually the same length and circumference, joints vary in size. A bong, also known as a water pipe, burns cannabis buds in the bowl and filters the smoke by water in the glass reservoir before the smoke is inhaled. A cannabis vaping pen is similar to an e-cigarette, the emission process of which involves heating and subsequent evaporation and condensation of cannabis vape liquid (Giroud et al., 2015). Unlike the e-liquid in an e-cigarette, which contains mostly volatile compounds like propylene glycol or glycerol (Zhao et al., 2017; Zhao et al., 2016), the cannabis vape liquid usually contains THC and cannabinoid (CBD) concentrates, vitamin E acetate, triglyceride oils, terpenes and relatively small amounts of propylene glycol and glycerol (Blount et al., 2020; Giroud et al., 2015), which are more viscous and less volatile than e-liquid.

There is little research about the characteristics of or exposure to fine particulate matter ($PM_{2.5}$) in SCS. It is known that optical $PM_{2.5}$ monitor output depends on the optical and physical characteristics of particles, including density, refractive index, and size distribution, which vary with $PM_{2.5}$ sources (Hinds, 2012). It is crucial that validated calibration factors (CFs) be determined for different aerosol mixtures of interest for a research-grade monitor, which then can produce accurate measurements of $PM_{2.5}$ mass concentrations. Health-based air quality standards are written in units of $\mu g/m^3$, increasing the importance of precise measurements of $PM_{2.5}$ mass concentrations for evaluating health risks. The SidePak (AM510, TSI Inc., Shoreview, MN) is one of the most popular research-grade, small, and portable $PM_{2.5}$ real-time monitors on the market. The CFs of

SidePaks have been developed and published for aerosols from a variety of particle sources (e.g., water pipes, cigarettes, stick incense, fireplace emissions, wildfires, candles, burning toast, etc.) (Dacunto et al., 2013; Jiang et al., 2011; Travers et al., 2018). Moreover, a number of published studies have used SidePak monitors to measure $PM_{2.5}$ mass concentrations from STS, taking advantage of the instrument's portability, 8-hour battery life, data logging capability, and validated CFs (Acevedo□Bolton et al., 2014; Cho et al., 2014; Klepeis et al., 2003; Klepeis et al., 2016; Ott et al., 2017; Repace et al., 2011). No previously published studies have estimated the SidePak CFs for $PM_{2.5}$ from cannabis sources. Therefore, to accurately assess the $PM_{2.5}$ exposure from SCS, we first focused on the CFs of SCS from four cannabis smoking methods. Using the results presented in this paper, we can add cannabis joints, bongs, glass pipe, and vaping to the long list of sources for which SidePak CFs have been developed for estimating mass concentrations.

Since gravimetric filter sampling is accurate but time-consuming, we also used a Piezobalance (also known as a piezoelectric microbalance, Model 8511, TSI Inc., Shoreview, MN), which is a real-time, portable gravimetric PM measurement device. A Piezobalance fitted with a $PM_{2.5}$ impactor collects $PM_{2.5}$ on a crystal, which oscillates in an electric circuit at a certain resonant frequency. As the mass of the crystal changes when $PM_{2.5}$ is deposited on it, the resonant frequency changes and this change is proportional to the mass of deposited $PM_{2.5}$ (Sem et al., 1977). In this study, we investigate the feasibility of using the Piezobalance to measure the $PM_{2.5}$ concentrations of SCS accurately.

This study, for the first time, characterizes the CFs, emission rates (*mg/puff*), particle size distributions, and removal rates of SCS from four cannabis smoking methods: glass pipe smoking, joint smoking, bong smoking, and cannabis vaping. We compare the emission rates of SCS with that of secondhand tobacco smoke (STS). The particle size distribution determines the deposition in human respiratory tracts and affects the removal on room surfaces (Nazaroff and Klepeis, 2003).

Thus, these results can serve as input for assessing exposure to SCS and for studying the impacts and fate of SCS indoors.

2. Method and Materials

2.1 Participant

A habitual user of cannabis and tobacco, who consumes cannabis in multiple ways, was recruited to help generate SCS. The study protocol was accepted by the participant, and a signed consent form was obtained before the experiments. The cannabis materials and consuming devices used in this study were provided by the participant. The study protocol was approved by the Institutional Review Board at Stanford University.

2.2 Cannabis Devices and Materials

Table 1. Pictures of the smoking devices and the THC and CBD proportions in the corresponding cannabis materials used in this study.

Device	Picture	Cannabis Materials*	
		THC Proportion (%)	CBD Proportion (%)
Glass Pipe		16.9	0.08
Joint		5.86	16.57
Bong		16.9	0.08
Vaping Pen		3.51	69.8

*Proportions as reported on the packaging labels.

Four cannabis consuming methods were investigated in this study: glass pipe smoking, joint

smoking, bong smoking, and cannabis pen vaping. Pictures of the devices and the THC and CBD proportions in the corresponding cannabis materials are shown in **Table 1**. The glass pipe was 10 cm in length and was equipped with a 2 cm diameter bowl. On each use, the habitual smoker put ~ 0.2 g of cannabis buds into the bowl before lighting it. The mass of cannabis buds was weighed on a microbalance (Model XPR6UD5, Mettler Toledo Inc., Columbus, OH). The joint was 64 mm in length, and its larger end was 8 mm in diameter while its smaller end, which was the mouthpiece, was 4 mm in diameter. The weight of each joint was ~0.8 g. The bong was 18 cm tall, and its reservoir was filled with ~100 mL water. On each bong use, the smoker placed ~ 0.2 g of cannabis buds into the bong's 2 cm diameter bowl. The battery-powered vaping pen was 8.7 cm long and 1.1 cm in diameter, and it was attached to a cannabis cartridge labeled *"18:1 CBD:THC"*. On each use, the participant selected the *High Heat* setting and pre-heated the vaping pen for about five seconds prior to using it. To compare the emission rates and removal rates of SCS with those of secondhand tobacco smoke (STS), we also included cigarette smoking in this study. The cigarettes were regular Marlboro cigarettes.

2.3 Real-time Particle Measurements

We used six SidePak monitors and two Piezobalances to measure the real-time $PM_{2.5}$ concentrations with a data logging time interval of 1-min. Before each experiment, we cleaned and greased the impactor inside each SidePak as recommended in the manual, and we zeroed each SidePak by attaching its inlet to a high-efficiency air filter. Before each experiment, the crystal in each Piezobalance was cleaned by applying a detergent to a sponge that was placed in direct contact with the crystal followed by a second sponge with distilled water to clean off the detergent. The sampling flow rate was verified to be 1.0 L/min by a flow meter (Sensidyne, Clearwater, FL, USA).

The particle number concentrations measured by an optical particle sizer (OPS 3330, TSI Inc., Shoreview, MN) ranged from 0.3 to 10 μm. The data logging interval was 1 min. We captured the

particle size distributions at 1, 30, and 90 mins after the smoking activity to examine the dynamics of SCS. The number of modes for each particle size distribution was determined via visual inspection. Then, we divided the spectrum into one or two sub-groups according to the number of modes. Each sub-group was fitted with a lognormal distribution by using Sigmaplot 12.5 lognormal three-parameter fitting procedure (Zhu et al., 2002), yielding the count median diameter (CMD) and geometric standard deviation (GSD) for each particle size distribution mode.

2.4 Gravimetric Sampling Method

Two custom-built cyclones (John and Reischl, 1980) were used to provide a 50% cut-size of 2.5 μm and to collect particles less than or equal to 2.5 μm on 47 mm PTFE filters (2 μm pore size, Pall Corp., Ann Arbor, MI). Each pump's sampling flow rate was ~18-20 L/min as designated by each cyclone and calibrated by a flow meter (Gilian Instrument Corp., West Caldwell, NJ). The filters were conditioned for 24-48 hours in an environmental chamber with a constant temperature of 24 ^{o}C and relative humidity (RH) within 30-40%, allowing equilibrium of semi-volatiles. Filters then weighed by a microbalance (Model XPR6UD5, Mettler Toledo Inc., Columbus, OH) with a readability of 0.5 μg before and after each sampling. Each filter was usually measured three times, and the absolute error was no more than 3 μg. The range of the sampling $PM_{2.5}$ concentrations was from 50 to 1500 $\mu g/m^3$. The sampling time was pre-estimated to aim for a collected mass of more than 100 μg on the filter. During a typical ~2.5 hours decay period in each experiment, we collected two or three filter samples. Therefore, when we sampled at a higher concentration range, the sampling time length was shorter. Certainly, when we sampled at a lower concentration range, the sampling time length was longer. An example of a sampling period, including time lengths, concentrations ranges, and mass collected on the filter, is shown in the **Supporting Information Table S1**. Finally, the collected mass on the filter, sampling time length, and pump flow rate were used to determine the mean $PM_{2.5}$ mass concentration during a sampling period.

2.5 Experimental Setting and Protocol

The study was conducted in a car that was used as an air chamber and parked in an attached garage in Redwood City, CA. The car was a Honda Element 2006, with no carpet covering. The second-row seats were removed to provide more space. The volume of the cabin was measured as 6.5 m^3 (SD=0.3 m^3, n=5) by using sulfur hexafluoride (SF_6) as the tracer gas. The measurement method with a diagram of the setup can be found in the **Supporting Information** and its **Figure S1**. The experiments were conducted from Dec. 2018 to Mar. 2019, when the indoor temperature and RH were within the range of 15 to 22 ^oC and 30 to 70%, respectively.

In the car chamber, six SidePak monitors were placed on the backseat behind the driver's seat. The Piezobalances, the OPS 3330, and the gravimetric sampling instruments were placed outside the car, and each was connected to the car with *Tygon*^{TM} tubing. The intake ends of the tubing were collocated with the SidePak sampling tubing inside the car. A small battery-powered fan with an 11-cm diameter blade was used inside the car to help mix the air.

Before each experiment, the car's doors and windows, as well as the garage's doors were opened to flush the chamber with ambient air. After that, the doors and windows were closed again, and we started the instruments and measured the background concentrations for at least 10 minutes. Then the smoker entered the car and sat on the driver's seat. The smoker smoked cannabis by one of the four methods and gave one to three puffs *ad libitum*. As observed, during a puff, the inhaling time was ~ 2 seconds, and the exhaling time was ~2 to 5 seconds. After that, the smoker exited the car promptly, and the car doors remained closed. We extinguished the cannabis combustion with water immediately to minimize the potential of increasing the $PM_{2.5}$ background in the garage. During the experiments, the garage doors remained closed.

By recruiting an experienced smoker to consume cannabis and tobacco *ad libitum*, this work is

intended to characterize SCS in a realistic situation. We did not provide the participant with any cannabis materials, smoking devices, or research cigarettes. Nor did we introduce smoking sensors to measure the puff topography and the heating temperature as our participant believed they would interfere with his/her consuming behaviors.

SidePak's data showed the background is not larger than 5 $\mu g/m^3$. As Jiang et al.(2011) showed, the calibration factor of SidePaks measuring ambient particles varied from 0.66 to 0.98. Therefore, we can reasonably assume that the actual $PM_{2.5}$ background concentration is lower than 5 $\mu g/m^3$.

In total, we conducted 28 experiments, including eight on glass pipe smoking, five on joint smoking, six on bong smoking, six on cannabis pen vaping, and three on tobacco cigarette smoking.

2.6 Data Processing

When calculating CFs for SidePaks, we compared the arithmetic mean of six SidePak-measured concentrations over a certain period of sampling time (i.e. 10-90 min) with the arithmetic mean of two masses on the filters. Then we plotted the gravimetric concentrations on the *y*-axis, the SidePak readings on the *x*-axis, and a regression line was forced through zero. The slope is the CF. The agreement among SidePak monitors was evaluated by their absolute percent error (APE) and the method can be found in Jiang et al., (2011). A CF of each SidePak was also obtained by comparing each SidePak's measured concentrations with the gravimetric concentrations by the same method. We also used the same method to determine CFs for the Piezobalances.

In this study, we determined the emission rate as the mass of emitted $PM_{2.5}$ per puff (*mg/puff*). Examples of SCS $PM_{2.5}$ concentration decay curves from four cannabis sources and cigarette smoking are shown in the **Supporting Information Figure S2**. The $PM_{2.5}$ time-series concentrations can be fit by an exponential decay equation with high R^2 values (≥ 0.98), which

197 indicated the well-mixed state of SCS in the car. As shown in Equation (1), g is the emission rate
198 ($mg/puff$), V (m^3) is the mixing volume of the car chamber, and n is the number of puffs per each
199 experiment, C_{max} (mg/m^3) is the maximum $PM_{2.5}$ concentration at the end of each emission period
200 and is calculated by extrapolating the exponential decay line back to the time when the emission
201 ended (Jiang et al., 2011; Ott et al., 2008).

$$g = \frac{C_{max} \times V}{n} \quad (1)$$

202 The particle removal rate is derived by subtracting air exchange rate (AER, h^{-1}) from the
203 particle concentration exponential decay rate (h^{-1}) in each experiment. The removal rate in this
204 study represents the removal due to both the particle surface deposition and evaporation. In this
205 study, we measured AERs in 10 experiments to obtain the removal rates for each secondhand
206 smoke source, including two samples each for the glass pipe, joints, bongs, vaping pens, and
207 tobacco cigarettes. The AER was measured by releasing pure carbon dioxide (CO_2) into the car
208 (Sherman, 1990) after the participant smoked and left the car, with peak CO_2 concentrations
209 reaching approximately 3000 ppm—about six times of the background levels. During this
210 experimental phase, all investigators left the garage to avoid increasing the CO_2 background
211 concentrations. During those sampling periods, we just collected one filter sample each time.
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214
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3. Results and Discussion

3.1 Calibration Factors

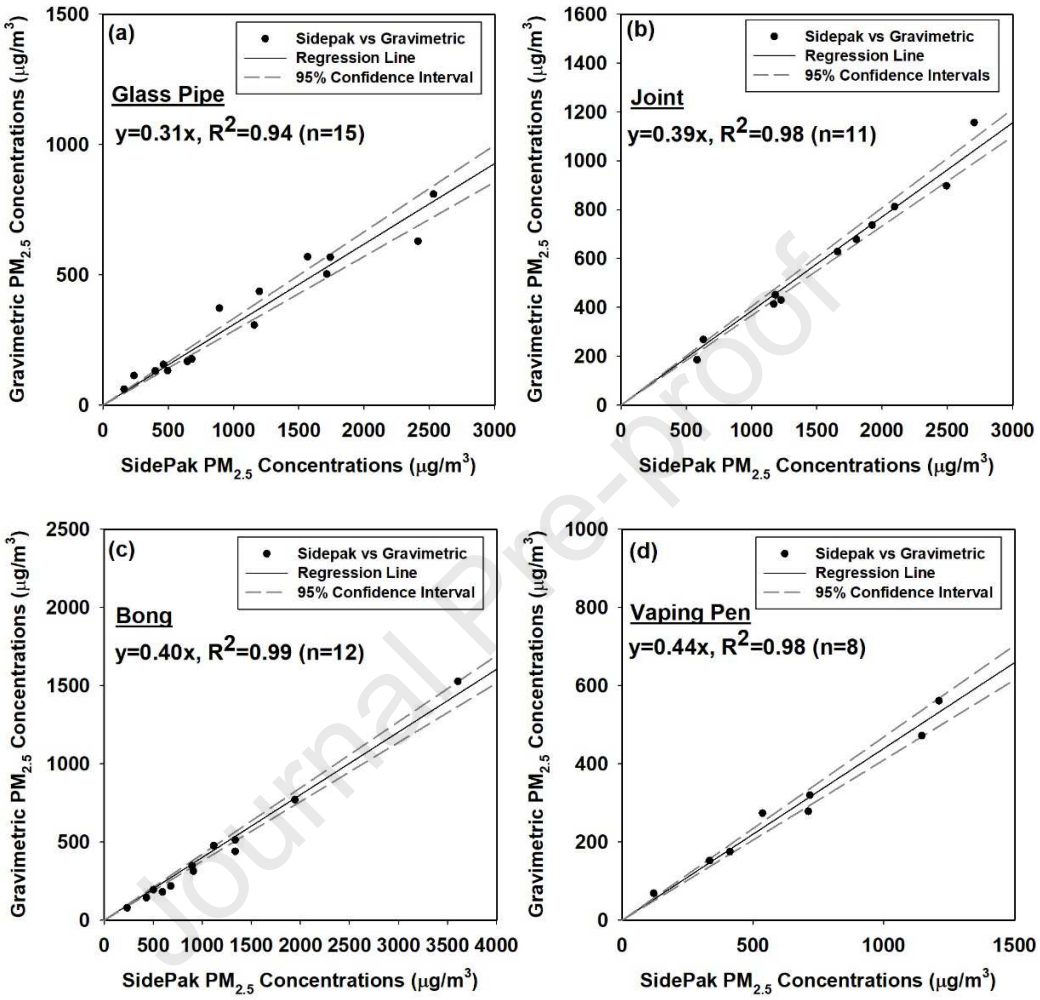

Figure 1. Comparison of gravimetric sampling with SidePak measured $PM_{2.5}$ concentrations for SCS from (a) glass pipe, (b) joint, (c) bong, and (d) vaping pen.

Figures 1a, **1b**, **1c**, and **1d** show that the SidePak's CFs for SCS from glass pipe smoking, joint smoking, bong **s**moking and cannabis e-vaping are 0.31 (SE=0.02), 0.39 (SE=0.02), 0.40 (SE=0.01), and 0.44 (SE=0.03), respectively. The CFs for SCS are larger than that for STS (CF=0.29) (Jiang et al., 2011). It is worth noting that the cannabis buds used in the study when smoking the glass pipe and the bong were the same.

The CFs are highly influenced by the physical characteristics of particles, including the size distribution, shape, density, and refractive index (Hinds, 2012). The CFs for bong and joint smoking were similar. The $PM_{2.5}$ from cannabis vaping had the largest CF, consistent with our previous finding that CFs for non-combustion heating processes (such as cooking on an electric stove) are larger than for combustion emissions (Dacunto et al., 2014).

Zhao et al. (2017) measured the real-time $PM_{2.5}$ concentrations of secondhand e-cigarette vaping aerosols from active human use in indoor environments. That study found that e-cigarette vaping aerosols went through quick evaporation, and the concentrations did not have a constant first-order decay rate. In contrast, we observed relatively constant decay rates in SCS from cannabis vaping in the car chamber (**Supporting Information Figure S2**).

Since six SidePak monitors were employed in this study, a CF for each monitor was also investigated (**Supporting Information Table S2**). The *R*-squared values for each linear regression result were all ≥ 0.94. We found discrepancies between a CF derived from an arithmetic mean of six SidePak readings and a CF for an individual SidePak (i.e., CF ranges for glass pipe: 0.27-0.37, joint: 0.33-0.40, bong: 0.35-0.45, and vaping pen: 0.38-0.50), although our SidePaks are factory-calibrated yearly. We found the APEs of all SidePaks were within 10%, except for one that was 16%. These results suggest it is desirable to derive a CF for each $PM_{2.5}$ optical monitor to ensure accurate exposure measurements.

The CFs for the Piezobalance measuring $PM_{2.5}$ in SCS from glass pipe smoking, joint smoking, bong smoking, and vaping are 1.06 (SE=0.05), 1.15 (SE=0.06), 1.03 (SE=0.02), and 0.86 (SE=0.04), respectively (as shown in **Supporting Information Figures S3a, S3b, S3c**, and **S3d**). The results are consistent with a previous study showing that the Piezobalance's results agree within 15% of gravimetric sampling mass for a variety of aerosols, including polymer beads, road dust, pollen, and tobacco smoke (Sem et al., 1977). The CF (1.06) of SCS from the glass pipe is almost

the same as that from a bong (1.03). This is different from the SidePak CFs for these two sources (Glass pipe: 0.31; Bong: 0.40 in **Figure 1**)—unlike SidePaks, the Piezobalance measurements do not vary with aerosol optical properties. Since gravimetric sampling is usually time-consuming and requires high-precision measurements of the mass, the Piezobalance can be used as a quick reference method.

3.2 Emission rates

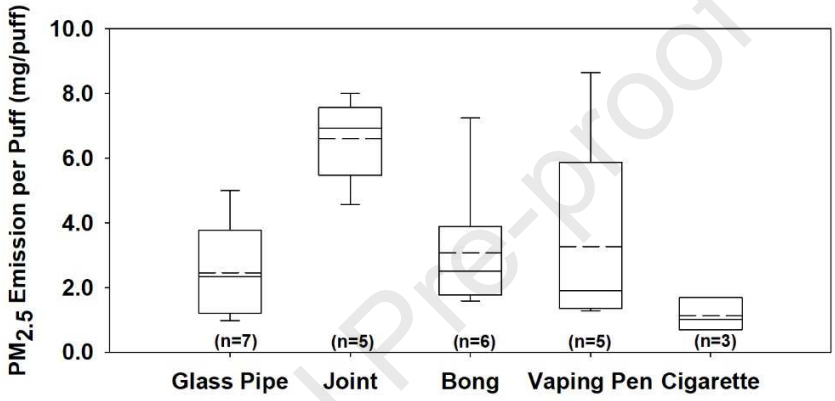

Figure 2. The emission rates (*mg/puff*) of glass pipe, joint, bong, vaping pen, and tobacco cigarette. (In each boxplot, the dashed line represents the arithmetic mean value, and the solid line represents the median value. The upper whisker represents the maximum value, while the lower whisker represents the minimum value.)

Although it is typical to express emission rates of STS as the emitted $PM_{2.5}$ mass per tobacco cigarette (*mg/cigarette*) or the emitted $PM_{2.5}$ mass per minute (*mg/min*), these methodologies cannot be generalized to SCS from various smoking methods. Glass pipe and bong smoking use cannabis buds, and the quantities of each depend on the smokers' preferences. Joints vary in size, as do cannabis vaping pens. Moreover, cannabis smoking often follows unique smoking patterns—cannabis glass pipe and bong smokers usually smoke for only one or two puffs at a time. The puff intervals vary and are difficult to estimate. Thus, we report the emission rate as the emitted $PM_{2.5}$ mass per puff (*mg/puff*).

As shown in **Figure 2**, the arithmetic mean emission rates of SCS from glass pipe smoking,

joint smoking, bong smoking and vaping are 2.5 (SD=1.6), 6.6 (SD=3.1), 3.1 (SD=2.1), and 3.3 (SD=3.1) mg/puff, while our measurement of the arithmetic mean emission rate of STS from cigarette smoking is only 1.1 (SD=0.5) mg/puff. The $PM_{2.5}$ emission rates (*mg/puff*) of the four SCS methods are ~2-6 times the emission rate of STS. Nazaroff and Klepeis (2003) summarized 17 studies and reported a median emission rate for cigarette smoking as 12.7 mg/cigarette (including both machine and human smoking), and these studies showed that a typical commercial cigarette is sustainable for 6-16 puffs (Klepeis et al., 2003; Loefroth et al., 1989; Singer et al., 2002). Thus, the emission rate of cigarette smoking can be estimated as 0.8-2 mg/puff, placing our STS data within this range.

We also observed that the cannabis buds often go out very quickly after each puff, so the SCS from a glass pipe and bong smoking might be mainly exhaled mainstream smoke. In addition, the SCS from vaping is entirely exhaled mainstream aerosol. Like STS from tobacco smoke, SCS from joint smoking is mostly a mixture of smoldering smoke between puffs (sidestream) and exhaled mainstream smoke, which might be the reason that it had the highest emission rate of the four cannabis sources tested.

3.3 Size Distributions

The size distributions of SCS from the four common smoking methods (i.e., glass pipe smoking, joint smoking, bong smoking, and cannabis pen vaping) at 1, 30, and 90 mins after each smoking activity are shown in the **Supporting Information Figures S4a**, **S4b**, **S4c**, and **S4d**, respectively. These data for glass pipe smoking, joint smoking, and bong smoking are based on a single puff, while the vaping experiment is based on three puffs. Because the background concentration was not significant compared to the SCS concentration, the size distribution of the background particles was not subtracted. The results showed that the number concentration of fresh SCS (1-minute after smoking) is bimodal—one mode located at ~380-420 nm and a smaller mode at ~800-840 nm. The

CMDs and GSDs for each mode are provided in **Supporting Information Table S3**. Our observation of a ~380-420 nm mode is similar to Hiller et al. (1984), in which a puffing machine was used to smoke a cannabis joint (85 mm in length and 25 mm in circumference) with the smoke quickly diluted 126,000-fold. Their results, measured by a single particle aerodynamic relaxation time analyzer, showed the mode ranged from 350 to 430 nm.

3.4 Removal Rates

Table 2. The removal rates of secondhand smoke from four methods of cannabis smoking and cigarette smoking.

Smoking Types	Experiment No.	Removal Rate* (/h)
Cannabis Smoking		
Glass Pipe	1	0.41
	2	0.40
Joint	1	0.49
	2	0.38
Bong	1	0.35
	2	0.53
Vaping Pen	1	0.61
	2	0.77
Cigarette Smoking	1	0.44
	2	0.41

* The removal rate represents the removal due to both the particle surface deposition and evaporation. The air exchange rate has been subtracted from the total decay rate.

The AER in the stationary car with closed windows and doors during ten experiments was 0.47-0.59/h, mainly governed by the forced airflows due to the gravimetric sampling (18-20 L/min

each), as well as the Piezobalances and OPS sampling (1 L/min each). As shown in **Table 2**, excluding ventilation, the removal rates of SCS from a glass pipe, joint, bong, and cigarette smoking were similar, ranging from 0.35 to 0.53/h. The SEs were all < 0.001. These removal rates were affected by the increased air velocity and therefore higher deposition rates produced by the sampling pumps (Lai and Nazaroff, 2000). The removal rates of SCS from the vaping pen were higher (0.61-0.77/h) than other sources. This might be partly due to the evaporation of glycols in cannabis vape liquid, even though as mentioned earlier, the evaporation of particles from cannabis vaping is not expected to be as significant as those from e-cigarette vaping. We observed that the removal rates showed a 20%-33% variation between the two runs for bong smoking, joint smoking, and vaping. The removal of particles was caused by several dynamics, and it can be affected by turbulent intensity, velocity gradient, etc. (Lai, 2002; Lai and Nazaroff, 2000; Thatcher et al., 2002). We cannot conclude a specific reason for the variances through this study. Other studies have investigated removal rates of STS in a car chamber, mostly under high ventilation conditions (Liu and Zhu, 2010; Ott et al., 2008). For low-ventilation conditions, Xu et al. (1994) reported that the arithmetic mean removal rate (subtracting the AER from an overall decay rate) of STS was 0.172/h for an AER of 0.02/h in a 36.5 m^3 room. These results could provide input data for modeling SCS dynamics in in-cabin and indoor environments.

3.5 Limitations of the Study

The large variety of cannabis materials available on the market—various sizes of smoking devices and materials as well as different manufacturing methods—may result in differences in emission rates. Since SCS from glass pipe smoking, bong smoking, and vaping consist mostly of exhaled mainstream smoke, the emission rates will be highly dependent on the puffing topographies. As one of the very first studies focusing on secondhand cannabis emissions, this study did not include a large number of samples. Therefore, various puffing topographies—recruiting a

larger group of participants or employing various machine-puffing simulations—should be taken into consideration in the future. The particle size distribution of SCS may also be affected by the cannabis materials and puffing topographies (Zhao et al., 2016).

Jiang et al. (2011) found that the CFs of SidePaks for a given emission source were robust. They derived similar CFs when conducting controlled chamber experiments (mean = 0.29, SD =0.02) by using Marlboro cigarettes with a human puffing, and when measuring CFs in casinos with various kinds of cigarettes and human puffing (mean = 0.33, SD = 0.04). They also used 16 SidePak monitors in two sets of controlled chamber experiments 15 months apart, and they found the mean CF for STS differed by only 3% in the two studies. Lee et al. (2008) used Marlboro cigarettes in eight experiments comparing a SidePak monitor with gravimetric filter measurements, reporting almost the same CF value (i.e., 0.295) as Jiang et al.,(2011) (i.e., 0.29). Dacunto et al., (2013) reported a similar CF value (mean = 0.32, SD = 0.01) for the Marlboro cigarette. Since CF values will depend on the sizes and chemical composition of the particulate emissions, they should remain fairly robust for a given source type. However, there may be minor changes in the CF with the age of the emissions, due to gradual changes in size distribution and perhaps the composition of the aerosol.

Emission rates can be computed as the emitted $PM_{2.5}$ mass normalized by the mass of consumed materials (*mg/g*), which offers a generalized method to compare emission rates. However, in this study, we did not collect data on the consumed mass of cannabis materials. Use of an emission rate based on *mg/puff* allowed very different types of sources to be compared with each other, such as a cannabis joint with a vaping pen, or a cigarette with a cannabis water bong. For a cannabis joint, a better measure might be the emitted mass per unit length consumed (*mg/mm*), which can be compared with tobacco emission rates.

Particle size distributions below 300 nm of SCS from different cannabis smoking and vaping

methods were not measured but could be valuable for future research. Anderson et al. (1989) found a mode with arithmetic mean CMD of ~ 100 nm when measuring the quickly diluted cannabis joint smoke using an electrical aerosol analyzer.

4. Conclusions

This study, for the very first time, characterized SCS from four cannabis consuming methods and investigated $PM_{2.5}$ calibration factors, emission rates, size distributions, and removal rates. For SCS from four common sources, the calibration factors for the optical monitors ranged from 0.31 to 0.44. Moreover, the CFs for the Piezobalances ranged from 0.86 to 1.15. Due to different smoking patterns between cannabis and tobacco smoking, we generalized the emission rate as emitted $PM_{2.5}$ mass per puff (*mg/puff*). The results showed the emission rates of SCS were ~2-6 times that of STS. Fresh SCS (1 min after smoking) was observed to have a bimodal distribution—one mode at ~380-420 nm and a smaller mode at ~800-840 nm. Under low-ventilation conditions, the indoor removal rates of SCS from the vaping pen were higher (i.e., 0.61-0.77/h) than those for the glass pipe, joint, bong, and cigarette smoking (which ranged from 0.35 to 0.53/h).

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466

Characteristics of Secondhand Cannabis Smoke from Common Smoking Methods: Calibration Factor, Emission Rate, and Particle Removal Rate

Tongke Zhao, Kai-Chung Cheng, Wayne R Ott, Lance Wallace, Lynn M Hildemann

Civil and Environmental Engineering, Stanford University,

Stanford, California 94305, United States

Highlights:

- Emission rates of secondhand cannabis smoke were 2-6 times of tobacco smoke;
- Fresh secondhand cannabis showed a bimodal size distribution;
- The indoor removal rates of secondhand cannabis vaping were slightly higher;

Declaration of interests

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

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