Title

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

Permalink

https://escholarship.org/uc/item/7c6743m6

Authors

Zhao, Tongke
Cheng, Kai-Chung
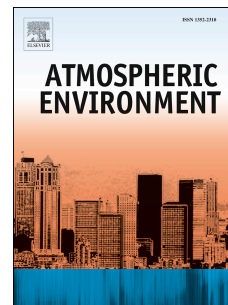Ott, Wayne R
et al.

Publication Date

2020-12-01

DOI

10.1016/j.atmosenv.2020.117731

Peer reviewed

Journal Pre-proof

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

Please cite this article as: Zhao, T., Cheng, K.-C., Ott, W.R., Wallace, L., Hildemann, L.M., Characteristics of secondhand cannabis smoke from common smoking methods: Calibration factor, emission rate, and particle removal rate, *Atmospheric Environment* (2020), doi: https://doi.org/10.1016/j.atmosenv.2020.117731.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Tongke Zhao: Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization

Kai-Chung Cheng: Conceptualization, Formal analysis, Investigation, Writing - Review & Editing, Funding acquisition

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

1 **Characteristics of Secondhand Cannabis Smoke from Common**

2 **Smoking Methods: Calibration Factor, Emission Rate, and Particle**

3 **Removal Rate**

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

5 Civil and Environmental Engineering, Stanford University,

6 Stanford, California 94305, United States

Abstract

8 The widespread legalization of recreational cannabis use raises growing concerns about

9 exposure to secondhand cannabis smoke (SCS). However, few studies are characterizing fine

10 particulate matter ($PM_{2.5}$) exposure from SCS. Here, we determined $PM_{2.5}$ calibration factors (CFs)

11 for SCS from four common cannabis consuming methods—glass pipe smoking, joint smoking,

12 bong smoking, and cannabis pen vaping—for widely used optical monitors (SidePak[TM] AM510,

13 TSI Inc., Shoreview, MN) by comparing the monitors with gravimetric mass measurements. We

14 furthermore investigated the emission rate, particle size distribution, and particle removal rate of

15 SCS. The CFs of SidePak $PM_{2.5}$ monitors measuring the four types of SCS were 0.31 (SE=0.02),

16 0.39 (SE=0.02), 0.40 (SE=0.01), and 0.44 (SE=0.03), respectively. The arithmetic mean emission

17 rates of the four SCS sources were ~2-6 times that of secondhand tobacco smoke (STS) on a per-

18 puff basis. The fresh SCS (1-min after smoking) showed a bimodal size distribution—one mode

19 located at ~380-420 nm and another at ~800-840 nm. Under low-ventilation conditions, the indoor

20 removal rates of SCS from cannabis vaping were slightly higher (i.e., 0.61-0.77/h) than those for the

21 other three sources (i.e., 0.35-0.53/h).

22 ***Key Words***: *cannabis; marijuana; particulate matter; calibration factor; size distribution; emission*

23 *rate; removal rate; PM$_{2.5}$; aerosols;*

24 **Graphical Abstract**

25
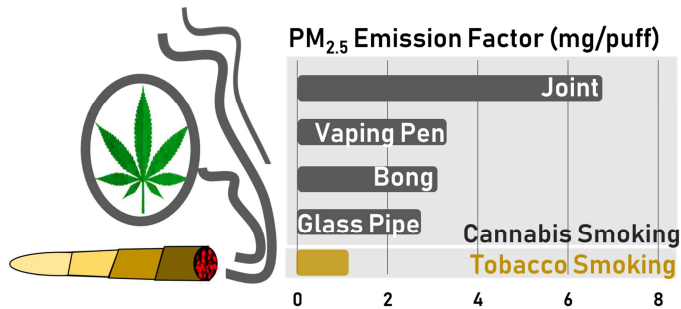
1. Introduction

27   With the expanding worldwide legality of adult recreational cannabis use (Shi et al., 2019), the

28 popularity of consuming cannabis continues to grow. As in June of 2019, eleven states in the United

29 States had legalized recreational cannabis use, and Canada and Uruguay have legalized cannabis

30 nationwide (Wikipedia, 2019). Studies showed that in legalized states, cannabis use increased in

31 both over and under 21-year-old people (Kerr et al., 2017; Parnes et al., 2019; Parnes et al., 2018).

32 Also, the legalization of cannabis use stimulates the growth of cannabis dispensaries, which tends to

33 increase the consuming population (Dills et al., 2016).

34   When smoking or vaping cannabis, the high-temperature combustion or vaporization process

35 produces high levels of fine particulate matter (PM$_{2.5}$) emissions, which is well-known to cause

36 respiratory and cardiovascular diseases (Dominici et al., 2006). This makes secondhand cannabis

37 smoke (SCS) an emerging air quality and health concern (Gates et al., 2014). The delta-9-

38 tetrahydrocannabinol (THC) in cannabis, which may cause psychosis-like effects (D'Souza et al.,

39 2004), is emitted into the air, leading to passive exposure (Balducci et al., 2009). It has been found

40 that children living in homes with indoor cannabis smoking had 83% higher odds of adverse health

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

42 Cannabis smoking methods are varied—including glass pipe, joint, and bong smoking, as well

43 as vaping—making the characteristics and exposure assessment of SCS complex. Glass pipe

44 smoking is a combustion particle source. The smoker lights up cannabis buds in the bowl of a glass

45 pipe and gives a puff. The joint is a pre-rolled cigarette filled with loose cannabis leaves. Unlike

46 regular commercial cigarettes, which are usually the same length and circumference, joints vary in

47 size. A bong, also known as a water pipe, burns cannabis buds in the bowl and filters the smoke by

48 water in the glass reservoir before the smoke is inhaled. A cannabis vaping pen is similar to an e-

49 cigarette, the emission process of which involves heating and subsequent evaporation and

50 condensation of cannabis vape liquid (Giroud et al., 2015). Unlike the e-liquid in an e-cigarette,

51 which contains mostly volatile compounds like propylene glycol or glycerol (Zhao et al., 2017;

52 Zhao et al., 2016), the cannabis vape liquid usually contains THC and cannabinoid (CBD)

53 concentrates, vitamin E acetate, triglyceride oils, terpenes and relatively small amounts of propylene

54 glycol and glycerol (Blount et al., 2020; Giroud et al., 2015), which are more viscous and less

55 volatile than e-liquid.

56 There is little research about the characteristics of or exposure to fine particulate matter ($PM_{2.5}$)

57 in SCS. It is known that optical $PM_{2.5}$ monitor output depends on the optical and physical

58 characteristics of particles, including density, refractive index, and size distribution, which vary

59 with $PM_{2.5}$ sources (Hinds, 2012). It is crucial that validated calibration factors (CFs) be determined

60 for different aerosol mixtures of interest for a research-grade monitor, which then can produce

61 accurate measurements of $PM_{2.5}$ mass concentrations. Health-based air quality standards are written

62 in units of $\mu g/m^3$, increasing the importance of precise measurements of $PM_{2.5}$ mass concentrations

63 for evaluating health risks. The SidePak (AM510, TSI Inc., Shoreview, MN) is one of the most

64 popular research-grade, small, and portable $PM_{2.5}$ real-time monitors on the market. The CFs of

65   SidePaks have been developed and published for aerosols from a variety of particle sources (e.g.,

66   water pipes, cigarettes, stick incense, fireplace emissions, wildfires, candles, burning toast, etc.)

67   (Dacunto et al., 2013; Jiang et al., 2011; Travers et al., 2018). Moreover, a number of published

68   studies have used SidePak monitors to measure $PM_{2.5}$ mass concentrations from STS, taking

69   advantage of the instrument's portability, 8-hour battery life, data logging capability, and validated

70   CFs (Acevedo☐Bolton et al., 2014; Cho et al., 2014; Klepeis et al., 2003; Klepeis et al., 2016; Ott et

71   al., 2017; Repace et al., 2011). No previously published studies have estimated the SidePak CFs for

72    $PM_{2.5}$ from cannabis sources. Therefore, to accurately assess the $PM_{2.5}$ exposure from SCS, we first

73   focused on the CFs of SCS from four cannabis smoking methods. Using the results presented in this

74   paper, we can add cannabis joints, bongs, glass pipe, and vaping to the long list of sources for which

75   SidePak CFs have been developed for estimating mass concentrations.

76   Since gravimetric filter sampling is accurate but time-consuming, we also used a Piezobalance

77   (also known as a piezoelectric microbalance, Model 8511, TSI Inc., Shoreview, MN), which is a

78   real-time, portable gravimetric PM measurement device. A Piezobalance fitted with a $PM_{2.5}$

79   impactor collects $PM_{2.5}$ on a crystal, which oscillates in an electric circuit at a certain resonant

80   frequency. As the mass of the crystal changes when $PM_{2.5}$ is deposited on it, the resonant frequency

81   changes and this change is proportional to the mass of deposited $PM_{2.5}$ (Sem et al., 1977). In this

82   study, we investigate the feasibility of using the Piezobalance to measure the $PM_{2.5}$ concentrations

83   of SCS accurately.

84   This study, for the first time, characterizes the CFs, emission rates (*mg/puff*), particle size

85   distributions, and removal rates of SCS from four cannabis smoking methods: glass pipe smoking,

86   joint smoking, bong smoking, and cannabis vaping. We compare the emission rates of SCS with

87   that of secondhand tobacco smoke (STS). The particle size distribution determines the deposition in

88   human respiratory tracts and affects the removal on room surfaces (Nazaroff and Klepeis, 2003).

89 Thus, these results can serve as input for assessing exposure to SCS and for studying the impacts

90 and fate of SCS indoors.

2. Method and Materials

2.1 Participant

93 A habitual user of cannabis and tobacco, who consumes cannabis in multiple ways, was

94 recruited to help generate SCS. The study protocol was accepted by the participant, and a signed

95 consent form was obtained before the experiments. The cannabis materials and consuming devices

96 used in this study were provided by the participant. The study protocol was approved by the

97 Institutional Review Board at Stanford University.

2.2 Cannabis Devices and Materials

99 **Table 1.** Pictures of the smoking devices and the THC and CBD proportions in the corresponding

100 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

101 *Proportions as reported on the packaging labels.

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

103   smoking, bong smoking, and cannabis pen vaping. Pictures of the devices and the THC and CBD

104   proportions in the corresponding cannabis materials are shown in **Table 1**. The glass pipe was 10

105   cm in length and was equipped with a 2 cm diameter bowl. On each use, the habitual smoker put ~

106   0.2 g of cannabis buds into the bowl before lighting it. The mass of cannabis buds was weighed on a

107   microbalance (Model XPR6UD5, Mettler Toledo Inc., Columbus, OH). The joint was 64 mm in

108   length, and its larger end was 8 mm in diameter while its smaller end, which was the mouthpiece,

109   was 4 mm in diameter. The weight of each joint was ~0.8 g. The bong was 18 cm tall, and its

110   reservoir was filled with ~100 mL water. On each bong use, the smoker placed ~ 0.2 g of cannabis

111   buds into the bong's 2 cm diameter bowl. The battery-powered vaping pen was 8.7 cm long and 1.1

112   cm in diameter, and it was attached to a cannabis cartridge labeled *"18:1 CBD:THC"*. On each use,

113   the participant selected the *High Heat* setting and pre-heated the vaping pen for about five seconds

114   prior to using it. To compare the emission rates and removal rates of SCS with those of secondhand

115   tobacco smoke (STS), we also included cigarette smoking in this study. The cigarettes were regular

116   Marlboro cigarettes.

117   **2.3 Real-time Particle Measurements**

118   We used six SidePak monitors and two Piezobalances to measure the real-time $PM_{2.5}$

119   concentrations with a data logging time interval of 1-min. Before each experiment, we cleaned and

120   greased the impactor inside each SidePak as recommended in the manual, and we zeroed each

121   SidePak by attaching its inlet to a high-efficiency air filter. Before each experiment, the crystal in

122   each Piezobalance was cleaned by applying a detergent to a sponge that was placed in direct contact

123   with the crystal followed by a second sponge with distilled water to clean off the detergent. The

124   sampling flow rate was verified to be 1.0 L/min by a flow meter (Sensidyne, Clearwater, FL, USA).

125   The particle number concentrations measured by an optical particle sizer (OPS 3330, TSI Inc.,

126   Shoreview, MN) ranged from 0.3 to 10 μm. The data logging interval was 1 min. We captured the

127   particle size distributions at 1, 30, and 90 mins after the smoking activity to examine the dynamics

128   of SCS. The number of modes for each particle size distribution was determined via visual

129   inspection. Then, we divided the spectrum into one or two sub-groups according to the number of

130   modes. Each sub-group was fitted with a lognormal distribution by using Sigmaplot 12.5 lognormal

131   three-parameter fitting procedure (Zhu et al., 2002), yielding the count median diameter (CMD) and

132   geometric standard deviation (GSD) for each particle size distribution mode.

133   **2.4 Gravimetric Sampling Method**

134   Two custom-built cyclones (John and Reischl, 1980) were used to provide a 50% cut-size of

135   2.5 μm and to collect particles less than or equal to 2.5 μm on 47 mm PTFE filters (2 μm pore size,

136   Pall Corp., Ann Arbor, MI). Each pump's sampling flow rate was ~18-20 L/min as designated by

137   each cyclone and calibrated by a flow meter (Gilian Instrument Corp., West Caldwell, NJ). The

138   filters were conditioned for 24-48 hours in an environmental chamber with a constant temperature

139   of 24 ^{o}C and relative humidity (RH) within 30-40%, allowing equilibrium of semi-volatiles. Filters

140   then weighed by a microbalance (Model XPR6UD5, Mettler Toledo Inc., Columbus, OH) with a

141   readability of 0.5 μg before and after each sampling. Each filter was usually measured three times,

142   and the absolute error was no more than 3 μg. The range of the sampling $PM_{2.5}$ concentrations was

143   from 50 to 1500 μg/m^3. The sampling time was pre-estimated to aim for a collected mass of more

144   than 100 μg on the filter. During a typical ~2.5 hours decay period in each experiment, we collected

145   two or three filter samples. Therefore, when we sampled at a higher concentration range, the

146   sampling time length was shorter. Certainly, when we sampled at a lower concentration range, the

147   sampling time length was longer. An example of a sampling period, including time lengths,

148   concentrations ranges, and mass collected on the filter, is shown in the **Supporting Information**

149   **Table S1**. Finally, the collected mass on the filter, sampling time length, and pump flow rate were

150   used to determine the mean $PM_{2.5}$ mass concentration during a sampling period.

151   **2.5 Experimental Setting and Protocol**

152   The study was conducted in a car that was used as an air chamber and parked in an attached

153   garage in Redwood City, CA. The car was a Honda Element 2006, with no carpet covering. The

154   second-row seats were removed to provide more space. The volume of the cabin was measured as

155   6.5 m^3 (SD=0.3 m^3, n=5) by using sulfur hexafluoride (SF_6) as the tracer gas. The measurement

156   method with a diagram of the setup can be found in the **Supporting Information** and its **Figure S1**.

157   The experiments were conducted from Dec. 2018 to Mar. 2019, when the indoor temperature and

158   RH were within the range of 15 to 22 ^{o}C and 30 to 70%, respectively.

159   In the car chamber, six SidePak monitors were placed on the backseat behind the driver's seat.

160   The Piezobalances, the OPS 3330, and the gravimetric sampling instruments were placed outside

161   the car, and each was connected to the car with $Tygon^{TM}$ tubing. The intake ends of the tubing were

162   collocated with the SidePak sampling tubing inside the car. A small battery-powered fan with an

163   11-cm diameter blade was used inside the car to help mix the air.

164   Before each experiment, the car's doors and windows, as well as the garage's doors were

165   opened to flush the chamber with ambient air. After that, the doors and windows were closed again,

166   and we started the instruments and measured the background concentrations for at least 10 minutes.

167   Then the smoker entered the car and sat on the driver's seat. The smoker smoked cannabis by one of

168   the four methods and gave one to three puffs *ad libitum*. As observed, during a puff, the inhaling

169   time was ~ 2 seconds, and the exhaling time was ~2 to 5 seconds. After that, the smoker exited the

170   car promptly, and the car doors remained closed. We extinguished the cannabis combustion with

171   water immediately to minimize the potential of increasing the $PM_{2.5}$ background in the garage.

172   During the experiments, the garage doors remained closed.

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

174 intended to characterize SCS in a realistic situation. We did not provide the participant with any

175 cannabis materials, smoking devices, or research cigarettes. Nor did we introduce smoking sensors

176 to measure the puff topography and the heating temperature as our participant believed they would

177 interfere with his/her consuming behaviors.

178   SidePak's data showed the background is not larger than 5 μg/m^3. As Jiang et al.(2011)

179 showed, the calibration factor of SidePaks measuring ambient particles varied from 0.66 to 0.98.

180 Therefore, we can reasonably assume that the actual PM$_{2.5}$ background concentration is lower than

181 5 μg/m^3.

182   In total, we conducted 28 experiments, including eight on glass pipe smoking, five on joint

183 smoking, six on bong smoking, six on cannabis pen vaping, and three on tobacco cigarette smoking.

184 **2.6 Data Processing**

185   When calculating CFs for SidePaks, we compared the arithmetic mean of six SidePak-

186 measured concentrations over a certain period of sampling time (i.e. 10-90 min) with the arithmetic

187 mean of two masses on the filters. Then we plotted the gravimetric concentrations on the *y*-axis, the

188 SidePak readings on the *x*-axis, and a regression line was forced through zero. The slope is the CF.

189 The agreement among SidePak monitors was evaluated by their absolute percent error (APE) and

190 the method can be found in Jiang et al., (2011). A CF of each SidePak was also obtained by

191 comparing each SidePak's measured concentrations with the gravimetric concentrations by the

192 same method. We also used the same method to determine CFs for the Piezobalances.

193   In this study, we determined the emission rate as the mass of emitted PM$_{2.5}$ per puff (*mg/puff*).

194 Examples of SCS PM$_{2.5}$ concentration decay curves from four cannabis sources and cigarette

195 smoking are shown in the **Supporting Information Figure S2**. The PM$_{2.5}$ time-series

196 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).

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

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.

212

213

214

215

216   **3. Results and Discussion**

217   **3.1 Calibration Factors**

218

219
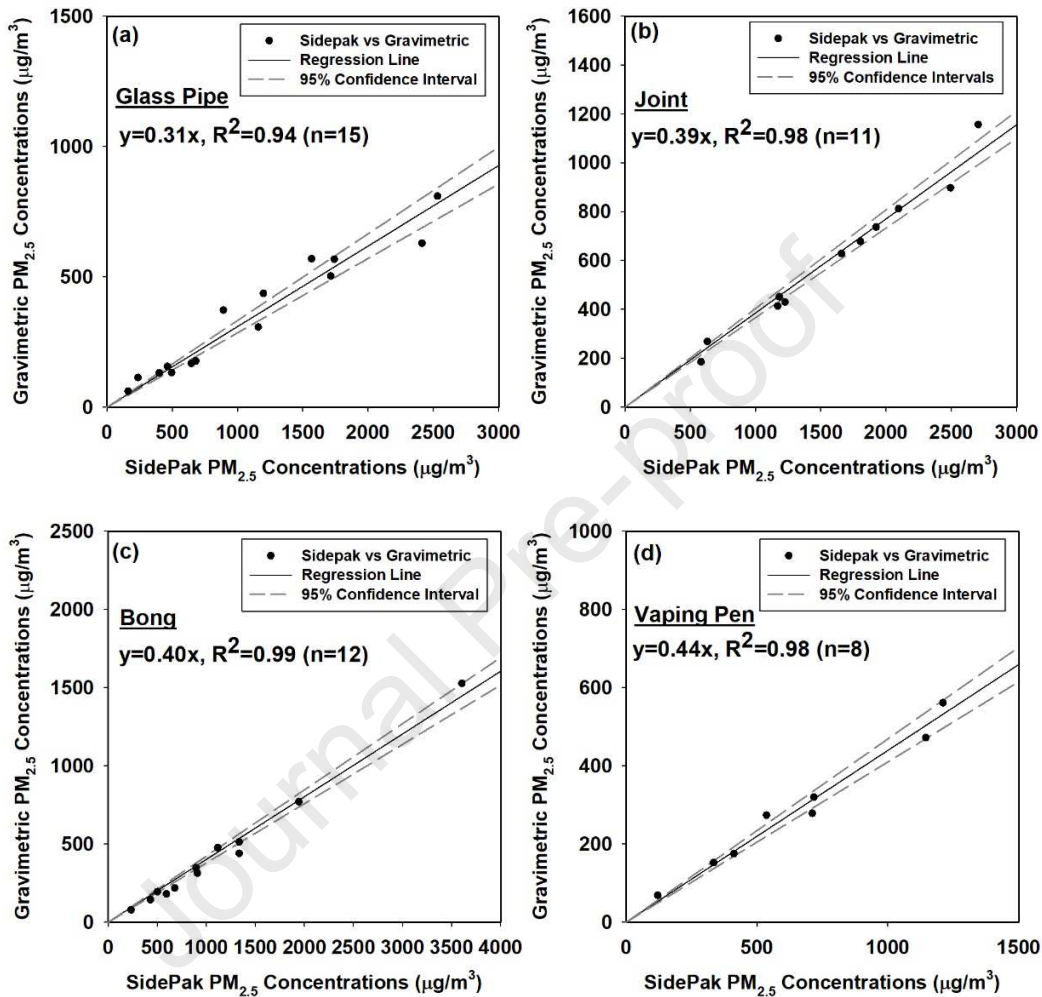
Figure 1. Comparison of gravimetric sampling with SidePak measured $PM_{2.5}$ concentrations for SCS from (a)

221   glass pipe, (b) joint, (c) bong, and (d) vaping pen.

222   **Figures 1a**, **1b**, **1c**, and **1d** show that the SidePak's CFs for SCS from glass pipe smoking,

223   joint smoking, bong smoking and cannabis e-vaping are 0.31 (SE=0.02), 0.39 (SE=0.02), 0.40

224   (SE=0.01), and 0.44 (SE=0.03), respectively. The CFs for SCS are larger than that for STS

225   (CF=0.29) (Jiang et al., 2011). It is worth noting that the cannabis buds used in the study when

226   smoking the glass pipe and the bong were the same.

227   The CFs are highly influenced by the physical characteristics of particles, including the size

228   distribution, shape, density, and refractive index (Hinds, 2012). The CFs for bong and joint

229   smoking were similar. The $PM_{2.5}$ from cannabis vaping had the largest CF, consistent with our

230   previous finding that CFs for non-combustion heating processes (such as cooking on an electric

231   stove) are larger than for combustion emissions (Dacunto et al., 2014).

232   Zhao et al. (2017) measured the real-time $PM_{2.5}$ concentrations of secondhand e-cigarette

233   vaping aerosols from active human use in indoor environments. That study found that e-cigarette

234   vaping aerosols went through quick evaporation, and the concentrations did not have a constant

235   first-order decay rate. In contrast, we observed relatively constant decay rates in SCS from cannabis

236   vaping in the car chamber (**Supporting Information Figure S2**).

237   Since six SidePak monitors were employed in this study, a CF for each monitor was also

238   investigated (**Supporting Information Table S2**). The *R*-squared values for each linear regression

239   result were all ≥ 0.94. We found discrepancies between a CF derived from an arithmetic mean of six

240   SidePak readings and a CF for an individual SidePak (i.e., CF ranges for glass pipe: 0.27-0.37, joint:

241   0.33-0.40, bong: 0.35-0.45, and vaping pen: 0.38-0.50), although our SidePaks are factory-

242   calibrated yearly. We found the APEs of all SidePaks were within 10%, except for one that was

243   16%. These results suggest it is desirable to derive a CF for each $PM_{2.5}$ optical monitor to ensure

244   accurate exposure measurements.

245   The CFs for the Piezobalance measuring $PM_{2.5}$ in SCS from glass pipe smoking, joint

246   smoking, bong smoking, and vaping are 1.06 (SE=0.05), 1.15 (SE=0.06), 1.03 (SE=0.02), and 0.86

247   (SE=0.04), respectively (as shown in **Supporting Information Figures S3a, S3b, S3c**, and **S3d**).

248   The results are consistent with a previous study showing that the Piezobalance's results agree within

249   15% of gravimetric sampling mass for a variety of aerosols, including polymer beads, road dust,

250   pollen, and tobacco smoke (Sem et al., 1977). The CF (1.06) of SCS from the glass pipe is almost

251   the same as that from a bong (1.03). This is different from the SidePak CFs for these two sources

252   (Glass pipe: 0.31; Bong: 0.40 in **Figure 1**)—unlike SidePaks, the Piezobalance measurements do

253   not vary with aerosol optical properties. Since gravimetric sampling is usually time-consuming and

254   requires high-precision measurements of the mass, the Piezobalance can be used as a quick

255   reference method.

256   **3.2 Emission rates**

257
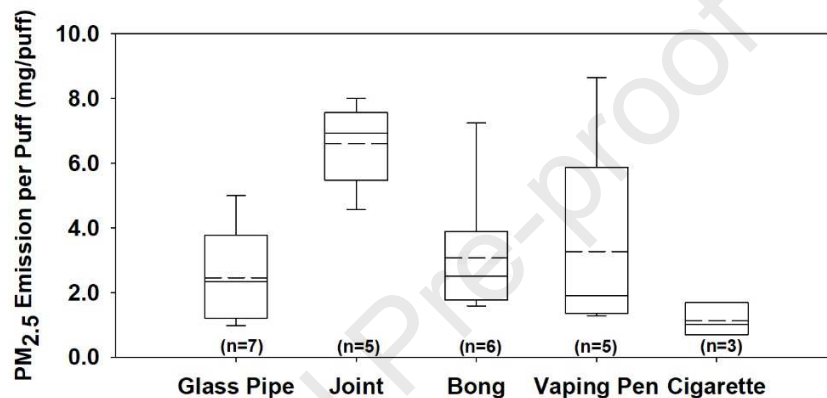
258   **Figure 2**. The emission rates (*mg/puff*) of glass pipe, joint, bong, vaping pen, and tobacco cigarette. (In each

259   boxplot, the dashed line represents the arithmetic mean value, and the solid line represents the median value.

260   The upper whisker represents the maximum value, while the lower whisker represents the minimum value.)

261   Although it is typical to express emission rates of STS as the emitted $PM_{2.5}$ mass per tobacco

262   cigarette (*mg/cigarette*) or the emitted $PM_{2.5}$ mass per minute (*mg/min*), these methodologies cannot

263   be generalized to SCS from various smoking methods. Glass pipe and bong smoking use cannabis

264   buds, and the quantities of each depend on the smokers' preferences. Joints vary in size, as do

265   cannabis vaping pens. Moreover, cannabis smoking often follows unique smoking patterns—

266   cannabis glass pipe and bong smokers usually smoke for only one or two puffs at a time. The puff

267   intervals vary and are difficult to estimate. Thus, we report the emission rate as the emitted $PM_{2.5}$

268   mass per puff (*mg/puff*).

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

270 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

271 (SD=3.1) mg/puff, while our measurement of the arithmetic mean emission rate of STS from

272 cigarette smoking is only 1.1 (SD=0.5) mg/puff. The $PM_{2.5}$ emission rates (*mg/puff*) of the four SCS

273 methods are ~2-6 times the emission rate of STS. Nazaroff and Klepeis (2003) summarized 17

274 studies and reported a median emission rate for cigarette smoking as 12.7 mg/cigarette (including

275 both machine and human smoking), and these studies showed that a typical commercial cigarette is

276 sustainable for 6-16 puffs (Klepeis et al., 2003; Loefroth et al., 1989; Singer et al., 2002). Thus, the

277 emission rate of cigarette smoking can be estimated as 0.8-2 mg/puff, placing our STS data within

278 this range.

279   We also observed that the cannabis buds often go out very quickly after each puff, so the SCS

280 from a glass pipe and bong smoking might be mainly exhaled mainstream smoke. In addition, the

281 SCS from vaping is entirely exhaled mainstream aerosol. Like STS from tobacco smoke, SCS from

282 joint smoking is mostly a mixture of smoldering smoke between puffs (sidestream) and exhaled

283 mainstream smoke, which might be the reason that it had the highest emission rate of the four

284 cannabis sources tested.

285 **3.3 Size Distributions**

286   The size distributions of SCS from the four common smoking methods (i.e., glass pipe smoking,

287 joint smoking, bong smoking, and cannabis pen vaping) at 1, 30, and 90 mins after each smoking

288 activity are shown in the **Supporting Information Figures S4a**, **S4b**, **S4c**, and **S4d**, respectively.

289 These data for glass pipe smoking, joint smoking, and bong smoking are based on a single puff,

290 while the vaping experiment is based on three puffs. Because the background concentration was not

291 significant compared to the SCS concentration, the size distribution of the background particles was

292 not subtracted. The results showed that the number concentration of fresh SCS (1-minute after

293 smoking) is bimodal—one mode located at ~380-420 nm and a smaller mode at ~800-840 nm. The

294   CMDs and GSDs for each mode are provided in **Supporting Information Table S3**. Our

295   observation of a ~380-420 nm mode is similar to Hiller et al. (1984), in which a puffing machine

296   was used to smoke a cannabis joint (85 mm in length and 25 mm in circumference) with the smoke

297   quickly diluted 126,000-fold. Their results, measured by a single particle aerodynamic relaxation

298   time analyzer, showed the mode ranged from 350 to 430 nm.

299   **3.4 Removal Rates**

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

301   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

302   * The removal rate represents the removal due to both the particle surface deposition and evaporation. The

303   air exchange rate has been subtracted from the total decay rate.

304   The AER in the stationary car with closed windows and doors during ten experiments was

305   0.47-0.59/h, mainly governed by the forced airflows due to the gravimetric sampling (18-20 L/min

306   each), as well as the Piezobalances and OPS sampling (1 L/min each). As shown in **Table 2**,

307   excluding ventilation, the removal rates of SCS from a glass pipe, joint, bong, and cigarette

308   smoking were similar, ranging from 0.35 to 0.53/h. The SEs were all < 0.001. These removal rates

309   were affected by the increased air velocity and therefore higher deposition rates produced by the

310   sampling pumps (Lai and Nazaroff, 2000). The removal rates of SCS from the vaping pen were

311   higher (0.61-0.77/h) than other sources. This might be partly due to the evaporation of glycols in

312   cannabis vape liquid, even though as mentioned earlier, the evaporation of particles from cannabis

313   vaping is not expected to be as significant as those from e-cigarette vaping. We observed that the

314   removal rates showed a 20%-33% variation between the two runs for bong smoking, joint smoking,

315   and vaping. The removal of particles was caused by several dynamics, and it can be affected by

316   turbulent intensity, velocity gradient, etc. (Lai, 2002; Lai and Nazaroff, 2000; Thatcher et al., 2002).

317   We cannot conclude a specific reason for the variances through this study. Other studies have

318   investigated removal rates of STS in a car chamber, mostly under high ventilation conditions (Liu

319   and Zhu, 2010; Ott et al., 2008). For low-ventilation conditions, Xu et al. (1994) reported that the

320   arithmetic mean removal rate (subtracting the AER from an overall decay rate) of STS was 0.172/h

321   for an AER of 0.02/h in a 36.5 m^3 room. These results could provide input data for modeling SCS

322   dynamics in in-cabin and indoor environments.

323   **3.5 Limitations of the Study**

324   The large variety of cannabis materials available on the market—various sizes of smoking

325   devices and materials as well as different manufacturing methods—may result in differences in

326   emission rates. Since SCS from glass pipe smoking, bong smoking, and vaping consist mostly of

327   exhaled mainstream smoke, the emission rates will be highly dependent on the puffing

328   topographies. As one of the very first studies focusing on secondhand cannabis emissions, this study

329   did not include a large number of samples. Therefore, various puffing topographies—recruiting a

330   larger group of participants or employing various machine-puffing simulations—should be taken

331   into consideration in the future. The particle size distribution of SCS may also be affected by the

332   cannabis materials and puffing topographies (Zhao et al., 2016).

333   Jiang et al. (2011) found that the CFs of SidePaks for a given emission source were robust.

334   They derived similar CFs when conducting controlled chamber experiments (mean = 0.29, SD

335   =0.02) by using Marlboro cigarettes with a human puffing, and when measuring CFs in casinos with

336   various kinds of cigarettes and human puffing (mean = 0.33, SD = 0.04). They also used 16 SidePak

337   monitors in two sets of controlled chamber experiments 15 months apart, and they found the mean

338   CF for STS differed by only 3% in the two studies. Lee et al. (2008) used Marlboro cigarettes in

339   eight experiments comparing a SidePak monitor with gravimetric filter measurements, reporting

340   almost the same CF value (i.e., 0.295) as Jiang et al.,(2011) (i.e., 0.29). Dacunto et al., (2013)

341   reported a similar CF value (mean = 0.32, SD = 0.01) for the Marlboro cigarette. Since CF values

342   will depend on the sizes and chemical composition of the particulate emissions, they should remain

343   fairly robust for a given source type. However, there may be minor changes in the CF with the age

344   of the emissions, due to gradual changes in size distribution and perhaps the composition of the

345   aerosol.

346   Emission rates can be computed as the emitted $PM_{2.5}$ mass normalized by the mass of

347   consumed materials (*mg/g*), which offers a generalized method to compare emission rates. However,

348   in this study, we did not collect data on the consumed mass of cannabis materials. Use of an

349   emission rate based on *mg/puff* allowed very different types of sources to be compared with each

350   other, such as a cannabis joint with a vaping pen, or a cigarette with a cannabis water bong. For a

351   cannabis joint, a better measure might be the emitted mass per unit length consumed (*mg/mm*),

352   which can be compared with tobacco emission rates.

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

354 methods were not measured but could be valuable for future research. Anderson et al. (1989) found

355 a mode with arithmetic mean CMD of ~ 100 nm when measuring the quickly diluted cannabis joint

356 smoke using an electrical aerosol analyzer.

357 **4. Conclusions**

358   This study, for the very first time, characterized SCS from four cannabis consuming methods

359 and investigated $PM_{2.5}$ calibration factors, emission rates, size distributions, and removal rates. For

360 SCS from four common sources, the calibration factors for the optical monitors ranged from 0.31 to

361 0.44. Moreover, the CFs for the Piezobalances ranged from 0.86 to 1.15. Due to different smoking

362 patterns between cannabis and tobacco smoking, we generalized the emission rate as emitted $PM_{2.5}$

363 mass per puff (*mg/puff*). The results showed the emission rates of SCS were ~2-6 times that of STS.

364 Fresh SCS (1 min after smoking) was observed to have a bimodal distribution—one mode at ~380-

365 420 nm and a smaller mode at ~800-840 nm. Under low-ventilation conditions, the indoor removal

366 rates of SCS from the vaping pen were higher (i.e., 0.61-0.77/h) than those for the glass pipe, joint,

367 bong, and cigarette smoking (which ranged from 0.35 to 0.53/h).

368 **Acknowledgment**

371 **References**

372 Acevedo-Bolton, V., Ott, W., Cheng, K.C., Jiang, R.T., Klepeis, N., Hildemann, L. (2014) Controlled experiments
373 measuring personal exposure to PM 2.5 in close proximity to cigarette smoking. Indoor Air 24, 199-212.

374 Anderson, P.J., Wilson, J.D., Hiller, F.C. (1989) Particle size distribution of mainstream tobacco and marijuana smoke.
375 American Review of Respiratory Disease 140, 202-205.

376 Balducci, C., Nervegna, G., Cecinato, A. (2009) Evaluation of principal cannabinoids in airborne particulates. Analytica
377 chimica acta 641, 89-94.

378 Blount, B.C., Karwowski, M.P., Shields, P.G., Morel-Espinosa, M., Valentin-Blasini, L., Gardner, M., Braselton, M.,
379 Brosius, C.R., Caron, K.T., Chambers, D. (2020) Vitamin E acetate in bronchoalveolar-lavage fluid associated with

380 EVALI. New England journal of medicine 382, 697-705.

381 Cho, H., Lee, K., Hwang, Y., Richardson, P., Bratset, H., Teeters, E., Record, R., Riker, C., Hahn, E.J. (2014) Outdoor
382 tobacco smoke exposure at the perimeter of a tobacco-free university. Journal of the Air & Waste Management
383 Association 64, 863-866.

384 D'Souza, D.C., Perry, E., MacDougall, L., Ammerman, Y., Cooper, T., Braley, G., Gueorguieva, R., Krystal, J.H. (2004)
385 The psychotomimetic effects of intravenous delta-9-tetrahydrocannabinol in healthy individuals: implications for
386 psychosis. Neuropsychopharmacology 29, 1558.

387 Dacunto, P.J., Cheng, K.-C., Acevedo-Bolton, V., Jiang, R.-T., Klepeis, N.E., Repace, J.L., Ott, W.R., Hildemann, L.M.
388 (2013) Real-time particle monitor calibration factors and PM 2.5 emission factors for multiple indoor sources.
389 Environmental Science: Processes & Impacts 15, 1511-1519.

390 Dacunto, P.J., Cheng, K.C., Acevedo-Bolton, V., Jiang, R.T., Klepeis, N., Repace, J., Ott, W., Hildemann, L. (2014)
391 Identifying and quantifying secondhand smoke in source and receptor rooms: logistic regression and chemical mass
392 balance approaches. Indoor Air 24, 59-70.

393 Dills, A.K., Goffard, S., Miron, J. (2016) Dose of reality: The effect of state marijuana legalizations. Cato Institute
394 Policy Analysis.

395 Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L., Samet, J.M. (2006) Fine particulate air
396 pollution and hospital admission for cardiovascular and respiratory diseases. The Journal of the American Medical
397 Association 295, 1127-1134.

398 Gates, P., Jaffe, A., Copeland, J. (2014) Cannabis smoking and respiratory health: consideration of the literature.
399 Respirology 19, 655-662.

400 Giroud, C., De Cesare, M., Berthet, A., Varlet, V., Concha-Lozano, N., Favrat, B. (2015) E-cigarettes: a review of new
401 trends in cannabis use. International journal of environmental research and public health 12, 9988-10008.

402 Hiller, C.F., Wilson Jr, F.J., Mazumder, M.K., Wilson, D.J., Bone, R.C. (1984) Concentration and particle size
403 distribution in smoke from marijuana cigarettes with different Δ9-tetrahydrocannabinol content. Toxicological Sciences
404 4, 451-454.

405 Hinds, W.C. (2012) Aerosol technology: properties, behavior, and measurement of airborne particles. John Wiley &
406 Sons.

407 Jiang, R.-T., Acevedo-Bolton, V., Cheng, K.-C., Klepeis, N.E., Ott, W.R., Hildemann, L.M. (2011) Determination of
408 response of real-time SidePak AM510 monitor to secondhand smoke, other common indoor aerosols, and outdoor
409 aerosol. Journal of environmental monitoring 13, 1695-1702.

410 John, W., Reischl, G. (1980) A cyclone for size-selective sampling of ambient air. Journal of the Air Pollution Control
411 Association 30, 872-876.

412 Kerr, D.C., Bae, H., Phibbs, S., Kern, A.C. (2017) Changes in undergraduates' marijuana, heavy alcohol and cigarette
413 use following legalization of recreational marijuana use in Oregon. Addiction 112, 1992-2001.

414 Klepeis, N.E., Apte, M.G., Gundel, L.A., Sextro, R.G., Nazaroff, W.W. (2003) Determining size-specific emission
415 factors for environmental tobacco smoke particles. Aerosol Science & Technology 37, 780-790.

416 Klepeis, N.E., Dhaliwal, N., Hayward, G., Acevedo-Bolton, V., Ott, W.R., Read, N., Layton, S., Jiang, R., Cheng, K.-C.,
417 Hildemann, L.M. (2016) Measuring indoor air quality and engaging California Indian stakeholders at the Win-River
418 Resort and Casino: collaborative smoke-free policy development. International journal of environmental research and
419 public health 13, 143.

420   Lai, A. (2002) Particle deposition indoors: a review. Indoor Air 12, 211-214.

421   Lai, A.C., Nazaroff, W.W. (2000) Modeling indoor particle deposition from turbulent flow onto smooth surfaces.
422   Journal of Aerosol Science 31, 463-476.

423   Lee, K., Hahn, E.J., Pieper, N., Okoli, C.T., Repace, J., Troutman, A. (2008) Differential impacts of smoke-free laws on
424   indoor air quality. Journal of Environmental Health 70, 24-30.

425   Liu, S., Zhu, Y. (2010) A case study of exposure to ultrafine particles from secondhand tobacco smoke in an automobile.
426   Indoor Air 20, 412-423.

427   Loefroth, G., Burton, R.M., Forehand, L., Hammond, S.K., Seila, R.L., Zweidinger, R.B., Lewtas, J. (1989)
428   Characterization of environmental tobacco smoke. Environmental Science & Technology 23, 610-614.

429   Nazaroff, W.W., Klepeis, N.E. (2003) Environmental tobacco smoke particles.

430   Ott, W., Klepeis, N., Switzer, P. (2008) Air change rates of motor vehicles and in-vehicle pollutant concentrations from
431   secondhand smoke. Journal of exposure science and environmental epidemiology 18, 312-325.

432   Ott, W., Wallace, L., McAteer, J., Hildemann, L. (2017) Fine and ultrafine particle exposures on 73 trips by car to 65
433   non-smoking restaurants in the San Francisco Bay Area. Indoor Air 27, 205-217.

434   Parnes, J.E., Rahm-Knigge, R.L., Smith, J.K., Conner, B.T. (2019) Young adult marijuana use: The influence of
435   individual differences and legalization. Personality and Individual Differences 141, 229-234.

436   Parnes, J.E., Smith, J.K., Conner, B.T. (2018) Reefer madness or much ado about nothing? Cannabis legalization
437   outcomes among young adults in the United States. International Journal of Drug Policy 56, 116-120.

438   Posis, A., Bellettiere, J., Liles, S., Alcaraz, J., Nguyen, B., Berardi, V., Klepeis, N.E., Hughes, S.C., Wu, T., Hovell,
439   M.F. (2019) Indoor cannabis smoke and children's health. Preventive medicine reports 14, 100853.

440   Repace, J.L., Jiang, R.-T., Acevedo-Bolton, V., Cheng, K.-C., Klepeis, N.E., Ott, W.R., Hildemann, L.M. (2011) Fine
441   particle air pollution and secondhand smoke exposures and risks inside 66 US casinos. Environmental Research 111,
442   473-484.

443   Sem, G.J., Tsurubayashi, K., Homma, K. (1977) Performance of the piezoelectric microbalance respirable aerosol
444   sensor. American Industrial Hygiene Association Journal 38, 580-588.

445   Sherman, M.H. (1990) Tracer-gas techniques for measuring ventilation in a single zone. Building & Environment 25,
446   365-374.

447   Shi, Y., Liang, D., Bao, Y., An, R., Wallace, M.S., Grant, I. (2019) Recreational marijuana legalization and prescription
448   opioids received by Medicaid enrollees. Drug and alcohol dependence 194, 13-19.

449   Singer, B.C., Hodgson, A.T., Guevarra, K.S., Hawley, E.L., Nazaroff, W.W. (2002) Gas-phase organics in
450   environmental tobacco smoke. 1. Effects of smoking rate, ventilation, and furnishing level on emission factors.
451   Environmental Science & Technology 36, 846-853.

452   Thatcher, T.L., Lai, A.C., Moreno-Jackson, R., Sextro, R.G., Nazaroff, W.W. (2002) Effects of room furnishings and air
453   speed on particle deposition rates indoors. Atmospheric Environment 36, 1811-1819.

454   Travers, M.J., Kulak, J.A., Vogl, L. (2018) Waterpipe cafés are hazardous to your health: determination of a waterpipe
455   specific calibration factor. International Journal of Hygiene and Environmental Health 221, 48-53.

456   Wikipedia Legality of cannabis, https://en.wikipedia.org/wiki/Legality_of_cannabis. Access date: 05/28/2019.

457 Xu, M., Nematollahi, M., Sextro, R.G., Gadgil, A.J., Nazaroff, W.W. (1994) Deposition of tobacco smoke particles in a
458 low ventilation room. Aerosol Science and Technology 20, 194-206.

459 Zhao, T., Nguyen, C., Lin, C.-H., Middlekauff, H.R., Peters, K., Moheimani, R., Guo, Q., Zhu, Y. (2017)
460 Characteristics of secondhand electronic cigarette aerosols from active human use. Aerosol Science and Technology 51,
461 1368-1376.

462 Zhao, T., Shu, S., Guo, Q., Zhu, Y. (2016) Effects of design parameters and puff topography on heating coil
463 temperature and mainstream aerosols in electronic cigarettes. Atmospheric Environment 134, 61-69.

464 Zhu, Y., Hinds, W.C., Kim, S., Sioutas, C. (2002) Concentration and size distribution of ultrafine particles near a major
465 highway. Journal of the Air & Waste Management Association 52, 1032-1042.

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: