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Measuring indoor fine particle concentrations, emission rates, and decay rates from cannabis use in a residence

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ABSTRACT

Fifteen states have legalized the sales of recreational marijuana, and California has the largest sales of any state. Cannabis is most often smoked indoors, but few measurements have been made of fine particle mass concentrations produced by secondhand cannabis smoke in indoor settings. We conducted 60 controlled experiments in a 43 m^3 room of a residence, measuring $PM_{2.5}$ concentrations, emission rates, and decay rates using real-time monitors designed to measure $PM_{2.5}$ mass concentrations. We also measured the room's air exchange rate. During each experiment, an experienced smoker followed an identical puffing protocol on one of four different methods of consuming marijuana: the pre-rolled marijuana joint (24 experiments), the bong with its bowl containing marijuana buds (9 experiments), the glass pipe containing marijuana buds (9 experiments), and the commercially available electronic vaping pen with a cartridge attached containing cannabis vape liquid (9 experiments). For comparison, we used the same puffing protocol to measure the $PM_{2.5}$ emissions from Marlboro cigarettes (9 experiments). The results indicated that cannabis joints produced the highest indoor $PM_{2.5}$ concentrations and had the largest emission rates, compared with the other cannabis sources. The average $PM_{2.5}$ emission rate of the 24 cannabis joints (7.8 mg/min) was 3.5 times the average emission rate of the Marlboro cigarettes (2.2 mg/min). The average emission rate of the cannabis bong was 67% that of the joint; the glass pipe's emission rate was 54% that of the joint, and the vaping pen's emission rate was 44% that of the joint. The differences compared to the joint were statistically significant.

1. Introduction

The District of Columbia and 15 US states – Alaska, Arizona, California, Colorado, Illinois, Maine, Massachusetts, Michigan, Montana, Nevada, New Jersey, Oregon, South Dakota, Vermont, and Washington – have legalized recreational marijuana sales, but few research studies have measured exposure to secondhand marijuana smoke in everyday settings. On January 1, 2018, California legalized the sale of recreational cannabis to adults, and the state currently has 358 state-licensed stores selling recreational cannabis products (Marijuana Business Daily, 2020).

Many studies have measured the psychoactive compound delta-9-tetrahydrocannabinol (THC) and other related cannabinoids produced by marijuana use (Tashkin et al., 1991; Hiller et al., 1984; Cone et al., 1987; Sheehan et al., 2018). Berthet et al. (2016) identified 958 papers on *passive exposure* to cannabis, and they selected 21 papers for review. These passive exposure studies generally employed biomarkers of exposure such as urine, blood, oral fluid, hair, and sebum to determine for forensic purposes whether an individual had recently used cannabis. For example, Moore et al. (2011) asked 10 healthy volunteers who were not marijuana smokers to spend up to 3 h in a Dutch coffee shop with heavy marijuana smoking. THC exceeding 4 ng/ml was detected in the oral fluid of half the volunteers but not the metabolite 11-nor-9-carboxy-THC (THC-COOH), so the authors recommended measuring this metabolite as an indicator to avoid falsely concluding a person was an active cannabis smoker. We reviewed 729 papers on exposure to marijuana in the scientific literature, and we found almost no published papers measuring fine particle mass concentrations from secondhand cannabis smoke in homes. Both marijuana and tobacco cigarettes produce fine particle mass concentrations ($PM_{2.5}$) consisting of airborne particles less than 2.5 μm in diameter.

Klepeis et al. (2017) and Posis et al. (2019) reported results from one of the few studies that measured indoor particles, a randomized clinical survey in San Diego of 298 predominantly low-income homes with an adult smoker and a child less than 14 years old. In each participating residence, a Dylos™ DC1700 monitor (Dylos Corporation, Riverside, CA, USA) was set up for a week to measure indoor particle counts.

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Homes without indoor smoking had 7-day average particle levels lower than homes with only cannabis smoking or homes with both cigarette and cannabis smoking, and 33 homes reported that marijuana smoking took place from 1 to 7 times per week. Hughes et al. (2018) present details of the San Diego study and its selection of participating families. The Dylos monitor provides an indication of particle levels, but it does not measure particle mass concentrations with the same accuracy as the gravimetric filter-and-pump "gold standard," or a research-grade air monitor with its calibration factor based on gravimetric filter measurements.

The common methods of smoking marijuana include a pre-rolled *joint*, which is similar to a cigarette or a cigar, a *pipe* or *bong* containing marijuana buds, and a vaping pen that vaporizes cannabis liquid from a commercially available cartridge. A nationwide survey of 4269 adults in 2014 found that 7.2% had used marijuana over the past 30 days (Schauer et al., 2016). Among current users, 10.5% reported medicinal use only, 53.4% reported recreational use only, and 36.1% reported both. More than half of current users reported only one method of use (58.8%); 22.4% reported two methods; and 18.8% reported three methods. For these users, the two most popular methods of smoking marijuana were the joint (49.2%) and the pipe (49.5%), with less popular use of the bong, water pipe, and hookah (21.7%). In 2014, 7.6% of the respondents reported using marijuana vaporizers, but more recently battery-powered pens using liquid cannabis cartridges have become increasingly popular for cannabis vaping. In 2015, 5.3–8.0 million children in the US lived with a parent who was a cannabis user, and both current cannabis use and daily cannabis use have been increasing among parents (Goodwin et al., 2018). National surveys showed the prevalence of marijuana vaping among US adolescents increased from 2017 to 2019 (Miech et al., 2019). Vaping among Grade 12 students in the last 30 days increased from 4.9% in 2017 to 7.5% in 2018, reaching 14% in 2019 (Johnston et al., 2019).

Cecinato et al. (2014a, 2014b) measured THC in four homes in Rome, Italy, reporting that the indoor THC concentration in two homes was 6.6 ng/m^3 indoors and 1.1 ng/m^3 outdoors. Indoor concentrations of THC and cannabidiol (CBD) often exceeded those measured at outdoor fixed air monitoring stations, indicating the sources were indoors. Chu et al. (2019) conducted a two-stage probability telephone survey of 2,812 respondents living in multiunit housing in Ontario, Canada, reporting that 7.5% reported being exposed involuntarily to secondhand cannabis smoke. The prevalence of involuntary exposure to cannabis smoke in multiunit buildings was similar to that from secondhand tobacco smoke.

Moir et al. (2008) compared a large number of toxic air pollutants produced by mainstream and sidestream marijuana and tobacco smoke, using a smoking machine to produce the smoke. For both marijuana and tobacco cigarettes, the mass of the pollutants measured in sidestream smoke was much greater than the mass of the pollutants measured in mainstream smoke for the majority of air pollutants. The amount of benzene, a known human carcinogen, measured in secondhand marijuana smoke was about the same as that measured in secondhand tobacco smoke (399 μg for a marijuana cigarette and 352 μg for a tobacco cigarette). These investigators also compared 30 polycyclic aromatic hydrocarbons (PAHs) measured in marijuana and tobacco smoke. They found that sidestream marijuana smoke contained about the same amount of the human carcinogen benzo(a)pyrene as sidestream tobacco smoke (101 ng compared to 91.7 ng). They also found that marijuana sidestream smoke contained about 1.5 times the amount of benzo(a) anthracene, another probable human carcinogen, as did tobacco smoke. In both mainstream and sidestream marijuana smoke, they reported the presence of many similar known carcinogens and other chemicals implicated in respiratory diseases.

Graves et al. (2020) compared tobacco and marijuana smoke particles and found them quantitatively similar in volatility, shape, density, and number concentration, with differences in particle size and chemical composition. Their study detected 4350 different compounds in tobacco smoke and 2575 different compounds in marijuana smoke, with 231 compounds common to both tobacco and marijuana smoke. Of these, 173 different tobacco smoke compounds and 110 marijuana smoke compounds (69 in common) were known to cause adverse health effects through carcinogenic, mutagenic, teratogenic, or other toxic mechanisms.

Ni et al. (2020) reviewed dozens of health studies on $PM_{2.5}$ related to tobacco smoking, concluding that indoor $PM_{2.5}$ from cigarette smoking is closely correlated with chronic lung disease. Due to the small size of these particles, they can go deep to the distal airways and deposit in alveolar regions, doing serious harm to the human respiratory system. They carry with them PAHs and many other toxic compounds. Although there are few studies of the health effects of marijuana aerosols, Wang et al. (2016) reported that 1-min of exposure to secondhand cannabis smoke can impair vascular endothelial function in rats.

In the US, marijuana is most often smoked indoors in homes (Berg et al., 2015, 2018), but relatively few measurements have been made of indoor air pollution from cannabis use in residences. Californians are prohibited from consuming legal cannabis in "any public place or area" or in "any location where tobacco smoking is prohibited," although legal cannabis can be consumed in private residences or in structures located on the grounds of a private residence (California Department of Public Health, 2020). Other residents of a home may find the odor from marijuana smoking objectionable, so the smoker may confine his or her smoking activity to a room with a closed door.

To provide data on the concentrations and emissions produced by cannabis use indoors in a home, we conducted 60 controlled experiments in the spare bedroom of an occupied residence. Twenty-four experiments were conducted on pre-rolled cannabis joints, and 9 experiments each were conducted on bongs, glass pipes, vaping pens, and tobacco cigarettes. These measurements of $PM_{2.5}$ from secondhand cannabis smoke were compared with $PM_{2.5}$ from secondhand tobacco smoke from Marlboro cigarettes (Philip Morris, Inc.), the most popular cigarette brand in the US (Cigarette brands most smoked in the US, 2019). Zhao et al. (2020) conducted cannabis experiments in a car using joints, bongs, glass pipes, and vaping pens as sources, developing gravimetric calibration factors for four different methods of smoking marijuana. These calibration factors were used for the same sources in the present study. Wallace et al. (2020) measured secondhand exposure to $PM_{2.5}$ from vaping marijuana in two different homes. To our knowledge, these efforts are the first systematic studies measuring $PM_{2.5}$ mass concentrations, source strengths, emission rates, and decay rates from secondhand cannabis smoke indoors in residences.

2. Methods and materials

2.1. Participant

A habitual user of cannabis and tobacco, who consumes cannabis in multiple ways, was recruited to help generate secondhand cannabis smoke. The study protocol was accepted by the participant, and a signed consent form was obtained before the experiments. The same participant who smoked and vaped the marijuana sources also smoked the tobacco cigarettes. No individual other than the participant was involved in the smoking or vaping activities, and no persons were present in the room during the air pollutant decay periods. The main focus of this research was on comparing the emission rates produced by different methods of smoking or vaping cannabis sources, not on the health impact on human subjects. The study protocol was approved by the Institutional Review Board at Stanford University. This study was supported by a grant awarded to Stanford University to study secondhand exposure to marijuana: Agreement #28IR-0062 sponsored by the University of California Office of the President; Tobacco Related-Disease Research Program (TRDRP). The cannabis materials used in this study were provided by the participant.

2.2. Measurement methods

The 60 controlled experiments measuring fine particle mass concentrations were carried out in an occupied residence in Redwood City, CA, on 24 dates between April 16 and November 25, 2019. All the experiments were conducted in a 43 m^3 spare bedroom that was set off from the rest of the house. This room had one window and one door, both of which were closed prior to the start of each experiment. The 60 experiments were conducted on 23 different dates, with one experiment conducted on each of three dates, two experiments conducted on five dates, three experiments on 13 dates, and four experiments on two dates. On dates with more than one experiment, the room's window and door were opened before each experiment to air out the room, and the home's front door, backdoor, and a kitchen window also were temporarily opened.

All experiments took place during the daytime hours, each lasting about 2–1/2 h. This provided sufficient time for mixing in the room and allowed for estimation of the $PM_{2.5}$ decay rate. Prior to starting each experiment, the monitors were operated for at least 10 min to measure the background $PM_{2.5}$ concentrations in the room. The background concentrations were relatively small and were subtracted prior to analyzing the $PM_{2.5}$ concentration data. The heating and air conditioning system of the home was turned off before and during all experiments, and the home's exterior doors and windows were closed.

We compared the $PM_{2.5}$ emissions produced by four different methods of consuming cannabis – joint, bong, glass pipe, and vaping pen – with the emissions from Marlboro tobacco cigarettes purchased in California in 2019. The first three cannabis consumption methods use combustion to produce $PM_{2.5}$, while the vaping pen uses a heated coil to vaporize cannabis liquid without combustion. We used TSI AM510 SidePak™ laser photometers (TSI, Shoreview, MN, USA) with the individual calibration factors of each monitor based on gravimetric measurements (Zhao et al., 2020). The calibrated SidePak mass measurements were found to agree well with measurements by the piezoelectric microbalance (Model 8510 Piezobalance, TSI, Shoreview, MN, USA), an instrument that measures real-time mass concentrations directly.

All the cannabis joints, bongs, buds, and vaping supplies used in this study were commercially available and were purchased from four state-licensed stores in three California towns in 2019: San Jose, Palm Desert, and Cathedral City. The 24 pre-rolled marijuana joints used in this study consisted of 9 different name brands that are widely available in California. A factory label that came with each joint listed its CBD and THC content. The CBD content of the 24 joints ranged from 0% to 1.5%, and the listed THC content ranged from 8.55% to 27.6%, with a mean of 17.7%. We used a laboratory scale to measure 0.3 g of cannabis buds into the bowls of the bong and the glass pipe, and the two types of cannabis buds used were "Mirage" (CBD 0% and THC 10.48%) and "Blueberry Muffin" (CBD 0.0% and THC 15.01%). The electronic vaping pen was manufactured by AbsoluteXtracts (ABX), and we attached two different vaping cartridges to the pen: a Care by Design 18:1 cartridge (CBD 69.8% and THC 3.51%) and a Care by Design 2:1 cartridge (CBD 46.1% and THC 21.9%; https://www.cbd.org/).

In each experiment, we used at least 2 AM510 SidePak monitors with their individual calibration factors based on the gravimetric filter measurements obtained by Zhao et al. (2020). Each SidePak was equipped with a physical 2.5 μm size impactor supplied by the manufacturer, and the data logging times were set to 1.0 min. Before starting each set of experiments, the grease on the monitor's particle size impactor was replaced, and the monitor was zeroed using a precision zero filter supplied by the manufacturer. Periodically we measured the flow rate of each monitor using a Gillibrator Primary Flow Calibrator (Sensidyne, St. Petersburg, FL, USA), verifying that it was within 5% of the 1.7 L/min flow rate specified by the manufacturer. We also used precision digital clocks synchronized with the atomic clock in Boulder, CO, to verify that the data logging times of each monitor were within ± 3 s of the correct time. Each experiment used a pair of SidePak monitors for redundancy and sometimes a third SidePak monitor as a backup. Each SidePak's internal calibration factor was set to 1.0, and the proper calibration factors for the monitors and source type, based on the gravimetric measurements of Zhao et al. (Table S1), were applied subsequently in the data analysis phase. A comparison of the two main SidePak monitors, each using a calibration factor for cannabis vaping based on gravimetric filter measurements, showed good agreement (R^2 = 0.9993 for n =179 pairs of observations with an intercept of 0.1 μg/m^3 and a slope of 1.015). In these experiments, we also used a pair of TSI 3007 condensation particle counters (CPC's) to measure ultrafine particles (UFP) greater than 10 nm in diameter at 1-min time intervals.

The monitors were placed near the midpoint of the room at a height above the floor of 0.6 m, and a small battery-powered fan with an 11 cm diameter blade was run for the duration of each experiment to assist with air mixing. Immediately after the smoking or vaping ended, the participant exited the room, carefully closing the door behind him. Thus, no one was exposed to secondhand smoke in the room during the decay period of about 100–130 min. A video camera was set up in the room with its lens pointed toward a SidePak monitor's display screen, sending readings of the measured $PM_{2.5}$ concentrations to computer screens outside the room.

We used a pair of Model T15n electrochemical Carbon Monoxide Measurers™ (Langan Products Co., San Francisco, CA, USA) to measure the CO concentrations in the room produced by releasing CO from a 105 L cylinder containing 10% CO gas in nitrogen (Ecosmart™, gasco.com). The CO gas was emitted into the room for approximately 6 min prior to the start of each experiment using an adjustable flow rate regulator set to 1 L/min. The resulting CO decay rate was used to estimate the room's air exchange rate, based on the negative slope of the logarithm of the background-corrected CO concentration. Ferro et al. (2009) used Brüel and Kjær Type 1302 photoacoustic sulfur hexafluoride (SF_6) monitors to measure the volume of this same room and its air exchange rate, and our air exchange rate measurements were consistent with their published measurements.

2.3. 3-Puff protocol

Our main objective was to compare the concentrations and emission rates produced by different methods of cannabis smoking and vaping, so it was important to apply the same procedure to each source in these experiments. All the smoking or vaping methods in these experiments followed the *3-Puff Protocol*, which consisted of a starting puff at time t = 0, followed by a 2nd puff at t = 60 s, followed by a 3rd puff at t = 120 s (Fig. 1). When a joint or a cigarette reached 3.0 min, the participant put it out by dipping the tip in water. This protocol is well-suited to combustion sources, which produce both mainstream and sidestream smoke. Sidestream smoke, which is emitted directly from the source between puffs and not exhaled by the smoker, has been shown to produce greater emissions than mainstream smoke (Moir et al., 2008; Schick and Glantz, 2005). Based on observations of the participant, the inhalation time of the puff was about 2 s, and the exhalation time was ~2–4 s, making the total puff time about 6 s. We applied the same 3-puff protocol to the AbsoluteXtracts vaping pen, which carried out an internal 15-s *pre-heat* mode prior to the start of puffing and produced little sidestream emissions between puffs.

An important advantage of the 3-puff protocol in our experiments is that it avoided the extremely high $PM_{2.5}$ concentrations expected to occur in the 43 m^3 room if a marijuana joint had been smoked completely in the room, thus allowing the participant to avoid exposure to unacceptably high concentrations. Based on our interviews with experienced cannabis smokers and information available on the Internet, we concluded that marijuana smoking often differed from tobacco cigarette smoking in several respects. Smoking a marijuana joint often takes place in a group setting, where more than one person smokes, following the rule, "take two puffs and pass it to the left." We

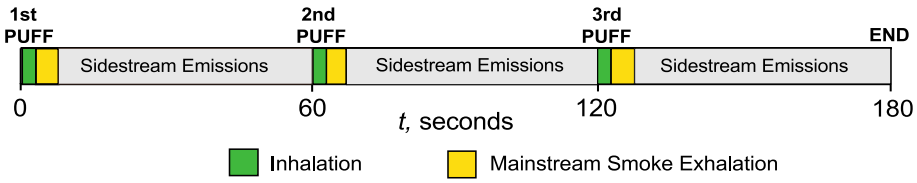

Fig. 1. Conceptual representation of 3-puff protocol timing for smoking a marijuana joint. The participant started the first puff at $t = 0$ by inhaling on the joint for about 2 s (green), followed by exhalation of the mainstream smoke for an additional ~2–4 s (yellow). Between puffs, the burning joint produced sidestream emissions (light grey). At time $t = 180$ s, the joint was put out. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

also learned that a marijuana smoker, when smoking alone, often takes just 2 or 3 puffs, then puts the joint out so it can be smoked later in the day. The 3-puff protocol in Fig. 1 includes nearly a minute between puffs for the burning joint to emit sidestream smoke, thus producing both mainstream and sidestream smoke in a realistic manner. This protocol also has a mathematical advantage for calculating emission source strengths, since the 3-min emission time is much shorter than the residence time of the room, which averaged 115 min for the 60 pre-rolled joints, bongs, glass pipes, vaping pens, and cigarettes. An objective of this study was to compare emission rates from different sources smoked in the same manner by a human participant. Although a smoking machine may reduce experimental variability, we focused on determining whether the differences between the mean emission rate of the pre-rolled marijuana joints and the mean emission rates of the other sources, including the tobacco cigarettes, were statistically significant.

2.4. Data analysis and modeling

The *source strength* is the total emissions produced by a given source, and the *emission rate* is the emissions per minute. We used the *peak-estimation approach* described in Ott et al. (2007) to estimate the source strength and the emission rate. Fig. 2 shows an example of one of our experiments with a sativa "Doobie" pre-rolled joint. The first step in the analysis was to graph the natural logarithm of the background-corrected $PM_{2.5}$ concentrations versus time during the decay period (Figure S1). Applying linear regression (SigmaPlot 11, Systat Software, San Jose, CA, USA), the $PM_{2.5}$ decay rate was found to be $\varphi = 0.00722\ min^{-1} = 0.433\ h^{-1}$ with a coefficient of determination of $R^2 = 0.995$ (Figure S1). The residence time τ, which is the reciprocal of φ, was τ =139 min. The background-corrected $PM_{2.5}$ concentration in the room $y(t)$ was modeled by piecewise continuous exponential solutions to the mass balance equation for short-term sources in a reasonably well-mixed room with a small fan and naturally-occurring turbulence (Mage and Ott, 1996; Ott, 2007; Ott et al., 2003; Dacunto et al., 2013):

$$y(t) = y_{max}e^{-\varphi t} \quad for\ t \geq 0 \quad (1)$$

Fig. 2 shows both the observed mass $PM_{2.5}$ concentration (black dots) and this exponential decay model (red line) with $y_{max} = 568\ \mu g/m^3$ and decay rate $\varphi = 0.00722\ min^{-1} = 0.433\ h^{-1}$ from our experiment with a sativa pre-rolled joint. For illustrative purposes, the graph of the model begins 16 min prior to time $t = 0$. The first puff started at time $t = 0$, and the overall experiment ended at $t = 390$ min. The exponential decay model fit to the decay curve (red line) enables the analyst to extend the decay curve "backward" to estimate the *true maximum*. The *false maximum* shown in Fig. 2 resulted from poor mixing very early in the experimental period. If the false maximum of 697 $\mu g/m^3$ had been used instead of the true maximum of 568 $\mu g/m^3$, the estimated source strength would have had an error of 23%.

The same methodology for calculating the decay rate illustrated in Figure S1 and Fig. 2 was applied to all 60 experiments in this study, but the decay time period was generally less than the 390 min shown in the example in Fig. 2. Usually, we found 100–130 min was sufficient for calculating the $PM_{2.5}$ decay rate and estimating the true maximum concentration. The $PM_{2.5}$ time series response can be accurately modeled by piecewise continuous equations that intersect at a *coincident point* (Ott, 2007). The concentration predicted at $t = 3.0$ min can be used by the exponential decay model to estimate the maximum concentration y_{max}. An alternative method is to estimate y_{max} using the intersection of the exponential decay model and the observed rise of the $PM_{2.5}$ concentration.

In Fig. 2, the intersection of the measured concentration rise and the decay model (red line) yielded a true maximum concentration of 568 $\mu g/m^3$ (green dot), and the source strength G was calculated as the product of the peak concentration and the volume of the room v:

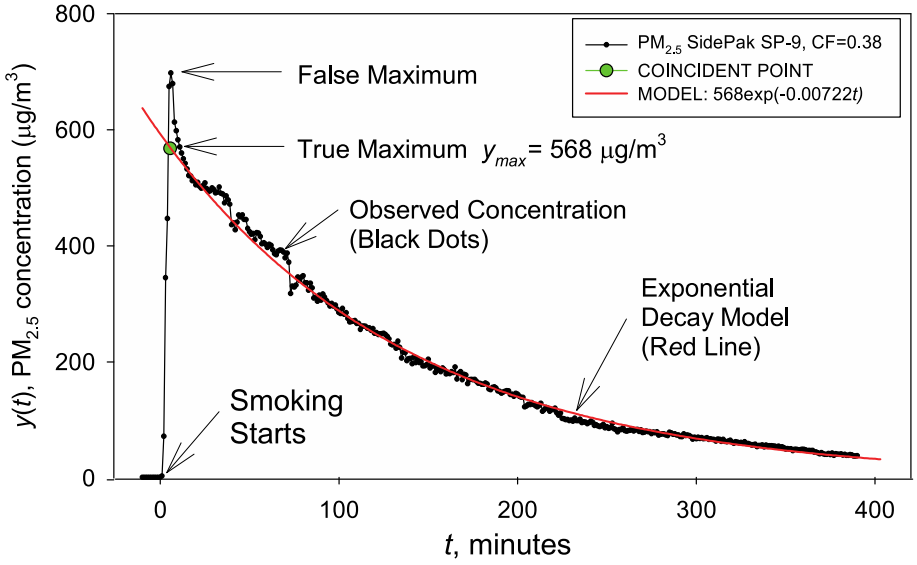

Fig. 2. $PM_{2.5}$ concentration time series produced by a sativa "Doobie" pre-rolled joint smoked with the 3-puff protocol. This figure shows the measured concentrations (black dots) for 390 min and an exponential decay model fit to the data (red line). The coincident point (green dot) is the true maximum concentration used to estimate the source strength. A false maximum also can be seen early in the experiment, before the room has had time to become sufficiently well-mixed. In this experiment, a 3.9 $\mu g/m^3$ background concentration was subtracted from the observed $PM_{2.5}$ concentration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$G = Source\ Strength\ = y_{max} v = 568\ \frac{\mu g}{m^3} \times\ 43\ m^3\ \times\ \frac{1\ mg}{1000\ \mu g}$$
$$= 24.4\ mg \quad (2)$$

Once the maximum concentration y_{max} had been estimated, it was used to calculate the source strength and the emission rate.

The emission rate g was obtained by dividing the source strength G by the emission time t_s:

$$g = \text{Emission Rate} = \frac{G}{t_s} = \frac{24.4\ mg}{3.0\ min} = 8.13\ mg \Big/ min \quad (3)$$

Here, g represents the average of the time-varying emissions over 3.0 min with discrete puffing.

In Fig. 2, the true maximum concentration was 568 μg/m^3 at time $t = 0$, and the $PM_{2.5}$ concentration decayed to 34 μg/m^3 at time $t = 390$ min. With a decay rate of $\varphi = 0.00722\ min^{-1} = 0.433\ h^{-1}$, the $PM_{2.5}$ concentration will reach 3.14 μg/m^3 in 12 h and 0.02 μg/m^3 in 24 h as it asymptotically approaches zero. Equation 4 provides a general expression for calculating the mean concentration $y_{mean}(T)$ for any averaging time T:

$$y_{mean}(T) = \frac{y_{max}}{T} \int_0^T e^{-\varphi t} dt = \frac{y_{max}}{T\varphi} \left(1 - e^{-T\varphi}\right) \quad (4)$$

Since the quantity $e^{-T\varphi}$ often turns out to be very small, the compact approximation shown in Equation 5 often provides a reasonably accurate result. In the experiment shown in Fig. 2, for

example, Equation 4 gives an exact 24-h mean of 54.66 μg/m^3, while Equation 5 gives a close 24-h mean of 54.67 μg/m^3.

$$y_{mean}(24) \cong \frac{y_{max}}{24\varphi} \quad (5)$$

2.5. Statistical methods

The statistical methods used in this study are designed to test whether there is a statistically significant difference between the means of two unpaired groups. The unpaired t-test is a parametric test based on estimates of the mean and standard deviation of normally distributed populations from which the samples were drawn. It tests whether the difference between two groups is greater than that caused by random sampling variation. The p value is the probability of being wrong in concluding that there is a true difference between the two groups. The smaller the p value, the greater the probability that the samples are drawn from different populations. We chose the probability $p < 0.05$ as our criterion for statistical significance.

The statistical analyses were performed using SigmaPlot 11 (SigmaPlot User's Guide, Part 2, Statistics, Systat Software, San Jose, CA, USA), which employs the Kolmogorov-Smirnov test for a normally distributed population. This program also tests for equal variances. If these conditions are met, it performs the unpaired t-test. If either of these conditions is not met, it informs the user that the data are unsuitable for the unpaired t-test, and it recommends using the nonparametric Mann-Whitney Rank Sum Test instead, which performs comparisons based on the ranks of the observations.

3. Results

3.1. Decay rates, source strengths, and emission rates

Table 1 provides summary statistics for the 60 experiments in this study with the various cannabis and tobacco sources, based on the 3-puff protocol. The background concentrations were subtracted from the measured $PM_{2.5}$ concentrations in Table 1, and the last two columns show the background $PM_{2.5}$ concentrations were much smaller than the background-corrected maximum $PM_{2.5}$ concentrations measured in the room for all five sources. The background-corrected y_{max} concentrations of $PM_{2.5}$ observed in the 24 experiments with pre-rolled joints had a mean of 540 μg/m^3 and ranged from 143 to 809 μg/m^3. By comparison, the $PM_{2.5}$ y_{max} concentrations in the 9 Marlboro tobacco cigarette experiments had a mean of 154 μg/m^3 and ranged from 22 to 209 μg/m^3. Each marijuana source produced a larger mean maximum concentration y_{max} than the tobacco cigarettes.

Table 1
$PM_{2.5}$ maximum concentrations and background concentrations.

Source Type	Measured Maximum $PM_{2.5}$ Concentration[a] y_{max} μg/m^3					Background $PM_{2.5}$ Concentration μg/m^3	
	n	Mean	SD	Min.	Max.	Mean	SD
Joint	24	540	162	143	809	3.2	1.4
Bong	9	361	261	65	762	2.7	1.3
Glass Pipe	9	294	187	73	606	3.6	1.2
Vaping	9	225	141	32	415	3.8	1.6
Cigarette	9	154	64	22	209	3.4	2.2

[a] Background-corrected.

Table 2 shows the summary statistics for the 60 experiments with five different sources. The 24 joints had a mean $PM_{2.5}$ emission rate of 7.8 mg/min, which was greater than all the other cannabis emission rates and was 3.5 times the mean $PM_{2.5}$ emission rate of the Marlboro cigarettes of 2.2 mg/min. The mean emission rates of the bong and the glass pipe were 67% and 54% of the joint's mean emission rate, respectively, and the mean emission rate of the vaping pen was 44% that of the mean emission rate of the joints.

The box plots shown in Fig. 3 illustrate the frequency distributions of the $PM_{2.5}$ emission rates, allowing them to be compared graphically. Only the pre-rolled cannabis joints had enough observations ($n = 24$) to show the 5th and 95th percentiles of the emission rates (large black dots), while all the box plots showed the 10th and 90th percentiles (whiskers). The box boundaries themselves represent the 25th and 75th percentiles, and the bong had the largest spread between these two percentiles. This result was consistent with Table 2, which shows the bong also had the greatest coefficient of variation (SD-to-mean ratio) of 0.71 for the five sources. The mean emission rate in Fig. 3 (red dashed line) was higher for the joint than for the cigarette, which also is evident in the emission rate column of Table 2. The median in Fig. 3 showed a pattern similar to that of the mean.

Table 3 shows the results of applying standard statistical tests to 10 comparisons of the different methods of smoking marijuana, vaping marijuana, and smoking tobacco cigarettes. In five of the comparisons, the t-test met the requirement that the data were normally distributed but did not meet the requirement of equal variances. In these five cases, Sigma-Plot substituted the nonparametric Mann-Whitney Rank Sum Test for the t-test. With both tests, the criterion for statistical significance was the probability $p < 0.05$. The difference between the mean emission rate of the joint and the mean emission rate of the bong was statistically significant ($p < 0.05$), and the differences between the mean emission rate of the joint and the mean emission rates of the glass pipe, vaping pen, and cigarette were highly statistically significant ($p < 0.001$). The

Table 2
$PM_{2.5}$ decay rates, air exchange rates, source strengths, and emission rates.

Source Type	Decay Rate[a] h^{-1}		Air Exchange Rate[a] h^{-1}		Source Strength[a] mg		Emission Rate[a] mg/min	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Joint	0.461	0.10	0.368	0.09	23.2	7.0	7.8	2.2
Bong	0.509	0.13	0.375	0.10	15.5	11.2	5.2	3.7
Glass Pipe	0.563	0.22	0.407	0.13	12.6	8.1	4.2	2.7
Vaping	0.690	0.23	0.369	0.09	9.7	6.1	3.4	1.8
Cigarette	0.501	0.26	0.290	0.06	6.6	2.8	2.2	0.9

[a] Background-corrected.

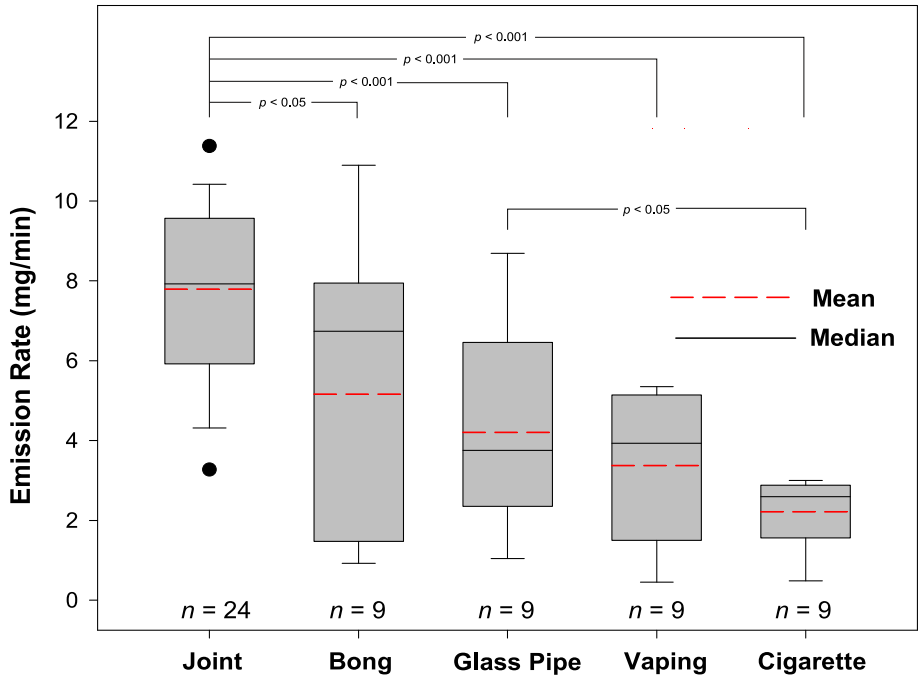

Fig. 3. Box plots comparing emission rates for 3 puffs from five different smoking sources based on 60 experiments. The boxes are the 25th and 75th percentiles; the whiskers are the 10th and 90th percentiles; the dots are the 5th and 95th percentiles, which appear only for $n = 24$. The probabilities listed above the box plots show the statistical significance of the differences between groups.

Table 3
Statistical significance tests comparing emission rates of five different sources.

Comparison	Statistical Test	p value	Statistically Significant?
Joint vs. Bong	Mann-Whitney	$p < 0.05$	Yes
Joint vs. Glass Pipe	t-Test	$p < 0.001$	Yes
Joint vs. Vaping	t-Test	$p < 0.001$	Yes
Joint vs. Cigarette	Mann-Whitney	$p < 0.001$	Yes
Bong vs. Glass Pipe	t-Test	$p = 0.541$	No
Bong vs. Vaping	Mann-Whitney	$p = 0.377$	No
Bong vs. Cigarette	Mann-Whitney	$p = 0.377$	No
Glass Pipe vs. Vaping	t-Test	$p = 0.474$	No
Glass Pipe vs. Cigarette	t-Test	$p < 0.05$	Yes
Cigarette vs. Vaping	Mann-Whitney	$p = 0.251$	No

probabilities listed above the box plots in Fig. 3 show the statistical significance of the differences between the groups.

Although there were $n = 24$ experiments with joints, there were only $n = 9$ experiments each with bongs, glass pipes, vaping pens, and Marlboro cigarettes. Comparisons of the bong vs. the glass pipe, the bong vs. vaping, the bong vs. the cigarette, the glass pipe vs. vaping, and the cigarette vs. vaping did not show a statistically significant difference in mean emission rates, which is partly due to the small sample sizes. An exception was the mean emission rate of the glass pipe compared to the mean emission rate of the cigarette, which was statistically significant ($p < 0.05$). In general, groups that did not include the joint were less likely to show a statistically significant difference when compared to groups that included the joint with its high emission rate and larger sample size. The difference between the mean emission rate of the marijuana joints and the mean emission rate of the tobacco cigarettes was highly statistically significant ($p < 0.001$).

The largest mean decay rate in Table 2 of 0.690 h^{-1} occurred with the cannabis vaping pen, while the other four mean decay rates were fairly close together, averaging 0.509 h^{-1}. When we compared the differences between the five mean decay rates, we found that only one difference was statistically significant: comparison of the mean decay rate of the 24 marijuana joints with the mean decay rate of the 9 vaping pen experiments. Based on the Mann-Whitney Rank Sum Test, the difference between the mean decay rate of the marijuana joints and the mean decay rate of the vaping pens was highly statistically significant ($p < 0.001$). This appears likely due to the volatility of the aerosol from the cannabis vaping pen.

The measured decay rate φ for the SidePak monitor is the sum of the air exchange rate a and the deposition rate k, as well as the other possible particle losses or gains due to evaporation, condensation, and coagulation. That is, the decay rate $\varphi = a + k + other$. If we subtract the observed air exchange rate from the observed decay rate, we are left with a term called the "removal rate" due to aerosol dynamics, which is the sum of the deposition rate k and all the other gain or loss mechanisms, excluding the effect of air exchange. For the 24 cannabis joints, the mean removal rate was 0.085 h^{-1}. For the bong, the glass pipe, and the cigarette, the mean removal rates were 0.111 h^{-1}, 0.096 h^{-1}, and 0.103 h^{-1}, respectively. The average removal rate of the four marijuana combustion sources was 0.10 h^{-1}, which was smaller than deposition rates listed by Thatcher et al. (2002) for a furnished room with a small fan or no fan. In contrast, the mean removal rate of the 9 vaping pen experiments was 0.321 h^{-1}, which was the largest removal rate of the five sources and was 3.2 times the average removal rate of the four combustion sources (joint, bong, pipe, and cigarette). It is likely that this larger removal rate of the vaping pen was due to volatility of the vaping aerosol and its greater evaporative losses. Evaporation of particles from cannabis vaping is not expected to be as great as evaporation from e-cigarette vaping (Zhao et al., 2017; Zhao et al., 2020). We believe this is an important topic for future research.

Since each new marijuana joint included a factory label showing the joint's percent THC content, we also compared the THC listed for each joint with our measurements of the joint's $PM_{2.5}$ source strength. Applying the t-test, we found the relationship between the THC percentage and the source strength was statistically significant ($p < 0.01$). However, this result may occur mainly because the larger joints in our study happen to have higher THC percentages, and their larger size may cause their greater source strength. A more detailed study that controls for the size of the joint would be useful.

Our measurements of ultrafine particles (UFP) > 10 nm used a pair of TSI 3007 condensation particle counters that were collocated with the

other monitors in the room during these experiments. The UFP results are summarized in Table S2. Of the five sources, the pre-rolled marijuana joints had the greatest average UFP source strength (2.0 x 10^{12} particles), while the Marlboro cigarettes had an almost equal UFP source strength (1.8 x 10^{12} particles). The mean UFP source strengths of the three other methods of consuming marijuana were 1.3 x 10^{12} particles for bongs, 6.4 x. 10^{11} particles for glass pipes, and 3.3 x 10^{11} particles for the vaping pens. Overall, the UFP source strengths of bongs, glass pipes, and vaping pens were smaller than the UFP source strengths of either the pre-rolled marijuana joints or the Marlboro cigarettes.

3.2. Estimating secondhand $PM_{2.5}$ emissions from fully-smoked Marijuana cigarettes

McClure et al. (2012) studied 20 heavy users of marijuana, reporting that heavy users smoked an average of 11–12 marijuana cigarettes per day, averaging 13–14 puffs per joint. Since our study compared the $PM_{2.5}$ emission rates based on 3.0 min of smoking or vaping, we also attempted to estimate the emissions produced by a fully-smoked marijuana joint.

We used a precision laboratory scale to measure the weights of the 24 marijuana joints before they were smoked, which ranged from 0.56 to 1.35 g with a mean of 1.024 g (SD 0.24 g). By comparison, the pre-smoking weights of the 9 Marlboro cigarettes ranged from 0.83 to 0.89 g with a mean of 0.863 g (SD 0.022 g). We found that measuring the difference in the weight of a joint before and after it was smoked was challenging, because the water used to put out the joint affected its tightly rolled cannabis leaves, causing the post-smoking weight sometimes to be larger than the original weight. In addition, it was difficult to account for the smoking ashes lost in the water. Therefore, we concluded that comparing the weights before and after smoking a joint would need to use a different method of putting out the joint. As an alternative approach, we explored using the average length to estimate the source strength of a fully-smoked joint.

The 24 marijuana joints used in the present study consisted of 9 different name brands that ranged in length from 59 to 91 mm. The mean length was 79 mm, which was the same as the mean length of the Marlboro cigarettes. Four of the name-brand joints were shorter than the Marlboro cigarette, one was the same length, and four were longer. Like the tobacco cigarettes, each joint had a mouthpiece that acted as a filter. Before and after each joint was smoked in our 24 joint experiments, we measured the length of the portion of the joint that contains the cannabis leaf. Before smoking, the mean length of the cannabis portion was 52.1 mm. After smoking, the mean length of the cannabis portion was reduced to 38.6 mm, indicating that the 3.0-min smoking period used up 52.1–38.6 mm = 13.5 mm of the marijuana-containing portion of the joint. Since this smoking period produced a mean source strength of 23.2 mg (Table 2), we estimated the average $PM_{2.5}$ emission per unit smoking length as (23.2 mg)/(13.5 mm) = 1.72 mg/mm. Thus, smoking the remaining 38.6 mm was estimated to add the mass emissions of (1.72 mg/min) × (38.6 mm) = 66.4 mg, bringing the estimated mean source strength of the fully smoked joint to 23.2 + 66.4 mg = 89.6 mg. We estimated this large source strength would produce a maximum $PM_{2.5}$ concentration in the room of 2080 μg/m^3, and we estimated the smoking time would be 11.6 min. It would be useful to evaluate the accuracy of these estimates in a future experimental study.

It also is instructive to compare our tobacco cigarette results with other studies of fully smoked tobacco cigarettes. Chen et al. (2018) recruited 2 volunteers to each smoke 5 Chinese tobacco cigarettes in a stainless steel mixing chamber. Their study used mass balance equations like those in the present study to calculate emission rates for each of the 10 fully-smoked cigarettes. Their observed mean $PM_{2.5}$ emission rate for the 10 cigarettes was 2.25 mg/min (SD 0.9 mg/min), which was extremely close to our mean emission rate of 2.2 mg/min (SD 0.9 mg/min) shown in Table 2.

We measured the lengths of the Marlboro tobacco cigarettes used in the present study and found they have a uniform manufactured length of 79 mm, which includes a 24 mm mouthpiece that acts as a filter. As a result, the length of the tobacco-containing portion of the cigarette is 79–24 mm = 55 mm. By measuring the cigarette length before and after each cigarette was smoked, we found the 3-puff protocol used up 31.7 mm of the tobacco-containing portion of the cigarette on average, producing the 6.6 mg average source strength listed in Table 2. Therefore, the Marlboro cigarettes emitted (6.5 mg)/31.76 mm) = 0.2082 mg/mm on average as they were being smoked, and smoking the remaining 55–31.7 mm = 23.3 mm would add 4.9 mg to the total, bringing the estimated total source strength for a fully smoked tobacco cigarette to 6.6 + 4.9 mg = 11.5 mg.

Repace (2007) presented a histogram of fine particle mass source strengths of 50 brands of tobacco cigarettes, representing 65.3% of the US market. The average source strength for a fully-smoked cigarette was 13.8 mg (SD 3.1 mg), which is close to the 11.5 mg source strength we estimated for a fully smoked Marlboro tobacco cigarette in the present study. Dacunto et al. (2013) reported a 19.9 mg source strength for a fully smoked Marlboro cigarette, and Chen et al. (2018) reported a mean source strength of 17.3 mg (SD 1.6 mg) per cigarette for 10 Chinese cigarettes smoked by two volunteer smokers.

4. Discussion

In the 60 experiments, the mean $PM_{2.5}$ decay rate for the 9 vaping pen experiments of 0.690 h^{-1} was greater than the mean decay rates of the four other sources, which ranged from 0.461 h^{-1} to 0.563 h^{-1}, and this difference was statistically significant ($p < 0.001$). In comparison, the differences between the decay rates of the joint, bong, glass pipe, and cigarette were not statistically significant. The larger decay rate for the vaping pen appears likely due to the greater volatility of its aerosol.

The 24 experiments with 9 different brands of pre-rolled joints produced extremely high $PM_{2.5}$ concentrations. With just 3 puffs, the maximum $PM_{2.5}$ concentrations in the room ranged from 143 to 809 μg/m^3 and averaged 540 μg/m^3. By comparison, the maximum $PM_{2.5}$ concentrations for the 9 experiments with tobacco cigarettes smoked in the same manner ranged from 22 to 209 μg/m^3 and averaged 154 μg/m^3. As a result, the mean secondhand smoke $PM_{2.5}$ emissions from Marijuana joints was 3.5 times greater than from the tobacco cigarettes. The $PM_{2.5}$ emissions from the three alternative methods of smoking or vaping marijuana – the bong, glass pipe, and vaping pen – were lower than the emissions of the joint, but all three methods produced greater $PM_{2.5}$ emissions than the tobacco cigarettes.

Zhao et al. (2020) conducted a similar set of experiments with an experienced smoker and the same five sources used in the present study. A car parked in a garage to reduce the effect of winds was used as a 6.5 m^3 mixing chamber. Like the present study, the marijuana joints had the greatest emission rates, while the tobacco cigarettes had the lowest emission rates. The emission rates of the vaping pen, bong, and glass pipe were in between the marijuana joints and the tobacco cigarettes.

Graves et al. (2020) measured several thousand different compounds present in mainstream marijuana and mainstream tobacco smoke, as well as Total Particulate Matter (TPM) mass concentrations. They collected the TPM on 47 mm quartz filters that were weighed on a laboratory microbalance. They report that the average TPM concentration in marijuana mainstream smoke was 3.4 times greater than the TPM concentration in mainstream tobacco smoke. Their 95% confidence interval around this ratio was ±0.6, and thus our ratio of 3.5 for the marijuana joint emission rate relative to the tobacco cigarette emission rate was within their 95% confidence interval. However, their result was for mainstream smoke, while our result was for secondhand smoke, which is a combination of mainstream and sidestream smoke.

Moir et al. (2008) reported the mainstream TPM mass concentrations in marijuana smoke was about the same as in tobacco smoke. They also measured the mass concentrations of 30 PAH compounds in both marijuana and tobacco smoke. Their study indicated that 89.8% of the

PAHs in secondhand marijuana smoke were from sidestream emissions while 10.2% were from mainstream emissions.

McClure et al. (2012) reported that the volume of the puffs from an adult smoker decreases steadily over the course of smoking a cigarette. Wu et al. (1988) studied 15 habitual marijuana smokers and reported the puff volume was smaller for the second half than for the first half of marijuana cigarettes, while Tashkin et al. (1991) reported mainstream CO, tar, and THC emissions were greater for the second half than for the first half of a marijuana cigarette. For estimating secondhand smoke emissions from a fully-smoked tobacco or marijuana cigarette, we feel our assumed linear relationship between secondhand smoke emissions and length smoked is reasonable and would be a good topic for future research.

5. Limitations of study

Since the marijuana joint has a long history of use and is one of the most popular methods of consuming cannabis, we chose the largest sample size, $n = 24$ experiments, for the pre-rolled joint. The bong, glass pipe, vaping pen, and cigarette all had smaller sample sizes of $n = 9$ experiments. Except for one case, the differences in the $PM_{2.5}$ emission rates between these four common methods of consuming marijuana or tobacco based on 9 experiments did not reach statistical significance at the $p < 0.05$ level.

The 24 marijuana joints used in the present study were obtained from four state-licensed stores in three California towns, and the joints included 9 different name brands that are popular in California. Only two different kinds of marijuana buds were used in the bong and glass pipe experiments, however, and the results should show greater variation if more types of cannabis buds were included and if sample sizes were larger. The AbsoluteXtracts (ABX) vaping pen used in the present study is battery-powered and uses an electronic microprocessor that controls the temperature of the vaping fluid. This vaping pen has several settings that a user can select by pressing a button on the side of the pen. In our vaping pen experiments, we chose the "pre-heat" mode recommended in the ABX instructions, and we selected the highest of three power levels. This approach pre-heats the vaping liquid for 15 s, followed by the 3-puff protocol that started within 1-1/2 min after pre-heating ended. A user might choose different settings of this vaping pen that could result in greater or lesser emissions. Using an identical ABX vaping pen, Wallace et al. (2020) reported that two different vaping protocols produced two different temperatures, resulting in about 3 times greater source strength for the high-heat protocol than for the low-heat protocol. In the present study, the 9 cannabis vaping experiments were limited to two different commercial vaping cartridges. Many other vaping cartridges are available with different levels of THC and CBD that could be compared in a future study with a larger sample size. To compare different source types with each other, the 60 experiments in this study used the same smoker, while future studies may choose to explore differences among smokers.

6. Conclusions

The methodology in this paper applied a standardized smoking protocol to compare $PM_{2.5}$ concentrations, source strengths, emission rates, and decay rates from different types of cannabis smoking and vaping methods in a 43 m^3 room of an occupied residence. The average $PM_{2.5}$ emission rate of the pre-rolled marijuana joints was found to be 3.5 times the average emission rate of Marlboro tobacco cigarettes, the most popular US cigarette brand. The average emission rate of the cannabis bong was 67% that of the joint; the glass pipe was 54% that of the joint, and the vaping pen was 44% that of the joint. These differences in emission rates compared to the marijuana joints were statistically significant, and the difference between the average emission rates of the marijuana joints and the tobacco cigarettes was highly statistically significant ($p < 0.001$).

This study shows that smoking a marijuana joint indoors can produce extremely high indoor $PM_{2.5}$ concentrations. Based on the results of 24 experiments, smoking cannabis joints for 3.0 min in a 43 m^3 room produced maximum $PM_{2.5}$ concentrations averaging 540 $\mu g/m^3$ that ranged from 143 to 809 $\mu g/m^3$. By comparison, the Marlboro tobacco cigarettes smoked in the same manner in the same room produced maximum $PM_{2.5}$ concentrations averaging 154 $\mu g/m^3$ that ranged from 22 to 209 $\mu g/m^3$.

The emissions from marijuana and tobacco cigarettes have been found to contain many of the same toxic chemicals and carcinogens (Moir et al., 2008; Sheehan et al., 2018; Graves et al., 2020). In view of the large emission rates from marijuana smoking measured in the present study and the many similar toxic air pollutants found in both marijuana and tobacco smoke in previous studies, we conclude that additional research is needed on the health effects of secondhand smoke from cannabis smoking and vaping. More research also is needed on personal exposure to secondhand marijuana smoke. To the best of our knowledge, this is the first systematic study measuring $PM_{2.5}$ concentrations, mass emission rates, and decay rates from secondhand smoke produced by using different cannabis sources indoors in a residence.

This study plan was approved by the Institutional Review Board at Stanford University. The authors declare this paper raises no ethical concerns.

CRediT authorship contribution statement

Wayne R. Ott: Methodology, Formal analysis, Writing – original draft. **Tongke Zhao:** Conceptualization, Methodology, Writing – review & editing. **Kai-Chung Cheng:** Conceptualization, Experimental Design, Investigation. **Lance A. Wallace:** Conceptualization, Methodology, Writing – review & editing. **Lynn M. Hildemann:** Conceptualization, Project administration.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2021.100106.

References

Berg, C.J., Buller, D.B., Schauer, G.L., Windle, M., Stratton, E., Kegler, M.C., 2015. Rules regarding marijuana and its use in personal residences: findings from marijuana users and nonusers recruited through social media. J. Eviron. Public Health, 476017. Accessed 3/10/21. https://doi.org/10.1155/2015/476017.

Berg, C.J., Haardörfer, R., Wagener, T.L., Kegler, M.C., Windle, M., 2018. Correlates of allowing tobacco product or marijuana use in the homes of young adults. Pediatrics 141, 2018. https://doi/10.1542/peds.2017-1026E.

Berthet, A., De Cesare, M., Favrat, B., Sporkert, F., Augsburger, M., Thomas, A., Giroud, C., 2016. A systematic review of passive exposure to cannabis. Forensic Sci. Int. 269, 97–112. https://doi.org/10.1016/j.forsciint.2016.11.017.

Business Daily, Marijuana, 2020. Accessed 8/1/2020. https://mjbizdaily.com/chart-number-california-licensed-recreational-marijuana-stores-falls-short/.

California Department of Public Health, 2020. Let's talk cannabis: what's legal for adult use. Accessed 11/1/20. https://www.cdph.ca.gov/Programs/DO/letstalkcannabis/CDPH%20Document%20Library/October%202017%20Update/CDPH-Legal.pdf.

Cecinato, A., Romagnoli, P., Perilli, M., Patriarca, C., Balducci, C., 2014a. Psychotropic substances in indoor environments. Environ. Int. 71, 88–93. https://doi.org/10.1016/j.envint.2014.06.008. Accessed 11/19/20).

Cecinato, A., Balducci, C., Romagnoli, P., Perilli, M., 2014b. Behaviours of psychotropic substances in indoor and outdoor environments of Rome, Italy. Environ. Sci. Pollut. Res. 21, 9193–9200. https://doi.org/10.1007/s11356-014-2839-2.

Chen, C., Zhao, Y., Zhao, B., 2018. Emission rates of ultrafine and fine particles generated from human smoking of Chinese cigarettes. Atmos. Environ. 194, 7–13. https://doi.org/10.1016/j.atmosenv.2018.09.014. Accessed 11/19/20.

Chu, A.K., Kaufman, P., Chaiton, M., 2019. Prevalence of involuntary environmental cannabis and tobacco smoke exposure in Multi-Unit Housing. Int. J. Environ. Res. Publ. Health 16, 3332. https://doi.org/10.3390/ijerph16183332.

Cone, E.J., Johnson, R.E., Darwin, W.D., Yousefnejad, D., Mell, L.D., Paul, B.D., Mitchell, J., 1987. Passive inhalation of marijuana smoke: urinalysis and room air levels of delta-9-tetrahydrocannabinol. J. Anal. Toxicol. 11, 89–96.

Dacunto, P.J., Cheng, K.-C., Acevedo-Bolton, V., Jiang, R.-T., Klepeis, N.E., Repace, J.L., Ott, W.R., Hildemann, L.M., 2013. Real-time particle monitor calibration factors and $PM_{2.5}$ emission factors for multiple indoor sources. Environ. Sci. Processes Impacts 15, 1511–1519. https://doi.org/10.1039/c3em00209h.

Ferro, A.R., Klepeis, N.E., Ott, W.R., Nazaroff, W.W., Hildemann, L.M., Switzer, P., 2009. Effect of interior door position on room-to-room differences in residential pollutant concentrations after short-term releases. Atmos. Environ. 43, 706–714. https://doi.org/10.1016/j.atmosenv.2008.09.032.

Goodwin, R.D., Cheslack-Postava, K., Santoscoy, S., Bakoyiannis, N., Hasin, D.S., Collins, B.N., Lepore, S.J., Wall, M.M., 2018. Trends in cannabis and cigarette use among parents with children at home: 2002-2015. Pediatrics 141 (6). https://doi.org/10.1542/peds.2017-3506.

Graves, B.M., Johnson, T.J., Nishida, R.T., Dias, R.P., Savareear, B., Harynuk, J.J., Kazemimanesh, M., Olfert, J.S., Boies, A.M., 2020. Comprehensive characterization of mainstream marijuana and tobacco smoke, *Scientific Reports*. Nature Research Journals. Accessed 3/10/21. https://doi.org/10.1038/s41598-020-63120-6.

Hiller, F.C., Wilson, F.J., Mazumder, M.K., Wilson, J.D., Bone, R.C., 1984. Concentration and particle size distribution in smoke from marijuana cigarettes with different Δ^9-Tetrahydrocannabinol content. Fund. Appl. Toxicol. 4, 451–454.

Hughes, S.C., Bellettiere, J., Nguyen, B., Liles, S., Klepeis, N.E., Quintana, P.J.E., Berardi, V., Obayashi, S., Bradley, S., Hofstetter, C.R., Hovell, M.F., 2018. Randomized trial to reduce air particle levels in homes of smokers and children. Am. J. Prev. Med. 54 (3), 359–367. https://doi.org/10.1016/j.amepre.2017.10.017. Accessed 11/19/20.

Johnston, L.D., Miech, R.A., O'Malley, P.M., Bachman, J.G., Schulenberg, J.E., Patrick, M.E., 2019. Monitoring the future: national survey results on drug use, 1975-2019, 2019 overview, key findings on adolescent drug use. https://files.eric.ed.gov/fulltext/ED604018.pdf.

Klepeis, N.E., Bellettiere, J., Hughes, S.C., Nguyen, B., Berardi, V., Liles, S., Obayashi, S., Hofstetter, C.R., Blumberg, E., Hovell, M.F., 2017. Fine particles in homes of predominantly low income families with children and smokers: key physical and behavioral determinants to inform indoor-air-quality interventions. PloS One 12 (5), e0177718. https://doi.org/10.1371/journal.pone.0177718. Accessed 11/19/20.

Mage, D.T., Ott, W.R., 1996. Accounting for nonuniform mixing and human exposure in indoor environments. In: Characterizing Sources of Indoor Air Pollution and Related Sink Effects, ASTM Publication Code Number (PCN):04-012870-17, STP 1287, Tichenor , B.A. American Society for Testing and Materials, West Conshohocken, PA, pp. 263–278.

Miech, R.A., Johnston, L., O Malley, P.M., Bachman, J.G., Schulenberg, J.E., Patrick, M.E., 2019. Monitoring the future: national survey on drug use, 1975-2018: secondary school students (Accessed 8/1/20. http://monitoringthefuture.org/pubs/monographs/mtf-vol1_2018.pdf.

Moir, D., Rickert, W.S., Levasseur, G., Larose, Y., Maertens, R., White, P., Desjardins, S., 2008. A comparison of mainstream and sidestream marijuana and tobacco cigarette smoke produced under two machine smoking conditions. Chem. Res. Toxicol. 21, 494–502.

Moore, C., Coulter, C., Uges, D., Tuyay, J., van der Linde, S., van Leeuwen, A., Garnier, M., Orbita, J., 2011. Cannabinoids in oral fluid following passive exposure to marijuana smoke. Forensic Sci. Int. 212, 227–230. https://doi.org/10.1016/j.forsciint.2011.06.019.

Ni, Y., Shi, G., Qu, J., 2020. Indoor $PM_{2.5}$, tobacco smoking and chronic lung disease: a narrative review. Environ. Res. 181, 108910. https://doi.org/10.1016/j.envres.2019.108910.

Ott, W.R., 2007. Mathematical modeling of indoor air quality. ch 18. In: Ott, W.R., Steinemann, A.C., Wallace, L.A. (Eds.), Exposure Analysis. Taylor and Francis, Boca Raton, FL, pp. 411–444.

Ott, W.R., Klepeis, N.E., Switzer, P., 2003. Analytical solutions to compartmental indoor air quality models with application to environmental tobacco smoke concentrations measured in a house. J. Air Waste Manag. Assoc. 53, 918–936.

Posis, A., Bellettiere, J., Liles, S., Alcaraz, J., Nguyen, B., Berardi, V., Klepeis, N.E., Hughes, S.C., Wu, T., Hovell, M.F., 2019. Indoor cannabis smoke and children's health. Prev. Med. Rep. 14, 100853. https://doi.org/10.1016/j.pmedr.2019.100853. Accessed 11/19/20.

Repace, J.L., 2007. Exposure to secondhand smoke. In: Ott, W.R., Steinemann, A.C., Wallace, L.A. (Eds.), Exposure Analysis. Taylor and Francis, Boca Raton, FL, pp. 201–235 ch 9.

Schauer, G.L., King, B.A., Bunnell, R.E., Promoff, G., McAfee, T.A., 2016. Toking, vaping, and eating for health or fun, Marijuana use patterns in adults, U.S., 2014. Am. J. Prev. Med. 50 (1), 1–8. Accessed 11/19/20. https://www.ajpmonline.org/article/S0749-3797(15)00320-7/fulltext.

Schick, S., Glantz, S., 2005. Scientific analysis of second-hand smoke by the tobacco industry, 1929-1972. Nicotine Tob. Res. 7 (4), 591–612. https://doi.org/10.1080/14622200500185082.

Sheehan, T.J., Hammett, H.J., Beasley, R., Fitzmaurice, P.S., 2018. Chemical and physical variations of cannabis smoke from a variety of cannabis samples in New Zealand. Forensic Sci. Res. 4 (2), 168–178. https://doi.org/10.1080/20961790.2018.1445937. Accessed 11/19/20.

Tashkin, D.P., Gliederer, F., Rose, J., Chang, P., Hui, K.K., Yu, J.L., Wu, T.-C., 1991. Tar, CO, and Δ^9THC delivery from the 1st and 2nd halves of a marijuana cigarette, *Pharmacol.* Biochem. Behav. 40, 657–661.

Thatcher, T.L., Lai, A.C.K., Moreno-Jackson, R., Sextro, R.G., Nazaroff, W.W., 2002. Effects of room furnishings and air speed on particle deposition rates indoors. Atmos. Environ. 36, 1811–1819.

Wallace, L., Ott, W., Zhao, T., Cheng, K.-C., Hildemann, L., 2020. Secondhand exposure from vaping marijuana: concentrations, emissions, and exposures determined using both research-grade and low-cost monitors. Atmos. Environ. X https://doi.org/10.1016/j.aeaoa.2020.100093. Accessed 11/19/20.

Wang, X., Derakhshandeh, R., Liu, J., Narayan, S., Nabavizadeh, P., Le, S., Danforth, O. M., Pinnamaneni, K., Rodriguez, H.J., Luu, E., Sievers, R.E., Schick, S.F., Glantz, S.A., Springer, M.L., 2016. One minute of marijuana secondhand smoke exposure substantially impairs vascular endothelial function. J. Am. Heart Assoc. 5, e003858 https://doi.org/10.1161/JAHA.116.003858, 2016.

Wu, T.-C., Tashkin, D.P., Rose, J.E., Djahed, B., 1988. Influence of marijuana potency and amount of cigarette consumed on marijuana smoking pattern. J. Psychoact. Drugs 20 (1), 43–46. https://doi.org/10.1080/02791072.1988.10524370. Accessed 11/19/20.

Zhao, T., Cheng, K.-C., Ott, W.R., Wallace, L.A., Hildemann, L.M., 2020. Characteristics of secondhand cannabis smoke from common smoking methods: calibration factor, emission rate, and particle removal rate. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2020.117731. Accessed 3/10/21.